An integrated, landscape-based approach to model the formation and hydrological functioning of wetlands in headwater catchments of the Umzimvubu River, South Africa

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ABSTRACT

An integrated, landscape-based approach to model the formation and hydrological functioning of wetlands in semiarid headwater catchments of the Umzimvubu River, South Africa

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Wetlands are very important elements of the landscape in almost every environment. Addressing the continued loss of wetland area worldwide, wetlands are recognized as highly vulnerable with regard to natural and anthropogenic system changes. Consequently, the research of their natural and socio-economical functions, importance for the water and nutrient cycles and their role as wildlife habitats received increasing scientific and public awareness in the past decades.

The landscape of the semi-arid Eastern Cape Province, South Africa, is characterized by the occurrence of different types of palustrine wetlands. Intensive afforestation in the headwaters of the Umzimvubu catchment since 1989 has changed downstream wetland characteristics, but little attention was given to evaluate and quantify these impacts. Addressing this research deficit, the main objectives of this dissertation are the development of an integrated, landscape-based research approach to improve the understanding of the formation, functioning and dynamics of wetlands and the prognostic modeling and assessment of afforestation impacts on these wetland systems.

The conceptual and methodological approach of this dissertation is based on three individual aspects: i) observation and data mining; ii) integrated system analysis; and iii) system modeling and assessment integrating empirical field studies, laboratory analysis, GIS and remote sensing techniques, system analysis and process-oriented, plant growth and hydrological modeling, This integrated research approach provides information regarding a generalized understanding of dominant environmental processes at wetland and catchment scale and the impact of afforestation on wetland and basin hydrology.

By means of this effort three main wetland types, being different in terms of landscape position, extent and size of the tributary catchment, soils, vegetation composition and hydrological dynamics, could be identified. The hydrodynamics of plateau and slope wetlands are mainly controlled by recharge mechanisms, while larger valley bottom wetlands are driven by interlinked ground-/surface water dynamics, discharge/recharge processes and direct rainfall input. Coupling plant growth and hydrological modeling, it was found that wetland dynamics and their landscape functions will be influenced by afforestation in terms of altered recharge/discharge mechanisms; reduced base flows addressed to increased interception losses and reduced water retention capability as a result of net loss of wetland area. In addition, such changes will affect environmental functions and biodiversity due to habitat loss and alterations. Integrating the results and information of the present study, an integrated landscape model was developed aiming to characterize wetland formation and emphasizing impacts of human activities on past and recent wetland and landscape dynamics.

Keywords: wetlands, landscape model, hydrological modeling, afforestation, South Africa

KURZFASSUNG

Ein integrierter, landschafts-basierter Ansatz zur Modellierung der Entstehung und Dynamik von Feuchtgebieten in den semiariden Quelleinzugsgebieten des Umzimvubu, Südafrika

A. EINLEITUNG UND MOTIVATION

Feuchtgebiete sind Ökosysteme, die weltweit verbreitet sind und ca. 6 % der Erdoberfläche bedecken (GORE, 1983; MITSCH & GOSSELINK, 2000). Natürliche oder naturnahe Feuchtgebiete sind in der Regel im Übergangsbereich von terrestrischen und aquatischen Ökosystemen zu finden. Sie treten daher entweder als Küsten- bzw. küstennahe Feuchtgebiete (z.B. Mangrovenwälder, Lagunen oder Marschen) oder Inlandsfeuchtgebiete (z.B. Moore, Feuchtwiesen, Auen oder Flachwasserseen) in Erscheinung. Künstlich angelegte Feuchtgebiete hingegen werden z.B. durch Reisfelder, Fischaufzuchtteiche oder Abwasserkläranlagen repräsentiert. Die Landschaftsfunktionen von Feuchtgebieten und deren Bedeutung für den Naturhaushalt werden in der Literatur ausführlich diskutiert (z.B. CARTER *et al.*, 1979; LUGO *et al.*, 1990; MITSCH & GOSSELINK, 2000; SUCCOW & JOOSTEN, 2001).

In Südafrika wird palustrinen Feuchtgebieten (Inlandsfeuchtgebieten), insbesondere in den semi-ariden Regionen entlang der „Großen Randstufe", eine zentrale Bedeutung im regionalen Wasserkreislauf beigemessen. Diese liegt vor allem in ihrer Speicherfunktion begründet, die zum einen Hochwasserspitzen in der Regenzeit kappt und zum anderen den Basisabfluss in der Trockenzeit kontrolliert. Obwohl ihre Bedeutung erkannt wurde, sind bisher keine wissenschaftlichen Untersuchungen zur Verbreitung der Feuchtgebiete in dieser Region sowie ihrer landschaftsbezogenen Funktionen und Dynamik durchgeführt wurden (ROWNTREE, 1993).

Als Folge der kommerziellen Aufforstung von über 30 000 ha ehemaligen Graslandes mit Kiefer- und Eukalyptusbeständen seit 1989 hat sich das Landschaftsbild im Oberlauf des Umzimvubu-Einzugsgebiets nachhaltig verändert. Die Auswirkungen der forstwirtschaftlichen Aktivitäten auf den Landschaftshaushalt sind vielfältig. Es ist davon auszugehen, dass die Aufforstungen Veränderungen der hydrologischen Systemdynamik, wie z.B. eine verstärkte Abflussreduzierung, erhöhte Interzeptionsverluste sowie die Veränderung der Grundwasser- und Interflowdynamik sowie ökologische Veränderungen, wie das Austrocknen von Feuchtgebieten und stehenden Gewässern, Biodiversitätsverluste sowie die Zerstörung von Habitaten verursachen. Eine qualitativ-quantitative Beschreibung entsprechender Phänomene liegt jedoch nicht vor (FORSYTH *et al.*, 1997).

Die vorliegende Untersuchung hat zum Ziel, einen Forschungsbeitrag zum besseren Verständnis der Entstehung, Verbreitung und Landschaftsdynamik palustriner Feuchtgebiete im Oberlauf des Umzimvubu-Flusses zu leisten sowie die Auswirkungen von Aufforstungen auf die Prozessdynamik der Feuchtgebiete und den Landschaftswasserhauhalt skalenübergreifend, d.h. auf der Hang-, Ökosystem- und Einzugsgebietsskala zu untersuchen.

B. STAND DER FORSCHUNG UND FORSCHUNGSBEDARF

Der weltweit zu beobachtende Rückgang von Feuchtgebieten hat die Problematik dieser komplexen und hochsensitiven Lebensräume hinsichtlich ihrer Stellung im Natur- und Landschaftshaushalt in den letzten Jahren zunehmend in den Mittelpunkt der öffentlichen und wissenschaftlichen Diskussion gerückt und damit zu einer Neubewertung ihrer Bedeutung als ökosystemare Einheiten geführt (MITSCH & GOSSELINK, 2000; SPIERS, 2001; WILLIAMS, 1990). In den letzten drei Jahrzehnten haben sich insbesondere im nordamerikanischen und europäischen Raum zahlreiche Forschungsfelder zur Analyse und Bewertung von Feuchtgebieten entwickelt, die abhängig von der Fragestellung durch unterschiedliche Disziplinen, wie z.B. Hydrologie, Geoökologie, Bodenkunde, aber auch Sozio-ökonomie bearbeitet werden. Der für diese Arbeit bedeutsame Forschungsstand kann wie folgt zusammengefasst werden.

Hydrologie von Feuchtgebieten: Aufgrund ihrer komplexen Funktionen für den Landschaftswasserhaushalt ist die Erfassung und Abschätzung des Wasserhaushaltes von Feuchtgebieten für eine nachhaltige Bewirtschaftung von Flusseinzugsgebieten von entscheidender Bedeutung (MITSCH & GOSSELINK, 2000). Für die Messung, Bilanzierung und Modellierung der einzelnen Wasserhaushaltskomponenten in Feuchtgebieten liegen zahlreiche Detailstudien vor (*Niederschlag*: CARTER, 1986; DUEVER *et al.*, 1994; GEHRELS & MULAMOOTTIL, 1990; *Evapotranspiration*: DOLAN *et al.*, 1984; GOODIN *et al.*, 1996 IDSO, 1981; JACOBS *et al.*, 2002; MOHAMED *et al.*, 2004; *oberirdischer Zu- und Abfluss:* HAMMER & KADLEC, 1986; KORENY *et al.*, 1999; LEITMANN *et al.*, 1982; MOORE & FOSTER, 1990; *Interflow*: DUEVER, 1988; LORENTZ & ESPREY, 1998; SKAGGS *et al.,* 1994; *Grundwasser*: COLE *et al.*, 1997; DAGAN, 1997; EULISS & MUSHET, 1996; GONTHIER, 1996; HUNT *et al.*, 1999; LABAUGH, 1986; LONG & NESTLER, 1996; MANN & WETZEL, 2000; NUTTLE, 1996). Im Hinblick auf die Wasserbilanzierung von Feuchtgebieten wird vielfach auf das Fehlen adäquater Daten und weiterer Detailstudien hingewiesen, da die gewonnenen Erkenntnisse häufig regionalbezogen und daher schwer übertragbar auf andere Gebiete sind (CARTER, 1986; COLE *et al.*, 1997; HUNT et al., 1998; LABAUGH, 1986). Weiterhin bestehen Defizite in der Erfassung der Saisonalität der hydrologischen Dynamik (HEMMOND & GOLDMAN, 1985) und der Landschaftsheterogenität (HUNT *et al.*, 1997). Messunsicherheiten engen zudem den Einsatz statistischer Verfahren ein (SHAFFER *et al.*, 2000).

Modellansätze in der Feuchtgebietshydrologie: In der Feuchtgebietshydrologie werden gängige Modellkonzepte der Hydrologie eingesetzt (CONSTANZA & SKLAR, 1985; LEWIS, 1995), wobei die Wasserbilanz durch mathematische Algorithmen berechnet wird (FENNEMA *et al.*, 1994). Hierzu zählen Entwicklungen wie DRAINMOD (SKAGGS *et al.*, 1994), PHIM (GUERTIN *et al.*, 1987), GERGAM-A (DELAAT *et al.*, 1981) und WATCROM (PARSONS *et al.*, 1991) oder Modifikationen von MIKE 21 (SOMES *et al.*, 1999). Das von WALTON *et al.* (1996a, b) entwickelte, modular strukturierte Wetland Dynamic Water Budget Model basiert auf der Zusammenführung verschiedener Modellkonzepte. Weiterhin wurden Grundwassermodelle (SIEGEL & GLASER, 1987; WINTER, 1988; MCNAMARA *et al.*, 1992) und Einzugsgebietsmodelle (ARNOLD *et al.*, 2001; STAUDENRAUSCH, 1996; ZACHARIAS *et al.*, 2004) in verschiedenen Feuchtgebietsmodellierungen untersucht. Zusammenfassend wurde deutlich, dass vorherrschende Modellkonzepte zur Modellierung von Feuchtgebieten bzw. deren laterale Verknüpfung zu ihrem Einzugsgebiet im Wesentlichen auf „Black Box Modellen“ basieren. Daraus folgt, dass hier Forschungsbedarf hinsichtlich der Entwicklung von physikalisch-basierten Modellkonzepten zur Bilanzierung der einzelnen Wasserhaushaltsgrößen in Feuchtgebieten und der Analyse und Simulation der Prozessdynamik unter besonderer Berücksichtigung sich ändernder Umweltbedingungen besteht.

Integration und Interdisziplinarität in der Feuchtgebietsforschung: Die Literaturauswertung hat gezeigt, dass Feuchtgebiete häufig nicht als integrierte Landschaftseinheiten verstanden werden, sondern regional losgelöst und thematisch isoliert analysiert wurden. DENNY (2001) verweist jedoch darauf, dass Feuchtgebieten, insbesondere aufgrund ihrer komplexen hydro-biochemischen Funktionen, eine integrale Schlüsselfunktion im regionalen Landschaftshaushalt zuerkannt wird. Vor diesem Hintergrund schlussfolgern TURNER *et al.* (2000) und BULLOCK & ACREMAN (2003), dass lediglich integrierte und interdisziplinäre Untersuchungsansätze eine landschaftsbezogene Analyse und Bewertung der Feuchtgebietsdynamik im Hinblick auf die ausgeglichene, nachhaltige und effiziente Bewirtschaftung von Einzugs- und Schutzgebietgebieten gewährleisten.

Südafrikanische Regionalstudien: In Einzugsgebieten mit semi-ariden bis semihumiden Klimabedingungen besteht die Gefahr, dass großflächige Landnutzungsänderungen, wie zum Beispiel Aufforstungen, den Wasserhaushalt von Feuchtgebieten und damit auch die hydrologische Dynamik von Flusseinzugsgebieten nachhaltig verändern. Obwohl Untersuchungen in südafrikanischen Einzugsgebieten gezeigt haben, dass infolge der Aufforstung grasland-dominierter Einzugsgebiete mit Kiefer- und Eukalyptusbeständen eine signifikante Reduzierung des Gesamtwasserabflusses eintritt (BOSCH, 1979; VAN LILL *et al.*, 1980; SCOTT & LESCH, 1997; SCOTT & SMITH, 1997), wurden bisher keine Studien zu den Auswirkungen entsprechender Aufforstungen auf die Dynamik von Feuchtgebieten und deren Wasserhaushalt durchgeführt. Da Feuchtgebiete häufig lateralen Zufluss aus Hangbereichen erhalten (LORENTZ & ESPREY, 1998), ist davon auszugehen, dass die Aufforstung der Einzugsgebiete von Feuchtgebieten eine deutliche Verringerung der Grundwasserneubildungsrate sowie deutlich reduzierte Einträge in das Feuchtgebietssystem bewirken, die insbesondere bei kleineren Feuchtgebieten zur Austrocknung führen können (ROWNTREE, 1993). Darüber hinaus sind Auswirkungen auf die Biodiversität entsprechender Systeme zu erwarten, die durch eine Habitatanpassungen von Flora und Fauna an trockenere Standorte charakterisiert sind.

Zusammenfassend wird deutlich, dass ***Forschungsbedarf*** hinsichtlich der regionalen Systematik von Feuchtgebieten, ihrer vom Landschaftshaushalt bestimmten Entstehungs- und Prozessdynamik sowie ihrer landschaftsökologischen Bedeutung, vor allem in semiariden Gebieten mit großflächigen Landnutzungsänderungen, besteht. Obwohl die integrale Bedeutung des Systems *Feuchtgebiet* für den Landschaftshaushalt erkannt wurde, finden integrierte Untersuchungsansätze, die eine ganzheitliche Betrachtung ihrer Landschaftsfunktionen ermöglichen, nur selten Anwendung.

C. ZIELSTELLUNG UND METHODISCHES VORGEHEN

Unter Berücksichtigung der oben diskutierten Forschungsdefizite sind die übergeordneten Zielstellungen der vorliegenden Arbeit:

i) die Entwicklung und Anwendung eines integrierten Forschungsansatzes zum verbesserten Verständnis der Entstehung, Verbreitung, Funktion und Dynamik von palustrinen Feuchtgebieten in den Quelleinzugsgebieten des Umzimvubu - Flusses und

ii) die prognostische, skalenübergreifende Modellierung und Bewertung der Auswirkungen von großflächigen Aufforstungen auf die Feuchtgebietsdynamik unter Berücksichtigung eines regionalisierten, landschaftsbasierten Modellansatzes.

Hierzu werden folgende drei Schwerpunktziele bearbeitet, welche die methodische Vorgehensweise widerspiegeln:

1. Zunächst wird eine Datengrundlage zur landschaftsbezogenen Charakterisierung der Feuchtgebiete hinsichtlich ihrer Verbreitung, Funktion und Hydrodynamik im semi-ariden Einzugsgebiet (EZG) des Umzimvubu durch die Verknüpfung von intensiven Geländeuntersuchungen, Laborarbeiten und der Analyse existierender Datenbestände entwickelt.
2. Mit Hilfe der integrierten Systemanalyse und prozessbasierter Modellierungen wird die Bedeutung der Prozessdynamik von Feuchtgebieten für den Landschaftshaushalt skalenübergreifend (Ökosystem-, Hang- und Einzugsgebietsskala) untersucht. Von wesentlicher Bedeutung ist hier die Bewertung der großflächigen Aufforstungen hinsichtlich ihrer Auswirkungen auf die Feuchtgebietdynamik und den Landschaftswasserhaushalt anhand von ausgewählten Nutzungsszenarien.
3. Die Analyseergebnisse der hydrologischen Systemdynamik und Modellierungen sowie der morphogenetischen Untersuchungen werden in einem integrierten Landschaftsmodell zusammengeführt und vor dem Hintergrund anthropogener Einflüsse auf die Entstehung, Dynamik und das nachhaltige Management der Feuchtgebiete bewertet.

D. UNTERSUCHUNGSGEBIET

Für die Untersuchungen wurden zwei Einzugsgebiete im Oberlauf des im Südosten Südafrikas gelegenen Einzugsgebietes des Umzimvubu (19.865 km²) ausgewählt. Das Mooi-EZG (307 km²) repräsentiert die Quelleinzugsgebiete der semi-ariden Südost-Abdachung der ‚Großen Randstufe' (Drakensberge). Die Höhen variieren zwischen 1.200 m NN am Mooi Wehr in Maclear und 2.700 m NN im Oberlauf. Das Landschaftsbild wird durch die triassischen Sedimente der Karoo-Sequenz bestimmt, die eine typische Schichtstufenlandschaft ausgebildet haben. Die Bodenentwicklung ist durch die Geologie (Sand- und Tonsteine), die jeweilige Reliefsituation sowie die lokalen hydro-klimatischen Bedingungen gekennzeichnet und führte damit zur Ausbildung eines kleinräumigen Verbreitungsmusters. Dominierende Bodentypen sind Regosole, Braun- und Parabraunerden sowie stauwasser- und grundwasserbeeinflusste Böden. Klimatisch ist die Region dem Sommerregengebiet (Oktober-März) zuzuordnen. Während der mittlere Jahresniederschlag 750 mm beträgt, ist die Jahresmitteltemperatur mit 14,1 °C angegeben (HERBERT, 1997). Beide Kenngrößen zeigen eine hohe raumzeitliche Variabilität. Die Vegetation wird durch den Typus des Highland Sourveld charakterisiert (ACOCKS, 1987), das durch verschiedene Sauergras-Spezies dominiert und weitgehend weidewirtschaftlich genutzt wird.

Im Untersuchungsgebiet sind verschiedene Typen von Feuchtgebieten verbreitet, die sich hinsichtlich ihrer Ausprägung, hydrologischen Dynamik und Nutzung unterscheiden. Ihre Entstehung ist an die lokal hydrologischen Gegebenheiten, ihre Lage im Relief sowie die unterliegende Geologie gebunden. Seit dem Beginn der Aufforstungen im Jahr 1989 wurden 19 % (59,2 km²) des Mooi-EZG mit Kiefer- und Eukalyptusbeständen aufgeforstet, während 63 % (193,5 km²) als Weideland genutzt werden und 11 % (34 km²) Feuchtgebiete repräsentieren.

Das 1995 für hydrologische Detailstudien eingerichtete Testgebiet Weatherley (1,4 km²) liegt im östlichen Mooi-EZG. Die Höhen variieren zwischen 1257 m NN am Gebietsauslass und 1350 m NN im Oberlauf. Im Jahre 2001 wurden 35 % des bis dahin als Weideland genutzten Graslandes mit Eukalyptus (17 ha) und Kiefern (32 ha) bepflanzt. Auf der Grundlage von Boden-, Vegetations- und Reliefanalysen wurden 25 % des Einzugsgebiets als Feuchtgebiet klassifiziert.

E. DATENGRUNDLAGE

Für das Mooi-EZG liegen langjährige Messreihen (1970-2005) täglicher Klimadaten (N, T_{Min}, T_{Min}, Windrichtung und -geschwindigkeit, rel. Luftfeuchte) von vier Stationen sowie Abflussdaten vom Pegel Maclear vor. Im Weatherley-EZG, das in den vergangenen Jahren kontinuierlich und systematisch messtechnisch ausgebaut wurde, liegen seit 1995 mittels Neutronensonden erfasste Bodenfeuchtemessungen auf wöchentlicher Basis vor. Hierbei wird der volumetrische Wassergehalt an 29 Messstellen, die entlang von sieben Transekten innerhalb des Einzugsgebietes verteilt sind, erfasst. Entlang der Transekte werden Saugspannung mittels automatischer Tensiometer sowie Grundwasserstände an Grundwasserbeobachtungsstellen gemessen (LORENTZ *et al.*, 2004). Im Jahr 1997 wurde die Instrumentierung mit der Installation zweier vollautomatischer Wetterstationen zur Erfassung von Niederschlag, Windgeschwindigkeit und –richtung, Temperatur und Strahlung in stündlicher Auflösung, der Einrichtung von fünf Anlagen zur Messung des Oberflächenabflusses sowie zweier Wehre zur Erfassung des Gebietsabflusses abgeschlossen.

Darüber hinaus stand eine Vielzahl an zeitlich und räumlich unterschiedlich aufgelösten GIS-Datensätzen aus vorherigen Studien zur Verfügung. Multiskalige und multitemporale Landnutzungsinformation wurde zum einen durch die Klassifikation von optischen Satellitendaten (Landsat TM/ETM) sowie zahlreiche Kartierkampagnen bereitgestellt (HELMSCHROT & FLÜGEL, 2002). Durch unfangreiche Geländeaufnahmen standen Daten zur Vegetationsverbreitung und -ausprägung (Vegetationszusammensetzung, Höhe, Wurzellänge etc.) für die wichtigsten Pflanzengesellschaften zur Verfügung. Räumliche Informationen zu den Forstbeständen (Spezies, Alter, Bestockungsgrad u.ä.), die zur Parametrisierung der Prozessmodelle (3-PG, PRMS) benötigt wurden, wurden aus der Forststandortdatenbank von Mondi Forest Ltd. (1996-2004) extrahiert. Digitale Höhenmodelle (DHM) standen für das Mooi-EZG (25 m²) und Weatherley (5 m²) zur Verfügung und wurden zur Ableitung von reliefbezogenen Einzugsgebietsparametern wie Einzugsgebietsgrenzen, Flussnetz, Hangneigung und –richtung ausgewertet. Eine digitale Bodenkarte des Testgebietes Weatherley wurde vom Institute for Soil, Climate and Water (Pretoria) zur Verfügung gestellt, die

Verbreitung des geologisch Anstehenden wurde von geologischen Karten (DEPARTMENT OF MINES, 1977) digitalisiert.

D. METHODIK

Für die Durchführung der Arbeit wurde ein integrierter Untersuchungsansatz entwickelt, der sich im Wesentlichen in vier methodische Schwerpunktbereiche gliedert:

i) Analyse hydro-meteorologischer Zeitreihen

Für die hydrologische Systemanalyse und die Modellierung wurden für verschiedene räumliche und zeitliche Skalen verfügbare, ***hydro-meteorologische Messreihen*** hinsichtlich Konsistenz und Homogenität geprüft und statistisch aufbereitet.

ii) Geländeaufnahmen und Laborarbeit

Zur Erfassung ***bodenphysikalischer und –chemischer Parameter*** (Bodentyp, Korngröße, Feldkapazität, pF, pH, N, S, Al, Fe, hydraulische Leitfähigkeit, Lagerungsdichte und Bodenfeuchte) wurden Bodenprofile und Bodenproben von im Einzugsgebiet verteilten Talquerprofilen und Feuchtgebietstransekten sedimentologisch ausgewertet (HELMSCHROT *et al.,* 2005). Der Aufbau und die Mächtigkeiten der Feuchtgebietssedimente wurden entlang ausgewählter Transekte in den Referenzfeuchtgebieten mittels ***geophysikalischer (Refraktionsseismik) und sedimentologischer Methoden*** aufgenommen. Diese Aufnahmen wurden durch einzelne ***ASM-Datierungen*** sowie ***Pollenuntersuchungen*** ergänzt.

Vegetationsparameter wie Artenzusammensetzung, Auftretenshäufigkeit, Blattflächenindex (LAI), Bedeckungsdichte, Wurzeltiefe, Vegetationshöhe und phänologischer Zustand wurden im Grasland und in verschiedenen Feuchtgebietstypen im Untersuchungsgebiet aufgenommen. Zur Beschreibung des Pflanzenwachstums in Forstbeständen wurden pflanzenphysiologische Parameter, wie z.B. Vegetationshöhe, LAI, Bedeckungsgrad, Bestockungsgrad, Stammvolumen, Brusthöhendurchmesser und Kronendurchmesser für dominante Spezies altersspezifisch gemessen bzw. aus der Forststandortdatenbank extrahiert.

iii) Ableitung der räumlichen System- und Modellparameter

Zur Abschätzung der räumlichen ***Variabilität des Niederschlags*** wurden die Niederschlagsdaten von 66 Stationen aufbereitet und mittels verschiedener Interpolationsverfahren (IDW, Kriging) regionalisiert.

Für die Systemanalyse auf verschiedenen räumlichen Skalen sowie zur Ausweisung von Hydrological Response Units (HRUs) wurden die verfügbaren Digitalen Geländemodelle (DGM) analysiert. Hierzu wurden ***Reliefparameter***, wie Hangneigung und –richtung, Fliessakkumulation und -richtung, Einzugsgebietsgrenzen und Flussnetz unter Verwendung von GIS-Werkzeugen abgeleitet. Im Rahmen der Reliefanalyse wurde weiterhin eine Auswahl geomorphometrischer Parameter (u.a. Höhe über Tiefenlinie, relative Hangposition) und topographischer Indizes (z.B. Topographischer Feuchteindex) berechnet. Unter der Annahme, dass die Dynamik, Verbreitung und Charakteristik der Feuchtgebiete im Untersuchungsgebiet durch das Relief bestimmt ist, wurde durch die Kombination verschiedener Parameter eine Feuchtgebietskarte erstellt, welche die Verteilung von Tal-, Hang- und Plateaufeuchtgebieten aufzeigt.

Die quantitative Erfassung der Aufforstungsdynamik erfolgte durch eine ***multitemporale Landnutzungsklassifikation***. Hierzu wurden Landsat TM/ETM-Daten von vier Aufnahmezeitpunkten (1989, 1995, 1999 und 2001) mittels eines 3-stufigen Klassifikationsansatzes klassifiziert und durch Genauigkeitsanalysen hinsichtlich der erreichten Klassifikationsgenauigkeiten bewertet. Zur Verbesserung der Klassifikationsergebnisse wurden die Landnutzungsklassifikationen mit digitalisierten Geländekartierungen, der Feuchtgebietsverteilungskarte sowie Forststandortkarten, altersspezifisch für jeden Aufnahmezeitpunkt aus der Forststandortdatenbank extrahiert wurden, verknüpft.

Bei der distributiven Einzugsgebietsmodellierung wird die Heterogenität der Einzugsgebiete durch die ***Ableitung von Hydrological Response Units (HRUs)*** berücksichtigt. FLÜGEL (1995) beschreibt HRUs als distributive, heterogen strukturierte und hinsichtlich ihrer hydrologischen Prozessdynamik aggregierte Modellobjekte, die einzeln parametrisiert werden, und auf denen die lateralen und vertikalen Wasser- und Stoffumsätze simuliert werden. Basierend auf einer umfassenden hydrologischen Systemanalyse wurden die Ableitungskriterien so gewählt, dass die Varianz der hydrologischen Prozessdynamik innerhalb einer HRU geringer als die der angrenzenden ist (FLÜGEL, 1995). Die HRUs wurden durch die GIS-basierte Verschneidung der Parameter Landnutzung und -bedeckung, Böden, Geologie, Relief (Neigung, Exposition) und Klima (Niederschlagsverteilung) abgeleitet. Dadurch beinhalten sie alle wesentlichen, die hydrologische Dynamik beeinflussenden Parameter, die während der Systemanalyse für das Untersuchungsgebiet auf der jeweiligen Skalenebene (Weatherley-EZG, Mooi-EZG) als relevant identifiziert wurden. Die ***topologische Verknüpfung der HRUs*** erfolgte konzeptionell, indem die Abflusskomponenten kaskadierend von den oberliegenden HRUs zu einer unterliegenden HRU oder dem Vorfluter weitergegeben werden. Hierbei wurde eine n:1–Beziehung eingesetzt, bei der ein benutzerdefinierter, prozentualer Anteil des Abflusses von n HRUs einer aufnehmenden HRU oder dem angebundenen Fluss-Segment zugeführt wird.

iv) Systemmodellierungen

Auf verschiedenen Raum- und Zeitskalen arbeitende Prozessmodelle wurden integriert, um die Auswirkungen großflächiger Aufforstungen auf den Gebietswasserhaushalt allgemein und den jeweiligen Feuchtgebietstyp im Speziellen abzuschätzen.

Die ***Forstwachstumsmodellierung*** wurde mit Hilfe des prozessbasierten Pflanzenwachstumsmodells 3-PG (LANDSBERG & WARING, 1997) durchgeführt. 3-PG benötigt monatliche Klimadaten (z.B. Niederschlag, T_{Min}, T_{Max}) sowie bestandesrelevante Parameter (z.B. Alter, Bestockung, Bewirtschaftungsformen) als Eingangsdaten. Diese Daten wurden durch eigene Geländearbeiten erarbeitet oder waren aus der Forststandortdatenbank verfügbar. Nach erfolgter Parametrisierung modelliert 3-PG flächengemittelte Stammvolumen und –durchmesser, Biomasse, bestandene Grundfläche sowie die zeitliche Dynamik des LAI. In 3-PG ist ein vereinfachtes 1-Schichten-Bodenwassermodell implementiert, das die Modellierung des individuellen Pflanzenwasserbedarfs sowie des pflanzenverfügbaren Bodenwassers auf monatlicher Basis ermöglicht. Die Verdunstung wird nach Penman-Monteith (MONTEITH & UNSWORTH, 1990) berechnet, während die Interzeption als anteiliger Niederschlag und Funktion des Bestandes-LAI simuliert wird. Verfügbares Bodenwasser, das die Bodenwasserhaltekapazität übersteigt, wird dem Bestandsabfluss und/oder der Tiefenversickerung zugeführt. Im Rahmen dieser Arbeit wurde die Wachstumsdynamik der im Untersuchungsgebiet dominierenden Spezies *Eucalyptus nitens*, *Pinus patula* und *Pinus radiata* simuliert. Für die Kiefernbestände wurde zusätzlich ein Modul implementiert, das kontinuierliche Durchforstungsmaßnahmen (*thinning*) in der Modellierung berücksichtigt.

Die ***Einzugsgebietsmodellierung*** wurde mit dem Precipitation-Runoff Modeling System (PRMS), einem modularen, physikalisch-basierten und distributiven Modellsystem (LEAVESLEY *et al.*, 1983) durchgeführt. Standardmäßig verfügt PRMS über eine Bibliothek von Prozessmodulen, die benutzerabhängig in verschiedenen Konfigurationen kombiniert und erweitert werden können. Als Mindesteingabeparameter dienen tägliche Niederschlagswerte sowie Minimal- und Maximaltemperaturen. Die Solarstrahlung wird modellintern berechnet, wenn keine tägliche Zeitreihe vorliegt. Die Parametrisierung der Prozessmodule erfolgt auf der Grundlage empirischer Parameter, während die HRU-spezifische Parametrisierung durch die Analyse von GIS- und Fernerkundungsdaten, die Einbindung der Ergebnisse anderer Modellierungen sowie Geländemessungen erfolgt. Als Modellausgabe werden auf täglicher Basis die wichtigsten Wasserhaushaltkomponenten für jede HRU berechnet, die durch Aufsummierung in gebietsbezogene Werte übertragen werden.

Im Rahmen der vorliegenden Arbeit wurden vier Modellsimulationen durchgeführt, die die hydrologische Dynamik beider Einzugsgebiete (Mooi, Weatherley) vor und nach der Aufforstung beschreiben. Hierzu wurden für alle Szenarien unterschiedliche Zeiträume für die Kalibrierung und die Validierung der Parametersätze definiert. Auf der Grundlage visueller Vergleiche und Regressionsanalysen zwischen modellierten und gemessenen Abflüssen wurde die Modellperformance für den Kalibrierungszeitraum untersucht und bewertet. Um die bestmögliche Anpassung des modellierten an den gemessenen Hydrographen zu erreichen, wurden im Verlauf der Sensitivitätsanalyse und Parameteroptimierung die Parameter identifiziert und angepasst, die wesentlichen Einfluss auf die Modellgüte haben. Hierzu zählen die Niederschlagsanpassung für jede HRU (*rain_adj*), der monatliche Korrekturkoeffizient (*jh_coeff*) sowie die den Bodenhaushalt steuernden Kenngrößen (*soil2gw, ssr2gw_rate, ssr_coeff, gwflow_coeff, smidx_exp*). Der Kalibrierungsdatensatz wurde anschließend für den Validierungszeitraum angewendet. Die Ergebnisse wurden mittels statistischer Gütemasse analysiert und bewertet.

Zunächst wurde PRMS in der Standardkonfiguration parametrisiert und kalibriert, doch zeigten die Modellergebnisse, dass das Modell die Abflussdynamik und hier insbesondere die Bodenwasser- und Speicherdynamik in den untersuchten Feuchtgebieten unzureichend abbildet. Dies ist zum einen darauf zurückzuführen, dass die Auffüllung des der Feuchtgebietsspeichers zu Beginn der Regenzeit deutlich unterschätzt und stattdessen Oberflächenabfluss simuliert wurde. Zum anderen wurden permanente und temporäre Feuchtgebiete hinsichtlich ihrer Wasserhaltekapazität unzureichend abgebildet, d.h. stehendes Wasser wurde umgehend durch Oberflächenabfluss abgeführt. Aus diesem Grund wurde ein Modul zur besseren Modellierung der Speicherdynamik in Feuchtgebieten entwickelt und implementiert. In dem Modul werden die Bodenzone und der Bodenwasserspeicher als eine physikalische Einheit behandelt. Die Kapazität des Bodenwasserspeichers ist hierbei als das verfügbare Bodenwasser zwischen Feldkapazität und Sättigung definiert. Bei Überschreiten der Speicherkapazität wird das überschüssige Wasser dem Oberflächenabfluss zugeführt.

E. ERGEBNISSE UND DISKUSSION

Im folgenden Kapitel werden die wesentlichsten Ergebnisse der vorliegenden Arbeit zusammengefasst. Die Gliederung dieses Kapitels orientiert sich weitgehend an den in Kapitel C formulierten Schwerpunktzielen.

E.1 Monitoring

Durch die Aufbereitung der ***hydro-meteorologischen Daten*** wurden für das Mooi-EZG langjährige Zeitreihen für Niederschlag (1970-2005), Temperatur (1980-2002), relative Luftfeuchte (1980-2005) sowie den Abfluss am Pegel Maclear (1970-2005) auf täglicher Basis erstellt. Für das Weatherley-EZG wurden für den Zeitraum von 1998 bis 2005 korrigierte Zeitreihen für Niederschlag, Temperatur, Strahlung und Abflüsse an beiden Wehren als Tagesmittel abgeleitet. Die Datenbasis wurde durch aufbereitete Daten der Grundwasserbeobachtungsstellen, der Tensiometernester und der Oberflächenabflussplots, die entlang verschiedener Transekte aufgenommen und für ereignisbezogene Analysen herangezogen wurden, ergänzt.

Im Rahmen der ***Bodenaufnahmen*** wurden 20 Profile im Weatherley-EZG und18 Profile in Feuchtgebietsböden im Gatberg Vlei und Ku'Ntombininzinzi Vlei detailliert aufgenommen und hinsichtlich ihrer bodenspezifischen Charakteristika horizontbezogen analysiert. Durch die Analyse ungestörter Bodenproben wurden für jeden der Hauptbodentypen hydraulische Leitfähigkeiten im ungesättigten Milieu sowie Durchlässigkeitsbeiwerte horizontspezifisch bestimmt. Diese Untersuchungen wurden durch Literaturwerte (ESPREY, 1997; HERBERT, 1997; LORENTZ *et al.*, 2001; LORENTZ *et al.*, 2004; ROBERTS *et al.*, 1996) verifiziert und ergänzt.

Mit Hilfe ***refraktionsseismischer Untersuchungen*** von 24 Längsprofilen in 6 verschiedenen Feuchtgebieten wurden die Mächtigkeiten und die Basismorphologie der feuchtgebietsbildenden Sedimente sowie deren strukturellen Eigenschaften erfasst. Die Ergebnisse der refraktionsseismischen Messungen zeigen, dass in allen Feuchtgebieten eine bezüglich der seismischen Wellengeschwindigkeiten relativ homogene Sedimentsequenz mit Mächtigkeiten zwischen 2 und 4 m dem anstehenden Sandstein aufliegt, die jedoch in allen Feuchtgebieten im mikro-skaligen Bereich infolge topographischer Effekte und abhängig von der jeweiligen Feuchtgebietssubmorphologie variiert. Die Mächtigkeit zeigt jedoch insgesamt keinerlei Zusammenhang zur Größe der Einzugsgebiete, den Feuchtgebietstypen oder der Lage im Relief. Parallel wurden entlang der Profile ***sedimentologische Aufnahmen*** durchgeführt, die zum einen zur Validierung der refraktionsseismischen Messungen und zum anderen zur Beschreibung des Aufbaus der Feuchtgebietssedimente herangezogen wurden. Zusätzlich zu den sedimentologischen Analysen wurde Probenmaterial für ***^{14}C-Datierungen*** extrahiert. Es wurden zwei Proben organischen Materials aus einem Aufschluss in einem großen Talfeuchtgebiet im Gatberg Vlei entnommen. Innerhalb der Sedimentsequenz sind die Proben der Basis der obersten Schicht aus Feinsediment zuzuordnen (in 220 und 240 cm Tiefe). Die Datierung ergab ein Alter von 3370 ± 51 ^{14}C-Jahren BP (Δ 13C: -15,1‰, Erl-

6949) und 3384 ± 58 ^{14}C-Jahren BP (Δ13C: -14,8‰, Erl-6950), woraus sich ein Minimalalter von etwa 3400 Jahren für die Sedimentation des Feinsubstrates ergibt, aus dem sich die Feuchtgebiete entwickelt haben. ***Palynologische Untersuchungen*** lieferten weitere Informationen zur Vegetationsdynamik während der Feuchtgebietsentstehung. Die Pollenuntersuchungen zeigen, dass die Proben aus allen Profiltiefen von Süß- und Sauergraspollen dominiert werden. Vereinzelt wurden Pollen von Kräutern gefunden. Das führt zu dem Schluss, dass das Einzugsgebiet des Feuchtgebietes während der Sedimentdeposition vom Grasland dominiert war und Baumgewächse nur vereinzelt auftraten oder nicht in der Lage waren, Pollen über weiter Distanzen zu verteilen. Der Vergleich der Anteile von Süß- und Sauergraspollen im Profil zeigt, dass der Anteil von Süßgräserpollen tendenziell zur Basis zunimmt. Dies wird auf die Sukzession oder Degradation des ehemals von Süßgräsern dominierten Graslandes zu den widerstandsfähigeren Sauergräsern infolge klimatischer Änderungen oder Brand- und Weidebewirtschaftung zurückgeführt.

Detaillierte ***Vegetationsuntersuchungen*** wurden in den verschiedenen Vegetationsgesellschaften durchgeführt. Dominanzanalysen in Grasland- und Feuchtgebieten haben gezeigt, dass beide Vegetationsgesellschaften durch *Cyperaceae, Poaceae* und *Juncaceae* Spezies dominiert werden. Neben der Artenzusammensetzung wurden für jeden Feuchtgebietstyp und Grasland Pflanzenparameter wie z.B. mittlere Höhe und Wurzellänge, Bedeckungsgrad und LAI bestimmt und im Rahmen der Systemanalyse (E.2) diskutiert. Auf der Grundlage von in 152 Forstbeständen gemessenen Daten wurde die altersspezifische Dynamik des LAI und Bedeckungsgrades, der Bestandesdichte und –höhe als Bestandsmittel für Kiefer (*P. pat.* und *P. rad.*) und Eukalyptus (*E. nit.*) erfasst. Ergänzend wurde die für die Abschätzung der Interzeption bedeutsame Streuauflage in den Beständen erfasst und hinsichtlich ihrer altersspezifischen Entwicklung untersucht.

Zur Bereitstellung genauer ***Landnutzungsinformation*** für das Mooi-EZG wurden die aus Landsat TM/ETM-Daten abgeleiteten Landnutzungsklassifikationen hinsichtlich ihrer Genauigkeit überprüft. Hierzu wurden Testgebiete ausgewiesen und in Geländekartierungen aufgenommen. Der Vergleich der Landnutzungsklassifikation mit Geländekartierungen zeigte eine Gesamtgenauigkeit im Bereich von 81 und 89 %, wobei die höchsten Genauigkeiten in den Waldgebieten (bis zu 98,4 %) und die geringsten Genauigkeiten in den stark degradierten Graslandbereichen (76,3) erreicht wurden. Die mit Hilfe der GIS-basierten Reliefanalyse durchgeführte, ***flächenhafte Bestandsaufnahme der Feuchtgebiete*** verdeutlicht, dass 15 % des Untersuchungsgebiets durch Feuchtgebiete charakterisiert sind. Dabei repräsentieren Talfeuchtgebiete 57 % der absoluten Feuchtgebietsfläche, während 37 % als Hangfeuchtgebiete und 6 % als Plateaufeuchtgebiete klassifiziert wurden. Die Genauigkeitsanalyse für die Feuchtgebietsverteilung ergab nach der Erfassung von 27 Testgebieten eine Übereinstimmung von 89,5 %. Hier wurden insbesondere die Hangfeuchtgebiete genau abgeleitet (97 %), während Plateaufeuchtgebiete (45,8 %) und Talfeuchtgebiete (85,5 %) geringe bis gute Übereinstimmung zeigten. Die Ungenauigkeiten bei Plateaufeuchtgebieten sind vor allem auf ihre geringe Flächenausdehnung zurückzuführen, während die Grenzen der durch jahrzehntelange Bewirtschaftung gekennzeichneten Talfeuchtgebiete im Gelände schwierig zu erfassen waren und zum Teil auch in den Randzonen mit Kiefern bepflanzt wurden. Beide Datensätze wurden mit den aus der Forststandortdatenbank abgeleiteten, jahresspezifischen Forstkarten verschnitten, so dass Landnutzungsinformation zur Beschreibung der Landnutzung vor und nach der Aufforstung in sehr guter Qualität vorlag. Im Weatherley-EZG wurde die Landnutzung unter Zuhilfenahme eines differentiellen GPS flächenscharf aufgenommen. Die für die Aufforstung vorgesehenen Bereiche wurden hier aus der Forstdatenbank extrahiert.

E.2 Integrierte Systemanalyse

Durch die Verknüpfung der Ergebnisse der Zeitreihenanalysen, Boden- und Vegetationsanalysen sowie der Informationen zur Landnutzungsänderung wurde eine ***integrierte Systemanalyse*** durchgeführt. Auf der Grundlage der Systemanalyse im Bereich der Hang-, Ökosystem- und Einzugsgebietsskala wurden die dominanten, hydrologischen Prozesse identifiziert und im Hinblick auf die skalenübergreifende Modellierung regionalisiert.

Die wichtigsten Ergebnisse der integrierten Systemanalyse lassen sich skalenübergreifend wie folgt zusammenfassen:

- Der ***Niederschlag*** liegt im langjährigen Mittel bei 849 mm (Min: 609 mm, Max: 1130 mm) und ist damit deutlich höher als das von WRC (1994) für die Eastern Cape angegebene Flächenmittel von 754 mm. Die höchsten Niederschläge fallen im Februar (141,9 mm), die geringsten im Juni (13,4 mm). Darüber hinaus zeigt der Niederschlag eine hohe räumliche Variabilität, die sich in höheren Niederschlägen entlang der Großen Randstufe widerspiegeln.
- Die Hydrographenanalyse zeigt, dass die ***Abflussdynamik*** beider Vorfluter durch die Saisonalität der Niederschlagsdynamik gesteuert wird. Es wird deutlich, dass mit Einsetzen der Regenzeit zunächst die Systemspeicher (Feuchtgebiete) gefüllt werden, d.h. trotz lichter, z.T. gebrannter Vegetationsdecke, die die Bildung von Oberflächenabfluss begünstigt, werden nur geringe Abflüsse generiert. Geländebeobachtungen haben gezeigt, dass die Auffüllung der Feuchtgebiete durch eine Kombination aus Oberflächenabfluss und lateralem Hangwasserabfluss, der vom Gradienten der Hangneigung gesteuert wird, erfolgt. Die Geländeaufnahmen belegten auch, dass der hangparallele Wasserzug häufig als Makroporenfluss und *Piping* in Erscheinung tritt. In der Trockenzeit wird der Vorfluterabfluss ausschließlich durch den Grundwasserabfluss aus den Feuchtgebieten bestimmt.
- Die Bodenanalyse verdeutlicht, dass die ***Böden*** in Nichtfeuchtgebieten tendenziell über höhere Anteile sandig-schluffiger Korngrößen und somit gute Drainageeigenschaften verfügen, während in Feuchtgebieten deutlich tonigere Böden zu finden sind. Die Feuchtgebietsböden sind in der Regel durch einen mit Fe- und Mn - Konkretionen und deutlich hydromorphen Merkmalen gekennzeichneten Stauer charakterisiert.
- Untersuchungen in den grasland-dominierten Gebieten haben gezeigt, dass deutliche Unterschiede hinsichtlich der ***Vegetationsausprägung in Grasland- bzw. Feuchtgebietsbereichen*** bestehen. Die Vegetationsdichte, -höhe und Wurzellänge nimmt in Feuchtgebieten deutlich zu, wobei auch zwischen den Feuchtgebieten Unterschiede festgestellt wurden. Weiterhin wurden expositionsbedingte Unter-

schiede in den Vegetationsgesellschaften nachgewiesen. So zeigen südexponierte Hänge, die durch eine geringere Einstrahlung und höhere Wasserverfügbarkeit gekennzeichnet sind, eine deutlich dichtere und höhere Vegetation als nordexponierte Hänge.

- In ***Forstbeständen*** wurde ein signifikanter Zusammenhang zwischen dem Alter der Bestände und der Bestandesdichte und dem LAI für alle untersuchten Spezies nachgewiesen. Auf dieser Grundlage wurde eine Klassifizierung der Baumbestände nach Alter vorgenommen.
- Die ***Analyse der Landnutzungsänderung*** hat gezeigt, dass Forstflächen in beiden Einzugsgebieten zugenommen haben (Mooi-EZG: 17 %, Weatherley-EZG: 35,9 %), während Graslandflächen und Ackerflächen abgenommen haben.
- Basierend auf den ***Untersuchungen zur Hangwasserdynamik*** in Weatherley (LORENTZ *et al.*, 2004; HELMSCHROT et al., 2005) wurde ein Modell zur Beschreibung der dominierenden Prozesse bei der Abflussentstehung am Hang entwickelt. Das Modell bestätigt die oben getroffenen Annahmen, nach denen die Abflussdynamik an Hängen in der Regenzeit durch schnellen Oberflächenabfluss, oberflächennahen Makroporenfluss und Grundwasserabfluss bestimmt wird. Ihre Anteile am Gesamtabfluss variieren mit der Niederschlagsdauer und –intensität.
- Durch die kombinierte Betrachtung der Kriterien Hydrodynamik, Boden und Vegetation sowie Lage im Relief können im Einzugsgebiet drei ***Feuchtgebietstypen*** differenziert werden:

  1. Talfeuchtgebiete sind in den fluvial bzw. durch Erosion abgelagerten, in der Regel 2 bis 4 m mächtigen Feinsedimenten der Talauen entwickelt. Ihre Genese wird auf die Grundwasserspiegelschwankungen und damit einhergehende Bodenbildungsprozesse zurückgeführt. Sie verfügen über eine hohe Wasserhaltekapazität. Die hydrologische Dynamik der Talfeuchtgebiete ist vorrangig durch die Grundwasserdynamik bestimmt, die wiederum eng an die Vorflut gekoppelt ist. Zusätzlich erhalten sie Wassereintrag durch Niederschläge und durch von den Hängen zufließenden Zwischenabfluss. Aufgrund ihrer positiven Wasserbilanz sind große Bereiche der Talfeuchtgebiete meist ganzjährig wassergesättigt und kontrollieren mit ihrer ausgleichenden Speicherfunktion in den temporär gesättigten Bereichen die Dynamik der Basis- und Hochwasserabflüsse ihrer zugehörigen Vorfluter.

  2. Hangfeuchtgebiete sind in den durch Erosion umgelagerten Sedimenten der Mittel- und Unterhangbereiche entwickelt. Diese in der Regel mittelgroßen und temporär gesättigten Feuchtgebiete werden vorrangig durch schnellen lateralen Wassereintrag durch Oberflächenabfluss und/oder Zwischenabfluss gesteuert. Sie sind durch wasserdurchlässige Bodenhorizonte mit hoher Infiltrationskapazität gekennzeichnet. Sie können isoliert in Erscheinung treten oder sind mit benachbarten oder unterliegenden Feuchtgebieten (kaskadierende Systeme) oder mit dem Vorfluter verbunden.

  3. Plateaufeuchtgebiete sind kleine, in Plateaulagen gelegene Vernässungszonen, die durch im Untergrundrelief des geologisch Anstehenden entwickelte Grundwasserlinsen oder lateralen Eintrag aus oberliegenden Bereichen sowie direkten Niederschlagseintrag gesteuert werden. Sie sind nicht an den Vorfluter angebunden.

Auf der Grundlage der Systemanalyse wurden die für die Modellierung der beiden Einzugsgebiete benötigten ***HRUs*** durch GIS-basierte Verschneidungsoperationen abgeleitet. Hierbei wurden die Datenschichten Landnutzung einschließlich verschiedener Feuchtgebietstypen und Forstflächen, Hangneigung und –richtung, Bodenverteilung, Geologie sowie topographische Einheit (Lage im Relief) berücksichtigt, so dass alle der als prozessrelevant identifizierten Steuergrößen in die Ableitung der HRUs eingehen. Szenarien zur Beschreibung der Landschaftsdynamik wurden insofern beschrieben, indem die Landnutzungsinformation verschiedener Zeiträume (vor und nach der Aufforstung) bei der HRU-Ableitung berücksichtigt wurde. Als Ergebnis der HRU-Ableitung wurden vier HRU-Datensätze für die Modellierung ausgewählt: ***i)*** Mooi-EZG vor der Aufforstung (70 HRUs); ***ii)*** Mooi-EZG mit Aufforstung (67 HRUs); ***iii)*** Weatherley-EZG vor der Aufforstung (25 HRUs); und ***iv)*** Weatherley-EZG mit simulierter Aufforstung (31 HRUs).

E.3 Modellsimulationen

E.3.1 Pflanzenwachstumsmodellierung mit 3-PG

Die Wachstumsdynamik sowie der Pflanzenwasserbedarf von Kiefern- und Eukalyptus-Beständen wurden mit Hilfe des prozessbasierten Pflanzenwachstumsmodells 3-PG (LANDSBERG & WARING, 1997) simuliert. Der Vergleich der Modellergebnisse mit Geländemessungen zeigt, dass für die Parameter Bestandsdichte, DBH, LAI und Biomasse eine gute Übereinstimmung erreicht wurde. Die in diesen Untersuchungen gewonnenen Erkenntnisse bilden die Grundlage für die Parametrisierung der Forstdynamik in der hydrologischen Modellierung. Als wichtige Ergebnisse der Pflanzenwachstumsmodellierung können zusammengefasst werden:

- Die Entwicklung der Bestandsdichte wurde für *E. nit.* (r^2=0,70) und *P. rad.* (r^2=0,76) gut simuliert. Die Dynamik der Bestandsdichte für *P .pat.* (r^2=0,61) wird dadurch beeinflusst, dass die vor der kommerziellen Aufforstung durch Farmer gepflanzten Bestände (> 12 Jahre) zum einen größere Pflanzabstände aufweisen und zum anderen nicht optimal bewirtschaftet wurden.
- Die altersspezifische Dynamik des DBH wurde in allen Beständen sehr gut modelliert (*E. nit.*:v=0,85; *P .pat.*: r^2=0,90 und *P. rad.*: r^2=0,81).
- Der LAI zeigte eine generell gute Übereinstimmung (*E. nit.*: r^2=0,38; *P .pat.*: r^2=0,69 und *P. rad.*: r^2=0,71), jedoch wurde deutlich, dass der LAI in Jungbeständen und nach dem Schluss der Kronendecke tendenziell überschätzt wird, während der LAI in der Phase des Kronenschlusses leicht unterschätzt wird.
- Die Entwicklung der Biomasse wurde aufgrund fehlender Vergleichsdaten lediglich für Jungbestände bis sechs Jahre verifiziert. Es wurde deutlich, dass die modellierten Biomassen für *E. nit.* und *P. rad.* eine gute Übereinstimmung mit gemessenen Biomassen aufweisen, während die Biomasse für *P. pat.* tendenziell untersimuliert wurde. Korrelationen wurden aufgrund der geringen Datendichte nicht gerechnet.

- Die Simulation der Durchforstungsmaßnahmen zeigt im Vergleich des LAI mit Geländedaten und Modellergebnissen von SUMMERTON (1995), dass 3-PG in der Lage ist, entsprechende Bewirtschaftungsformen zu modellieren.
- Die Analyse des Wasserverbrauchs in Kiefernbeständen hat gezeigt, dass 87% (*P.rad.*) und 89 % (*P.pat.*) des Bestandsniederschlags für biochemische und hydrologische Prozesse in den Beständen umgesetzt werden.

E.3.2 Hydrologische Modellierung mit MMS/PRMS

Zunächst wurde die hydrologische Dynamik des Weatherley-EZG mit dem Ziel simuliert, das neu eingebundene Bodenmodul hinsichtlich seiner Wirkungsweise zu testen. Zur Kalibrierung des Modells sowie zur Parameteroptimierung und Sensitivitätsanalyse wurde zunächst der Zeitraum 1998-99 modelliert, während für die Modellvalidierung die gesamte Zeitreihe (1998-2002) berücksichtigt wurde. Die Ergebnisse zeigen, dass durch den Einsatz des neuen Moduls eine Verbesserung des Modellergebnisses (r^2=0,77) durch die verbesserte Abbildung der Speicher- und Abflussdynamik zu Beginn der Regenzeit gegenüber der PRMS-Standardkonfiguration (r^2=0,71) erzielt wurde.

Anschließend wurde die hydrologische Dynamik des Mooi-EZG für die Bedingungen vor und nach der Aufforstung separat untersucht. Zur Simulation der Aufforstung wurden hierbei Forstparameter aus der Pflanzenwachstumsmodellierung mit 3-PG herangezogen. Es wurde deutlich, dass das Modell die hydrologische Dynamik unter Berücksichtigung der Änderungen der Landschaftsausstattung im Einzugsgebiet abbildet. Dies wird durch die Korrelationen zwischen gemessenen und simulierten Abflüssen von r^2=0,66 (vor der Aufforstung) und r^2=0,81 (nach der Aufforstung) bestätigt.

Zur Abschätzung der Auswirkungen der Aufforstungen auf den Wasserhaushalt und die Feuchtgebietsdynamik wurde das Weatherley-EZG unter Aufforstung modelliert. Hierzu wurden die Parameter für 15 Jahre alte Bestände in gutem Zustand aus der Modellierung des Mooi-EZG auf die für die Bepflanzung in Weatherley vorgesehen HRUs übertragen. Die Ergebnisse zeigen, dass eine Abflussverringerung zwischen 11 und 21% als Folge der Aufforstungen und hier insbesondere durch höhere Interzeptions- und Evapotranspirationsraten zu erwarten ist. Darüber hinaus weist der Interflow (bis -18%) deutlich stärkere Verluste als der Oberflächen- (bis - 9%) bzw. Grundwasserabfluss (bis -4 %) auf. Dies ist vor allem dadurch begründet, dass die in der Regel in den Hangbereichen gepflanzten Bäume das verfügbare Bodenwasser aufnehmen und die Bildung von Zwischenabfluss hierdurch verhindert bzw. reduziert wird. Oberflächenabfluss wird in der Regel auf vegetationslosen Hangbereichen während intensiver Niederschlagsereignisse erzeugt und beeinflusst daher weniger die aufgeforsteten Bereiche.

Der Einfluss der Aufforstungen auf die Feuchtgebietsdynamik wurde anhand der detaillierten Analyse der Abflusskomponenten für jeden Feuchtgebietstyp im Weatherley-EZG untersucht. Als die wichtigsten Ergebnisse können zusammengefasst werden:

- die flächengewichteten Abflussverluste der Feuchtgebiete variieren zwischen 13,6 und 21,3 %;

- die Abflussverluste der relativ kleinen Plateau-Feuchtgebiete variieren zwischen 26,6 und 47,8 %. Der Wassereintrag beschränkt sich lediglich auf Niederschlagseintrag, da das Wasser der Oberhänge durch die Forstbestände aufgebraucht wird;
- die Abflussverluste der mittelgroßen Hang-Feuchtgebiete variieren zwischen 11,1 und 19,9 % und sind im Wesentlichen auf verringerte Einträge durch Oberflächenabfluss und Interflow aus den oberliegenden Hangbereichen zurückzuführen;
- die Talfeuchtgebiete zeigen mit Schwankungen zwischen 3,9 und 8,7 % relativ geringe Abflussverluste, was auf deren grundwassergesteuerte Dynamik und die direkte Anbindung an die Vorflut zurückzuführen ist.

F. LANDSCHAFTSMODELL

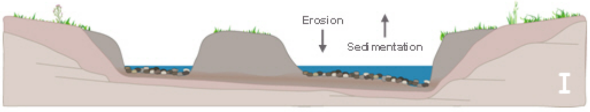
Die Synthese der sedimentologischen und geophysikalischen Ergebnisse mit den Ergebnissen anderer Studien (FEELY, 1987; SCOTT & LEE-THORP, 2004; HUFFMANN, 1996; TYSON & LINDESAY, 1992) ermöglichte die Rekonstruktion der holozänen Landschaftsgenese. Basierend auf der holozänen Landschaftsentwicklung wurde ein Landschaftsmodell abgeleitet, das die Entstehung der Feuchtgebiete hinsichtlich Morphodynamik, Vegetation und Landnutzung in 6 verschiedene Phasen untergliedert, die in Abbildung 1 skizziert sind.

Zusammenfassend kann die spätholozäne Verfüllung der Talböden beginnend vor etwa 3.400 Jahren als initialer Prozess der Feuchtgebietsentstehung angesehen werden. Klimatische und anthropogene Ursachen werden gleichermaßen für diese Sedimentationsdynamik (Phase III) verantwortlich gemacht. Eine im Anschluss an die Sedimentation einsetzende stabile Phase ohne nennenswerte Erosions- und Akkumulationsprozesse führt darüber hinaus zur Ausbildung einer wasserstauenden Bodenschicht, welche sich auf die saisonale hydrologische Dynamik (Grundwasserfluktuation, Retentionsvermögen der oberen Bodenschichten, etc.) auswirkt und damit die Entstehung der heutigen Feuchtgebiete bewirkt.

Die Untersuchungen unterstützen die Hypothese, dass die Feuchtgebiete im Untersuchungsgebiet deutlich jünger sind als bisher angenommen. Ihre Entstehung und Entwicklung wurde vor allem durch nachhaltige Änderungen in der Vegetationsdynamik, die auf klimatische und/oder anthropogene Einflüsse während des mittleren und späten Holozäns zurückgeführt werden können, gesteuert. Vor dem Hintergrund des vorgestellten Landschaftsmodells der Feuchtgebietsentstehung sind die Aufforstungen und die damit verbunden Auswirkungen auf den Wasserhaushalt kritisch zu bewerten.

Die rezente hydrologische Dynamik der Feuchtgebiete wird im Wesentlichen durch die hydrologischen Rahmenbedingungen (Saisonalität) bestimmt. Die Untersuchungen haben gezeigt, dass die Talfeuchtgebiete weitgehend durch die Grundwasserdynamik unterstützt durch Hangwasserzufluss gesteuert werden, während die Hangfeuchtgebiete von lateral zufließendem Hangwasser entweder oberflächlich oder durch Interflow gespeist werden. Plateaufeuchtgebiete sind in ihrer Dynamik an die durch die Untergrundtopographie vorgegebene Entstehung von Grundwasserlinsen (hangendes Grundwasser) gebunden. Die Auswirkungen der Aufforstungen auf die Hydrologie der Feuchtgebiete wurden im Rahmen dieser Arbeit untersucht.

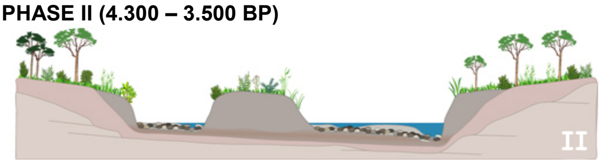
PHASE I (älter als 4.300 BP)



Prozessdynamik
Einschneidung und anschließende Akkumulation von Kiesen als Folge einer veränderten fluvialen Dynamik im Zusammenhang mit spätholozänen Klimaänderungen

Vegetation
spärliche Vegetation

PHASE II (4.300 – 3.500 BP)



Prozessdynamik
relativ stabile Phase, fluviale Dynamik bedingt ausgewogene Erosions- und Sedimetationsdynamik

Vegetation
zunehmend dichte Vegetation, artenreich

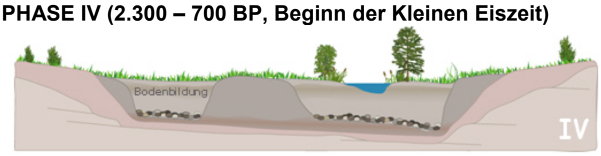
PHASE III (3.400 – 2.400)

Prozessdynamik
verstärkter Sedimenteintrag infolge klimatischer Abkühlung und Auflichtung der Vegetation führt zur Feinmaterialakkumulation in den Talböden

Vegetation
Gras- und Buschvegetation

Landnutzung
natürliche oder anthropogen induzierte Auflichtung der Vegetation bzw. Entwaldung (?)

PHASE IV (2.300 – 700 BP, Beginn der Kleinen Eiszeit)

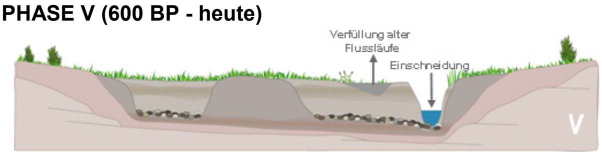


Prozessdynamik
stabile Phase, Bodenbildungsprozesse, Bildung einer wasserstauenden Schicht (Feuchtgebietsbildung)

Vegetation
Gras- und Buschvegetation, Auenvegetation

Landnutzung
Jäger und Sammler, frühe Farmer

PHASE V (600 BP - heute)

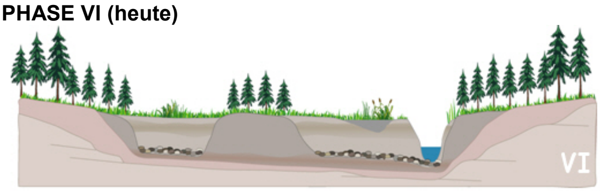


Prozessdynamik
Einschneidung, Gullyerosion, teilweise verstärkt durch Drainage der Feuchtgebiete und Brandbewirtschaftung der beweideten Hänge und Feuchtgebietsflächen

Vegetation
Grasland

Landnutzung
extensive Weidewirtschaft (seit 600 BP), Feuermanagement, Be- und Überweidung

PHASE VI (heute)



Prozessdynamik
Einfluss durch rezenten Landnutzungswandel, Erosion oder Sedimentation (?)

Vegetation
Grasland, Kiefer- und Eukalyptusforste

Landnutzung
Extensive Weidewirtschaft, Aufforstung seit 1989

Abbildung 1: Landschaftsmodell, welches die rekonstruierte Genese der Feuchtgebiete im Untersuchungsgebiet hinsichtlich morphodynamischer Aspekte, Vegetationscharakteristika sowie anthropogener Einflüsse in 6 Phasen gliedert (Altersangaben verweisen auf Richtalter).

Die Modellierungen haben gezeigt, dass die Hangwasserdynamik der als Weide genutzten Hänge infolge der Aufforstungsmaßnahmen und dem damit verbundenen Wasserentzug durch die Forstbestände maßgeblich verändert wird. Damit wäre auch die Erhaltung der vom Hangwasser gespeisten (Hangfeuchtgebiete) und der an Grundwasserlinsen gekoppelten (Plateaufeuchtgebiete) Feuchtgebietstypen gefährdet. Diese Annahme wird durch Geländebeobachtungen in einzelnen Feuchtgebieten bestätigt. Die detaillierte Untersuchung entsprechender Auswirkungen zeigt aber auch, dass das Ausmaß der Auswirkungen in engem Zusammenhang mit der Größe und der Lage des jeweiligen Feuchtgebiets, der Charakteristik des jährlichen Niederschlags (Trockenjahr oder Feuchtjahr) sowie dessen Management steht. Grundwassergesteuerte Systeme sind von diesen Prozessen nur indirekt betroffen. Es ist davon auszugehen, dass ihre saisonale Dynamik insofern beeinflusst wird, dass die Auffüllung zu Beginn der Regenzeit mehr Zeit in Anspruch nimmt und die Abgabe in der Trockenzeit, insbesondere in trockenen Jahren, deutlich geringer ausfällt. Durch die Einschränkungen ihrer hydrologischen Speicher- und Ausgleichsfunktionen, können Auswirkungen für den meso- und makroskaligen Landschaftswasserhaushalt nicht ausgeschlossen werden, sind jedoch in weiterführenden Untersuchungen zu überprüfen.

G. ZUSAMMENFASSUNG UND AUSBLICK

Als Zusammenfassung der vorliegenden Arbeit lassen sich folgende Schlussfolgerungen formulieren.

- Die Verknüpfung von Zeitreihenanalysen und integrierter, skalenübergreifender Systemanalyse mit innovativen, prozess-orientierten Modellwerkzeugen ist geeignet, landschaftsdynamische Prozesse, wie die Entstehung, Funktion und Dynamik von Feuchtgebieten, landschaftsbezogenen zu beschreiben und zu bewerten.
- Die Auswertung der geophysikalisch-sedimentologischen Befunde hat zur Entwicklung eines Landschaftsmodells geführt, dass die Entstehung der Feuchtgebiete auf das Zusammenwirken von klimatischen Rahmenbedingungen und der Vegetationsdynamik auf den Hängen im Holozän zurückführt.
- Das vorgestellte Landschaftsmodell zur Entstehung der Feuchtgebiete geht von der Annahme aus, dass der Mensch durch die Bewirtschaftung der Hänge die Vegetationszusammensetzung und –dichte und damit die Sedimentationsdynamik in den Talauen, die zur Entstehung der Feuchtgebiete führte, maßgeblich beeinflusst oder verursacht hat.
- Der in dieser Untersuchung entwickelte, integrierte Untersuchungsansatz wurde erfolgreich zur Modellierung der Auswirkung von großflächigen Aufforstungen auf die hydrologische Einzugsgebiets- und Feuchtgebietsdynamik eingesetzt.
- Die Simulation der hydrologischen Dynamik zweier Einzugsgebiete vor und nach der Bepflanzung zeigt, dass die Aufforstung deutlich den Wasserhaushalt und hier insbesondere die Abflussdynamik maßgeblich beeinflusst.
- Die detaillierte Untersuchung entsprechender Auswirkungen auf den Wasserhaushalt von Feuchtgebieten sowie deren Abflussdynamik bestätigt, dass das Ausmaß der Auswirkungen in engem Zusammenhang mit der Größe, der Lage und dem Typ des jeweiligen Feuchtgebiets sowie dessen Management steht.

Somit wurde, den Zielstellungen des Vorhabens Rechnung tragend, ein Beitrag zum verbesserten Verständnis der Entstehung, Verbreitung, Funktion und Dynamik von palustrinen Feuchtgebieten in den Quelleinzugsgebieten des Umzimvubu Flusses sowie der prognostischen, skalenübergreifende Modellierung und Bewertung der Auswirkungen von großflächigen Aufforstungen auf die Feuchtgebietsdynamik unter Berücksichtigung eines landschaftsbasierten Modelansatzes geleistet.

Aus den hier vorgestellten Untersuchungen lassen sich folgende weiterführende Forschungsziele ableiten:

- Das Landschaftsmodell sollte durch zusätzliche morphogenetische Untersuchungen mit weiteren Datierungen und Pollenanalysen in vergleichbaren Feuchtgebietssystemen sowie in den umliegenden Hangbereichen verifiziert werden.
- Eine detaillierte Analyse der Abflussdynamik im Mooi-EZG und weiteren Einzugsgebieten (Tsitsa, Wildebees oder Gatberg) ermöglicht die Quantifizierung der Auswirkungen entsprechender Aufforstungen auf einer größeren Skala sowie die Verifizierung der in dieser Studie erarbeiteten Annahmen.
- Aufgrund ihrer Bedeutung für die Interflowdynamik sollten hanglateraler Makroporenfluss und *Piping*-Prozesse in zukünftigen Modellierungen Berücksichtigung finden.
- Hinsichtlich ihrer Bedeutung für die saisonale Landschaftsdynamik sollte das Landmanagement in den Graslandbereichen (Weidebewirtschaftung, jährliches Brennen) und Forstbeständen (Durchforstung) in der prozessorientierten Modellierung Berücksichtigung finden.

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ACRONYMS, SYMBOLS AND UNITS

^{14}C dating	Carbon dating
3-PG model	Physiological Processes in Predicting Growth model
AAS	Atom Absorption Spectrometer
ACRU	Agrohydrological Modelling System
AMC	Antecendent moisture content
AMS	Accelerator-Mass-Spectrometry
ASCII	American Standard Code for Information Interchange
asl	About Sea Level
BP	Before Present
CCWR	Computing Centre for Water Research
CEC	Cations exchange capacity
CSIR	Centre for Scientific Industrial Research
DBH	Diameter at breast height (over bark)
DCCA	Detrended Canonical Correspondence Analysis
DEM	Digital Elevation Model
DIN	DEUTSCHES INSTITUT FÜR NORMUNG e.V.
DSTV	Diurnal Surface Temperature Variation
DVWK	Deutscher Verband für Wasserwirtschaft und Kulturbau e. V.
DWAF	Department of Water Affairs and forestry
ECDB	Environmental Conservation Data Base
EPA	Environmental Protection Agency
FAO	Guidelines for soil description
FORTRAN	FORmula TRANslation
GIS	Geographical Information System
GPR	Ground Penetrating Radar
GPS	Global Positioning System
HRU	Hydrological Response Units
IDW	Inverse Distance Weighting
ISCW	Institute for Soil, Climate and Water
LAI	Leaf Area Index
Landsat TM/ETM	Landsat Thematic Mapper / Enhanced Thematic Mapper
LIA	Little Ice Age
MAP	Mean Annual Precipitation
MARE	Mean absolute relative error
MODFLOW	MODular three-dimensional finite-difference ground-water FLOW model
MWE	Medieval Warm Epoch
NDVI	Normalized Difference Vegetation Index
NECF	North East Cape Forests
NFSAM	National Food Security Act Manual
NOAA AVHRR	National Oceanic & Atmospheric Administration Advanced Very High Resolution Radiometer
NPP	Net primary production
NSM36	Natural System Model
OCR	Oxidizable Carbon Ratio

OFM	Overland Flow Model
OSL	Optically Stimulated Luminescence
PAR	Photosynthetic active radiation
PEST	Parameter ESTimation
PHIM	Peatland Hydrologic Impact Model
PRMS	Precipitation-Runoff-Modeling System
P-waves	Compressional or longitudinal waves
RDM	Resources Directed Measures
RMSE	Root Mean Square Error
PWL	Plateau wetland
SAWB	South African Weather Bureau
SBEEH	School of Bioresources Engineering & Environmental Hydrology
SHE	Systéme Hydrologique Européen
SRC	Schonland Research Centre, Johannesburg
SRTM	Shuttle Radar Topography Mission
SVAT-model	Soil Vegetation Atmosphere-Transfer
SWAT	Soil and Water Assessment
S-waves	Transversal or shear waves
SWL	Slope Wetland
T	Temperature
TDR	Time Domain Reflectometry
TOC	Total Organic Carbon
TWI	Topographic Wetness Index
UKZNP	University of KwaZulu-Natal
VPD	Vapor Pressure Deficit
VWL	Valley Bottom Wetland
WAIT	Wetland-Aquifer Interaction Test
WET	Wetland Evaluation Technique
WETFLOW	Wetland Flow model
WETMOD	Wetland Ecosystem Model
WUE	Water Use Efficieny
yr/yrs	Year/Years
θ	Volumetric soil moisture
ψ	Local capillary potential
°C	Degrees Celsius
µm	Micrometer
mm, cm	Millimeter, centimeter
ha	Hectare
km, km^2	Kilometer, square kilometer
m, m^2, m^3	Meter, square meters, cubic meters
ha	Hectare
l, $l\ s^{-1}$	Liter, liter per second
$m^3\ s^{-1}$	Cubic meter per second

Chapter 1

Introduction

Wetlands are complex natural or man-made systems and represent very important features of the landscape in almost every environment. They cover about 6 % of the land surface of the earth (GORE, 1983; MITSCH & GOSSELINK, 2000). Natural wetlands are mostly found at the interface of terrestrial and aquatic ecosystems, and thereby usually identified either as coastal wetlands (e.g. mangroves, lagoons and marshes) or inland wetland systems (e.g. bogs, fens and riparian ecosystems) in different stages of succession. In human environments wetlands often occur as constructed wetland systems (e.g. paddy fields, pond systems for fishery and treatment wetlands). Because of their wide range of hydrological, hydro- and biogeochemical as well as ecological functions at global, regional and ecosystem scale, wetlands provide a variety of goods and services to the society such as fish and wildlife habitats, flood mitigation, water quality improvement, and shoreline protection (BRANDER *et al.*, 2006). Nevertheless, natural wetlands have faced a continuous loss over the last centuries with a peak in the 20th century resulting from extensive drainage for agriculture and commercial forestry or filling for residential, commercial or industrial development (MITSCH & GOSSELINK, 2000; SPIERS, 2001; WILLIAMS, 1990). Addressing the tremendous loss of wetland area worldwide, they have been treated as endangered ecosystems, and thus have received an increasing scientific and public awareness worldwide during the last years. As a result, national legislation and environmental laws as well as international programs such as the *'Ramsar Convention'* have been initiated to preserve and manage wetlands sustainably all around the world (MITSCH & GOSSELINK, 2000).

The scientific community has provided a wide spectrum of wetland research fields arising from disciplines like hydrology, bio-ecology, soil sciences, and socio-economics to improve the understanding of wetlands functioning and to identify their ecological and economic benefits in natural and human environments (MITSCH & GOSSELINK, 2000). Detailed studies concerning the classification, functioning and management of wetlands are widely limited to North America and Europe, even though some promising studies have been carried out in Asia, Australia and Africa within the last years. These studies reflect an increasing interest in wetland research in other parts of the world which is often associated to conservation activities, environmental regulations or water resources management issues (DENNY, 2001).

As shown by numerous studies, wetlands are usually being investigated as individual and isolated landscape features (MITSCH & GOSSELINK, 2000). Since these studies focused on specific research objectives, they have rarely explored the potential of interdisciplinary approaches; nor have they taken the interactivity of wetlands with its adjacent landscapes into account. Recent trends in wetland research indicated that integrated and interdisciplinary approaches are necessary to understand and assess the complex nature of wetland systems in a landscape perspective (TURNER *et al.*, 2000). According to PRICE *et al.* (2005) and MITSCH & GOSSELINK (2000), such approaches need to be based on the integration of ***i) traditional observation and measurement techniques, ii) multifaceted system analyses*** and ***iii) innovative modeling and assessment tools***. Since wetlands are recognized as key components of the regional water cycle (BULLLOCK & ACREMAN, 2003), they need to be considered as an integral part of water resources management activities (TURNER *et al.*, 2000); in particular, in arid and semi-arid regions where water is one of the most important natural resources (DENNY, 2001).

Researching wetland dynamics in South Africa is a rather young research field given a major focus on wetland inventory and loss (GOWAN, 1995). Inventory studies have shown that wetlands are among the most threatened aquatic habitats in South Africa (KOTZE *et al.*, 1995; TAYLOR *et al.*, 1995). It is estimated that up to 50 % of wetlands have been lost or degraded as result of human activities such as channelization, drainage, crop production, afforestation and water abstraction in recent years (KOTZE *et al.,* 1995). The continuous loss of wetland areas resulted in noticeable efforts initiated by South African national water and environmental policy to preserve and manage the sustainability of South African wetlands. Programs like *'Working for Wetlands'* initiated by the Department of Environmental Affairs and Tourism address the protection, rehabilitation and sustainable use of wetlands; but they are currently focused primarily on rehabilitation of degraded wetlands in several parts of the country.

As discussed by DUGAN (1992) and DENNY (2001), the quantity and quality of information on wetlands need to be increased to provide a thorough scientific background for wetland conservation and rehabilitation activities, and integrated water resources management in Southern Africa. For example, palustrine wetlands in the semi-arid headwaters of South African river basins have been identified as important ecosystems fulfilling essential eco-hydrological functions such as flood flow attenuation, groundwater recharge, baseflow control, and sediment and nutrient trapping (ROWNTREE, 1993). In contrast, little attention has been given in the past regarding distribution, functioning and sustainable management of these wetlands, nor the impact of human activities on wetland formation and recent dynamics have been taken into account (FORSYTH *et al.*, 1997).

Since greater parts of the upper Umzimvubu basin in the Eastern Cape Province are facing a remarkable land use transformation from natural grassland to commercial forestry starting 1989, these areas are assumed to be hydrologically affected by pine and eucalyptus plantations (FORSYTH *et al.*, 1997). Various studies have shown that pine and eucalyptus afforestation of former grassland significantly reduce annual streamflow (BOSCH, 1979; VAN LILL *et al.,* 1980; SCOTT & LESCH, 1997; SCOTT & SMITH, 1997). So far, little attention has been given to its impact on wetland dynamics. It is indicated that afforestation in the catchment of a wetland is therefore likely to decrease groundwater recharge and the inflow into the wetland, resulting in progressive desiccation (FORSYTH *et al.*, 1997; ROWNTREE, 1993).

Given these assumptions, research needs have been identified to provide knowledge on the dynamics and functioning of palustrine wetland systems in the semi-arid areas of the Eastern Cape Province in South Africa in order to answer following questions:

What are the different types of wetlands occurring in the headwaters of the Umzimvubu basin and where are they located?

What are the driving environmental variables controlling wetland processes, dynamics and functioning and how are the interactions with the adjacent landscape?

How can process-oriented models working on different spatial and temporal scales be integrated to simulate and quantify the impact of afforestation on the catchment hydrology in general and on different wetland types in particular?

How is afforestation affecting the hydrological processes and dynamics on wetland and catchment scale?

What is the potential of integrated research approaches to identify the human impact on wetland formation and recent dynamics of wetlands?

Towards addressing these questions, the main objectives of this dissertation are to improve the understanding of formation, functioning and dynamics of palustrine wetlands in this region and the prognostic modeling and assessment of afforestation impacts on these wetland systems incorporating a landscape-based model approach. With respect to the multi-scale nature of these objectives, the investigations will be performed by means of a nested catchment approach working at four different scale levels: ***i) hillslope scale, ii) ecosystem scale, iii) catchment scale,*** and ***iv) landscape scale***.

Given attention to the research questions and objectives outlined above, this study integrates concepts and methods of various disciplines. Integrating empirical field studies, laboratory analysis, GIS and remote sensing techniques, system analysis and process-oriented modeling, the conceptual and methodical approach of this dissertation is based on three individual aspects: ***i) observation and data mining; ii) integrated system analysis;*** and ***iii) system modeling and assessment***. Such an integrated research approach provides information regarding a generalized understanding of dominant hydrological processes at wetland and catchment scale and the impact of afforestation on wetland and basin hydrology. Based on this confluence of information, an integrated landscape model will be developed. This model aims to characterize wetland formation and possible impacts of human activities on past and recent wetland and landscape dynamics. Finally, this study will form the base to identify requirements for sustained landscape management and the maintenance of the hydrological functions of these wetlands.

Regarding the integrated and interdisciplinary nature of this study, this dissertation can be seen as a contribution in the field of integrated wetland research and, moreover, supports regional studies regarding the distribution and functioning of South African wetland systems.

This dissertation is structured to address the research topics and the methodological approach presented above. Chapter 2 outlines and discusses the theoretical background of this study by means of a comprehensive research review addressing the state-of-the-art and recent tendencies in wetland research in general and related regional studies from South Africa. Based on the research needs identified in Section 2.5, the research objectives as well as the applied methodological and conceptual approach are highlighted in Chapter 3. A detailed description of the study area is given in Chapter 4, while Chapter 5 summarizes the data base which was used for this study. Chapter 6 describes methods utilized for the measurement, analysis and modeling purposes. Chapter 7 presents the results of the system analysis and modeling at several scales. Integrating the results presented in Chapter 7, Chapter 8 illustrates the synthesis of the study aiming to provide an integrated landscape model and to assess the human impact on wetland dynamics in a landscape perspective.

Chapter 2

Research Review

The ongoing research has shown that wetlands are complex and endangered ecosystems which have received an increasing scientific and public awareness worldwide during the last two decades. As a consequence, a variety of fields were established in wetland research ranging from scientific disciplines like *inter alia* hydrology, biology, soil sciences, and eco-logy to socio-economic disciplines.

Because the hydrology of palustrine wetlands and its interaction with land use dynamics in the Eastern Cape Province are of interest in this study, this research review is merely focused on research activities in this context. An overview of additional research efforts such as biochemistry of wetlands, functioning and wise use of wetlands as well as valuation can be found in BRANDER *et al.* (2006), FINLAYSON et al. (2001), MITSCH & GOSSELINK (2000), LEWIS (1995) and WILLIAMS (1990). In addition, a variety of case studies is published in *Wetlands* the Journal of the Society of Wetland Scientists which has been publishing wetland related research since 1981.

This Chapter provides a background on basic concepts in wetland hydrology and its integration in existing hydrological model approaches. In recent years the polymorphism of wetland complexity and their multifunctional importance for local and regional environments led to a variety of different concepts aiming to define, classify and delineate wetlands. Based on a general overview, problems associated with the definition, classification and delineation of wetlands, including promising methods of research are discussed in Section 2.1. Section 2.2 introduces theoretical considerations and principles of wetland hydrological research. Section 2.3 gives basic background on wetland research activities in South Africa mainly focusing on palustrine wetlands. Section 2.4 evaluates palaeoecological and palaeoclimatatological research which can be used to characterize landscape dynamics within the study area, and thereby bridging the gap between wetland formation and landscape evolution. Summarizing the research review, Section 2.5 highlights research deficits which are concluded from this research review.

2.1 Wetlands – Definition, Classification and Delineation

The term "wetland" is discussed by a number of studies. Consequently, a variety of classification and delineation approaches have been developed. This section provides theoretical considerations and an overview of recent trends in the field of wetland research.

2.1.1 Wetland Definition

Differing understanding of wetland systems has resulted in controversial discussions in the literature on how to define a wetland (MITSCH & GOSSELINK, 2000; SKAGGS *et al.*, 1994). Summaries of the different, multidisciplinary concepts and their critical discussion can be found in KENT (1994), LEWIS (1995) and WILLIAMS (1990).

In spite of this controversy, numerous studies have shown that a consensus has been reached regarding three basic criteria for identifying and characterizing wetlands. According to LEWIS (1995) those criteria are: ***i) the hydrological criterion*** (recurrent, sustained saturation); ***ii) the substrate criterion*** (physical and chemical conditions in the substrate that reflect recurrent, sustained saturation) and ***iii) the biological criterion*** (presence of organisms that are specifically adapted to recurrent, sustained saturation of the substrate). Even if the importance of those criteria and their indicators may vary for different wetland types, water is considered to be the most important factor, because neither the wetland substrates nor wetlands biota can develop in the absence of hydrologic conditions. Wetlands are essentially either temporarily, seasonally or permanently, whereas the most discernable wetlands in terms of diversity and biological productivity are commonly those that dry out periodically. Nevertheless, a generalized definition of wetlands that considers the criteria concept and seems to be appropriate to characterize main wetland types can be given according to COWARDIN *et al.* (1979) and LEWIS (1995) as follows:

„Wetlands are defined as areas which are transitional between terrestrial and aquatic systems, the water table is usually at or close the surface, or the area is covered with shallow water at some time during the annual growing season, and which under normal circumstances supports or would support vegetation typically adapted to life in saturated soil conditions."

2.1.2 Wetland Classification

Numerous classification approaches were introduced to the scientific community during the past years. As a consequence of differing research interests they are induced by different disciplines (hydrology, soil sciences, ecology, economy, etc.). Although most classification systems consider the criteria mentioned above, they are critically discussed in the literature due to their limitations and restriction for generalization and specific application. In the following the most common approaches to classify wetlands are summarized.

The wetland classification system developed by COWARDIN *et al.* (1979) is regarded as one of the most comprehensive and versatile classification systems. Since it was successfully introduced in the US for inventory purposes, COWARDIN's system found consideration in many other classification systems in the world (FINLAYSON & VAN DER VALK, 1995). It also was transferred to the global scale by the Ramsar classification system (LEWIS, 1995). Basically, the applied hierarchy considers systems such as marine, estuarine, riverine, lacustrine and palustrine and sub-systems which are associated with specific hydrological, geomorphological, chemical and biological characteristics. So-called modifiers are used to differentiate sub-systems in terms of classes and sub-classes. According to COWARDIN *et al.* (1979) those are categorized in terms of: ***i)***

water regime (tidal/non-tidal, temporary, permanent, etc.); ***ii) water chemistry*** (salinity, pH, etc.), ***iii) soils*** (organic, mineralized, etc.), and ***iv) specific, use-related modifiers*** (drained, managed, artificial, etc.). COWARDIN's system contributes to the unification of wetland terminology and thereby provides a basic framework for wetland classification, which can be adapted and extended to specific needs and regions.

The ongoing research however, criticizes the absence of components related to landscape evolution in COWARDIN's concept and its modifications (BRINSON, 1993). Therefore, an alternative, landscape-related concept was introduced with the "Hydrogeomorphic Classification System" (BRINSON, 1993; COLE *et al*, 1997; SHAFFER *et al.*, 1999; SMITH *et al.*, 1995, WHIGHAM *et al.*, 1999). It is based on an integrated examination of three components: ***i) geomorphic setting*** (landscape positioning); ***ii) water source type*** (rainfall, surface, near-surface flow, and groundwater) and ***iii) hydrodynamics*** (flow and strength of water movement) of wetlands. Since the three components are treated separately, considerable interdependency can be achieved. As a consequence, resulting redundancies are used to reduce errors of interpretation and to reinforce the underlying principles that characterize wetland functions (BRINSON, 1993). According to SMITH *et al.* (1995) the major benefit of this approach is assumed to be its flexibility and independency due to varying scales. Since it is based on a level hierarchy, regionally adapted sub-classes of different scales can be utilized to classify wetlands considering functional characteristics. An example is given by COLE *et al.* (1997) who compared several types of wetlands to evaluate wetland hydrology as a function of hydrogeomorphic sub-classes. A modified geomorphic approach to the classification of natural inland wetlands was presented by SEMENIUK & SEMENIUK (1997). The approach incorporates landform and hydroperiod to describe all types of wetlands on primary level around the globe. Since deficits were shown for the Ramsar classification system, the authors emphasized to reconcile the proposed approach and the Ramsar classification system by incorporating landform as the first-tier of the Ramsar system, and thereby to re-order its hierarchical structure. As a result inland wetlands can be described, classified and compared systematically on a global scale (SEMENIUK & SEMENIUK, 1997).

A functional-oriented classification approach (Wetland Evaluation Technique – WET) was developed by ADAMUS *et al.* (1987). Conceptually the authors weight ecological, hydrological and societal functions, such as importance for water retention, water quality, sediment and nutrient retention, biodiversity, recreation potential, etc. using physical, chemical and biological as well as socio-economic indicators. Functional approaches involve either qualitative results with little predictive value, or include subjective considerations based on best professional judgement and are therefore limited in their application. As summarized by THIESING (2001) such approaches are critical for cumulative impact assessment and for the conservation of biodiversity, since they ignore macro-scale, landscape and system-level functions of wetlands.

In contrast KANGAS (1990) developed an energy theory of landscape, whereas he considers the spatial form and pattern of environmental energy sources (water) in order to differentiate wetlands. Herein, the author utilized variables like water distribution and water flow as indices to characterize respective energy sources and used them in classifying forested wetland systems. Based on the hybrid *Detrended Canonical Correspondence*

Analysis (DCCA) method, HALSEY *et al.* (1997) investigated the influence of climatic and physiographic conditions on the evolution of different wetland types and thereby discuss their distribution patterns to classify wetlands in Manitoba, Canada. The authors conclude that the origin and distribution of wetlands in the northern parts of the study area is predominantly controlled by climatic drivers (seasonal dryness, annual mean of temperatures and rainfall) and soil moisture dynamics, while the geologic-geomorphological set-up controls wetland dynamics in the southern part.

2.1.3 Concepts for Wetland Identification and Delineation

Wetland identification and delineation concepts received considerable progress in wetland research over the last 20 years (TINER, 1999). This progress is strongly associated with initiatives aiming at the conservation and rehabilitation of disturbed wetlands and their consideration in laws and national and international conservation programs (MITSCH & GOSSELINK, 2000). Identification of wetlands is understood as the process to differentiate wetlands from their surrounding landscape by utilizing wetland indicators, while delineation describes the detailed examination and surveying of wetlands in a particular landscape (TINER, 1999; LEWIS, 1995).

As a consequence of different research disciplines numerous techniques have been provided to identify wetlands based on environmental indicators related to soils, wetland vegetation and fauna, hydrology, and geomorphic settings as well as combinations of those (MITSCH & GOSSELINK, 2000; TINER, 1999). Although attempts are undertaken to develop standardized methods for wetland delineation, relatively few publications provide pragmatic guidelines to derive and evaluate indicators in the field. A regulatory for the identification and mapping of wetlands utilizing field-based indicator assessment and delineation was introduced by the *Environmental Protection Agency* (1988) for the United States. The guideline introduced by the *Federal Interagency Committee for Wetland Delineation* (1989) is basically similar, but more focused on jurisdictional wetland aspects. Both manuals provide the user with mandatory technical criteria as well as methods to delineate field indicators based on vegetation composition and soil properties. The *Soil Conservation Service* (1994) presented a guideline for wetland delineation which was assigned to use criteria associated with agricultural land specifically. The manual provided by *National Food Security Act Manual* (NFSAM, 1994) requires an independent assessment of hydric soil, hydrology and hydrophyte vegetation. It considered 'disturbed wetlands' for the first time. A thorough discussion of the pro's and con's of wetland delineation manuals published in the USA is given in TINER (1999) and LEWIS (1995).

As shown by KARATHANASIS *et al.* (2003) difficulties arise during the process of wetland delineation, because the accepted criteria for wetland delineation include the presence of a hydrophytic plant community, hydric soils and hydrology. The identification of hydrophytic vegetation frequently requires expertise in plant taxonomy, while determination of hydrologic regimes, particularly in seasonal wetlands, often mandates several years of measurement of soil saturation or water table levels, thus, making it a time-consuming and expensive task. In the absence of hydrologic data or vegetation analysis, delineators solely are depended on hydric soil criteria. Nevertheless, several approaches to identify and delineate wetlands based on hydrological criteria or plant indicators and their applicability and potential for wetland inventory are intensively discussed in *inter alia* LEWIS (1995), MITSCH & GOSSELINK (2000), and ORME (1990).

Wetland inventories have been developed on several scales. Inventory and mandatory guidelines are available at a national base for the USA (COWARDIN *et al.,* 1979; FRETWELL *et al.,* 1996; WILEN & BATES, 1995), and India (GOPAL & SAH, 1995); on a regional scale for the Mediterranean area (COSTA *et al.,* 1996), Southern Africa (TAYLOR *et al.,* 1995), and Central America (ELLISON, 2004); on a continental scale for Africa (HUGHES & HUGHES, 1992; STEVENSON & FRAZIER, 2001), Asia (FINLAYSON *et al.*, 2002), and Australia (PRESSEY & ADAM, 1995); and on a global scale (FINLAYSON & VAN DER WALK, 1995; SCOTT & JONES, 1995; SPIERS, 2001).

Recent wetland delineation studies have shown, that remote sensing techniques provide useful data and innovative methods to support wetland inventory and moreover to allow the monitoring of wetlands. Given the plant-specific compositions as well as their hydrological dynamics, wetlands show a highly spatio-temporal variability. This can be found in their varying spectral significance. While Color Infrared Red aerial photographs have successfully been applied for habitat mapping for decades (TAMMI, 1994; WILEN & PYWELL, 1992), recent studies investigate the potential of data from optical sensors for wetland delineation (ANDERSON & PERRY, 1996; JENSEN *et al.*, 1995; SADER *et al.,* 1995) and monitoring (HOUHOULIS & MICHENER, 2000; MUNYATI, 2000) in mesoscale applications. Airborne multispectral imagery (CASI) were successfully applied for the environmental monitoring of wetland, surface water and land cover changes by ORMISTON & SHEA (2000), while BARTSCH *et al.* (2004) delineated the extent and distribution of wetlands in Siberia utilizing Envisat ASAR WS data. Moreover, BROOKS *et al.* (2004) developed an integrated approach to evaluate wetland condition changes using remote sensing and GIS techniques.

Since techniques to demarcate wetlands from their surroundings are well established, authors emphasized problems associated with intra-zonal differentiation of wetlands (TINER, 1999; LEWIS, 1995). In most cases such approaches utilize field indicators like spatial differences of chemical and morphological properties of hydric soils (KOTZE *et al.*, 1994; MAUSBACH, 1994; VEPRASKAS *et al.*, 1999), vegetation changes (LUGO *et al.*, 1990; MCPHERSON & HALLEY, 1996; WAKELEY & LICHVAR, 1997) or combinations of those indicators (ANDERSON *et al.*, 1980; TAMMI, 1994). In contrast MEGONIGAL *et al.* (1993) and BISHEL-MACHUNG (1996) present an approach to delineate reference wetland areas based on soil properties like density, texture, color, organic content, nitrogen content and pH-value and relate those parameters to landscape dynamics.

2.2 Wetland Hydrology and Modeling

Wetland hydrology comprises the spatio-temporal distribution, circulation and physico-chemical characteristics of surface and subsurface water in the wetland. This section gives solely a background on aspects of wetland hydrology. It summarizes theoretical considerations regarding the importance of selected water cycle components. More details on recent work in wetland hydrology are given in e.g. BROOKS (2005), MITSCH & GOSSELINK (2000), O'CONNEL (2003), PRICE *et al.* (2005), RICHARDSON *et al.* (2001) and WOO (2002).

2.2.1 Wetland Water Budget

Wetland water budget estimates are important to calculate energy fluxes and nutrient balances as well as for prognostic modeling of natural and anthropogenic impacts on wetland ecosystems in general and in particular its water components. Basically, the water balance of a given wetland is expressed as the difference between water storage and inflows and outflows. According to MITSCH & GOSSELINK (2000) a general balance equation for wetlands is formulated as

$$\frac{dV}{dt} = P_n + S_i + G_i - ET - S_o - G_o(\pm T) \quad [2.1]$$

where V is the volume of water storage in wetlands,
dV/dt is the change in volume of water in wetland per unit time,
ET is the evapotranspiration,
P_n is the net precipitation ,
S_i is the surface inflow, including flooding streams,
G_i is the groundwater inflow,
S_o is the surface outflow,
G_o is the groundwater outflow,
T is the tidal inflow (+) or outflow (-).

Each variable in Equation 2.1 can be expressed in terms of depth per unit time (e.g. cm/yr) or in terms of volume per unit time (e.g. m^3/yr).

Since the water depth is widely used to characterize wetland budgets, the mean water depth *d*, at any specific time, can further be described (MITSCH & GOSSELINK 2000) as

$$d = \frac{V}{A} \quad [2.2]$$

where A is the wetland surface area.

As shown by numerous studies, wetland water budget estimates are usually based on the measurement and modeling of one or more of the water cycle components. Summarizing those studies it can be concluded that the accuracy of such balances is strongly dependent on the quality of the measured and estimated parameters and their associated faultiness. In this context, several authors refer to insufficient data availability for quantitative estimates as well as the lack of detailed studies about efficiency and accuracy of measurement methods (CARTER, 1986; COLE *et al.*, 1997; GILMAN, 1994; LABAUGH, 1986; SKAGGS *et al.*, 1994). According to HUNT *et al.* (1998), traditional physical measurements are prerequisites for an improved understanding of wetland systems. Nevertheless, the authors emphasized that the potential of such methods is restricted by ***i) the seasonality of hydrological dynamics of wetlands***; ***ii) the measurement uncertainties*** (HEMMOND & GOLDMANN, 1985) and ***iii) problems related to scale dependency and heterogeneity*** (HUNT *et al.*, 1997). As a consequence, the authors demand the development of innovative techniques to complete existing measurement methods and to reduce those deficits. Another problem is related to the representation of measurement intervals (SHAFFER *et al.*, 2000). The authors studied the effects of several measurement frequencies on water-level statistics in seven wetlands intensively. As a result they suggested that the frequency and duration of sampling in hydrological studies must be adjusted to meet the purposes of the planned analyses.

Given these mentioned deficits, numerous studies have been presented concerning the measurement of individual components of the water cycle of wetlands and its accuracies. They are therefore discussed in the following sections separately.

2.2.1.1 Precipitation

Since precipitation is one of the key drivers of wetland dynamics, its importance for wetland water budgeting is discussed in the literature intensively (LEWIS, 1995; DUEVER *et al.*, 1994). While precipitation primarily controls the hydrological process dynamic of wetlands in tropical environments, rainfall is assumed to be less important in relation to groundwater and interflow and thereby secondary for wetland hydrology in semi-arid areas (LEWIS, 1995; MITSCH & GOSSELINK, 2000).

The determination of the amount and intensity of precipitation for small-scale wetlands is usually done by extrapolation of point measurements made at nearby reference station or by weighted averages (CARTER *et al.*, 1986). For large wetland areas the relief-induced variability of rainfall is of importance for the process dynamics. Therefore it needs to be taken into account when modeling spatial distribution patterns (DUEVER, 1988). Detailed descriptions of techniques and equipment to measure precipitation are given in respective literature (e.g. BEVEN, 2001a; WOHLRAB *et al.*, 1995; GEHRELS & MULAMOOTTIL, 1990).

2.2.1.2 Evapotranspiration

Evapotranspiration is commonly classified into two stages by considering the soil water availability (IDSO *et al.*, 1974; BRUTSAERT & CHEN, 1995). First stage evaporation (potential evaporation) has adequate water near the surface so that the evaporation rate is limited by available energy. Second stage evaporation occurs during drying soil conditions when the evaporation rate is limited by the available soil water coupled with the available energy. In a wetland water is evaporated from saturated and unsaturated soils, open water bodies and by vascular plants (transpiration). Factors affecting evapotranspiration rates in wetlands are solar radiation, wind speed, relative humidity and soil moisture as well as vegetation composition and density (*inter alia* DUEVER, 1988; MITSCH & GOSSELINK, 2000).

As it was shown by numerous studies (BEVEN, 2001a,b; JACOBS *et al.*, 2002; KADLEC *et al.*, 1988; MOHAMED *et al.*, 2004; WESSEL & ROUSE, 1994; WOHLRAB, *et al.*, 1995; XU & LI, 2003), evapotranspiration can be estimated precisely utilizing indirect methods like energy balance method, BOWEN ratio, empirical equations like THORNTHWAITE, HAUDE, PENMAN, PENMAN-MONTEITH, PRIESTLEY-TAYLOR or hybrid methods. Direct measurements of evapotranspiration (A-Pan, lysimeters, gravimeters, etc.) are usually difficult and expensive due to technical needs and require long time series for validation (ABTEW & OBEYSEKERA, 1995; LOTT & HUNT, 2001; WOHLRAB *et al.*, 1995). A description the potential and limitations of existing methods to determine evapotranspiration from land surfaces is given among others in SHUTTLEWORTH (1992) and DVWK (1996).

Evapotranspiration rates are often determined as the resulting component of the water budget equation in wetland studies (CARTER, 1986; IDSO, 1981; MITSCH & GOSSELINK, 2000; SUCCOW & JOOSTEN, 2001). A number of studies have been conducted to determine evapotranspiration for a range of wetland systems that have been reviewed by DOLAN *et al.* (1984) and BURBA *et al.* (1999). Most of these studies have focused on systems where the water table is at or above the land surface. When the wetlands are inundated, evapotranspiration occurs at the first stage evapotranspiration rate. First stage evaporation is fairly well understood and has been modeled for wetland systems using the PRIESTLEY-TAYLOR model, the PENMAN model, and the PENMAN-MONTEITH model (e.g., ABTEW, 1996; SOUCH *et al.*, 1998; BURBA *et al.*, 1999). As discussed by LOTT & HUNT (2001) those approaches tend to underestimate evapotranspiration rates in vegetated wetlands especially when off-site data are considered or point measurements are extrapolated to wetland scale.

Studies in permanently saturated wetlands have also shown that the energy balance method has been applied successfully to delineate evapotranspiration rates (PARKHURST *et al.,* 1998). SALVUCCI (1997) reviewed physically-based approaches to estimate moisture-limited evapotranspiration. He summarized that these approaches show potential in experimental research conducted on bare soils, but when they are transferred to specific wetland surfaces, most of them seemed not to be viable. DOLAN *et al.* (1984) used a relation between water fluctuation and evapotranspiration losses to calculate daily evapotranspiration rates in vegetated wetlands. As shown by GOODIN *et al.* (1996), the analysis of surface radiation and energy microclimate and its application in empirical equations provides a certain potential for spatial evapotranspiration estimates in heterogeneous wetlands. As presented by STANNARD *et al.* (2004) fetch-induced errors in BOWEN ratio energy budget measurements are relatively small in shallow prairie wetlands, but increase with a decreasing fetch-to-height ratio, with increasing aridity and with increasing atmospheric stability over the wetland

Second stage evaporation is usually estimated with an empirically-based approach. This method determines evaporation by combining the potential evaporation (i.e., the evaporation if soil water was not limiting) with a proportionality coefficient or reduction factor (B), where B is a function of soil moisture. This method is commonly used in hydrologic models to calculate actual evaporation based on potential evaporation (e.g. BEVEN, 2001a; BRUTSAERT, 1991; SCHULZE, 1995).

Summarizing the research on wetland evapotranspiration it was found, that the evapotranspiration estimation in vegetated wetlands has become the subject of controversial debate, since studies have shown that the presence of wetland vegetation can result in either higher or lower rates of evaporation compared to open water (e.g., ABTEW, 2001; IDSO, 1981; SUCCOW & JOOSTEN, 2001). MITSCH & GOSSELINK (2000) concluded from several studies that the overall wetland water loss is less affected by the plant species variations than by the season and the specific type of wetland ecosystem. INGRAM (1983), for example, has shown that fens have about 40 % more evapotranspiration than do treeless bogs and that evaporation from the bogs is less than potential evapotranspiration in the summer and greater than potential evapotranspiration in the winter.

Transpiration results from root uptake by emergent plants and the subsequent loss through leaf surface area. Estimates of transpiration rates are related to vegetative density, soil moisture content, and depth to the deep root zone. Regarding to SUCCOW & JOOSTEN (2001) the transpiration rate from wetland plants is a very critical component to measure and to quantify, and thereby evaporation and transpiration are usually combined in wetland water balance studies to a single estimate of water loss. Nevertheless, a few studies refer to estimates of transpiration in macrophyte dominated wetlands. For example, transpiration rates for cattails (*Typha sp.*) have been reported to range from 4 to 14 mm/day showing typical diurnal pattern with a maximum at about midday (ABTEW *et al.*, 1995; ALLEN *et al.*, 1992; MARTIN *et al.*, 2003). Mean transpiration was highest at the end of June coinciding with the peak of growth and with the maximum leaf area both at individual and plot scales. KOCH & RAWLICK (1993) compared two macrophyte species in a subtropical environment. They found that *Typha dom.* possessed higher transpiration and conductance rates than *Cladium jam.* during the winter and spring months, but rates for the two species converged and were not significantly different during the summer and fall months. Moreover, MORO *et al.* (2004) describe the novel application of the stem heat-balance method for measuring sap flow, and, therefore, transpiration, from reeds (*Phragmites spp.*) in a semi-arid wetland. The research reveals the very high rates of transpiration that are possible in isolated wetlands in a semi-arid setting, where the advection of heat and dry air from surrounding dry land enhances rates of water loss.

In addition, a few studies have shown that evapotranspiration can be determined using remote sensing techniques. For example, regional water evaporation and transpiration from wetlands in Florida has been successfully estimated by combining Normalized Difference Vegetation Index (NDVI) and Diurnal Surface Temperature Variation (DSTV) derived from NOAA AVHRR thermal and visible/near-infrared bands (CHEN *et al.*, 2002).

2.2.1.3 Interception

Canopy interception loss, the proportion of incident precipitation which is intercepted, stored and subsequently evaporated from the leaves, branches and stems of vegetation, is a significant and sometimes a dominant component of evapotranspiration from vegetated surfaces (ACREMAN, 2003; BEVEN, 2001a; WOHLRAB *et al.*, 1995). It is approximated as the difference between incident precipitation measured above the canopy and the sum of throughfall and stemflow below the canopy.

Research on forest canopy interception showed that it can account for 10-35 % of gross precipitation (PRETZSCH, 2001), and therefore similar rates are assumed for forested wetlands (MITSCH & GOSSELINK, 2000; VAN SETERS & PRICE, 2001). Little consideration has been given to interception of rainfall in non-forested wetlands, but it is indicated that rates of emergent herbaceous macrophytes are comparable to that measured in grassland or croplands (MITSCH & GOSSELINK, 2000). Interception, however, is assumed to be notable, if not significant in terms of species, density, canopy structure, vegetation physiology and different climatic conditions in wetland hydrology, but there is still a need of detail studies regarding the measurement and quantification of interception losses in wetlands (MITSCH & GOSSELINK, 2000; PRICE *et al.*, 2005).

2.2.1.4 Surface Water Flow

Surface water flows of wetlands, i.e. inflow, through flow and outflow, are basically dependent on permanent, seasonal or temporary characteristic of the wetland. Surface flow can either occur as *Horton Overland* flow (non-channelized sheet flow). It usually results from direct intensive rainfall events or snow melt excess of infiltration capacity, or channelized streamflow if connected to a drainage basin. TODD *et al.* (2006), for example, showed that a rising water table during snowmelt sustained surface saturation in the wetland and at the wetland-upland interface, and saturation overland flow generated the bulk of annual runoff in a wetland-dominated drainage basin in south central Ontario, Canada.

Wetlands can also receive surface inflow from temporary floods from adjacent streams that are not hydrologically connected with the wetland system. In some cases surface flow is generated by overflow from lakes or man-made dams as well as from leaking groundwater by impermeable bedrocks. Moreover, LEIBOWITZ & VINING (2003) found that intermittent surface water connections show a high spatio-temporal variability as it was shown for a pothole complex in the USA. Moreover, the dynamic of surface water flow is usually controlled by factors like water level fluctuation, vegetation density, micro-topography and evapotranspiration processes.

According to MITSCH & GOSSELINK (2000) general estimations of surface inflow volumes from a basin are determined directly by

$$S_i = R_p \cdot P \cdot A_w \qquad [2.3]$$

where S_i is the direct surface runoff into wetlands [m^3 per storm event],
R_p is the hydrologic response coefficient, i.e. fraction of P that becomes S,
P is the average precipitation in watershed [m],
A_W is the area of wetland watershed [m^2].

The *rational runoff method* can be used to calculate peak runoff into a wetland caused by a specific event. The equation (MITSCH & GOSSELINK, 2000) is given by

$$S_{i(pk)} = 0.278 \cdot C \cdot I \cdot A_w \qquad [2.4]$$

where $S_{i(pk)}$ is the peak runoff into wetlands [$m^3 s^{-1}$],
C is the rational runoff coefficient ranging from 1 (sealed) to 0.1 (sandy soils),
I is the rainfall intensities [$mm\ h^{-1}$],
A_w is the area of wetland watershed [m^2].

Streamflow of channels into and out of wetlands is described as the product of the cross-sectional area of the channel (*A*) and the average velocity (*v*) and can be determined by velocity measurements in the field (MITSCH & GOSSELINK, 2000):

$$S_{i/o} = A_x v \qquad [2.5]$$

where $S_{i/o}$ is the channelized flow into or out of wetlands [$m^3 s^{-1}$],
A_v is the cross-sectional area of a stream [m^2],
v is the average velocity [$m\ s^{-1}$].

In- and outflow of surface water can be directly measured using a variety of standardized methods which are described in detail by GEHRELS & MULAMOOTTIL (1990), MITSCH & GOSSELINK (2000) and KORENY *et al.* (1999). Normally, methods are based on the measurement of runoff (weir) or water levels (water level meters) and thereby allow conclusions concerning base flow, water transfer volumes and storage dynamics.

Problems have been experienced by direct measurements and estimations of saturation and overland flow. Both are evidently influenced by vegetation and microtopography and are thereby determined by a roughness coefficient (MOORE & FOSTER, 1990). A guideline for estimates of roughness coefficients in channels and wetland areas is given by ARCEMENT & SCHNEIDER (1989). Detailed studies on modeling and quantification of wetland discharge (HAMMER & KADLEC, 1986; GEHRELS & MULAMOOTTIL, 1990; LEACH *et al.*, 1972, cit. in DUEVER, 1988; PARKER, 1974; cit. in DUEVER, 1988) and runoff velocities in wetlands (LEITMANN *et al.*, 1982) are only published for the United States.

2.2.1.5 Subsurface Water Flow

Although the importance of subsurface hydrology for wetland ecosystem occurrence, functioning, and productivity is recognized, there are only few detailed analyses of shallow subsurface water flow through wetland ecosystems. Basically, subsurface water flow in wetlands is very complex. It needs to be differentiated into groundwater flow, i.e. water flow under saturated conditions and subsurface flow in unsaturated environments that is often referred to interflow and soil moisture dynamics. Since the majority of accomplished studies are focused on dynamics of the saturated soil zone and groundwater, noteworthy progress has been achieved over the last decades in this field (DAGAN, 1997).

Subsurface water flow in, through and out of a wetland is usually described by DARCY's law which is empirical in nature and based on experimental observations. It states that the saturated water flow is proportional to the hydraulic gradient (i.e. the slope of the water table or piezometric surface) and the hydraulic conductivity (i.e. the capacity of the soil to conduct water flow). DARCY's law is expressed as

$$v_x = -K \cdot \frac{\mathrm{d}\phi}{\mathrm{d}x} \qquad [2.6]$$

where G is the is velocity in the x direction [volume per unit time],
$-K$ is the hydraulic conductivity [length per unit time],
ϕ is the total potential or hydraulic head.

Since DARCY's law was established for saturated media, RICHARDS (1931) generalized DARCY's law for the case of unsaturated flow by making the assumption that the same linear relationships holds but that the constant of proportionality should be allowed to vary with soil moisture content or capillary potential. It is then expressed as

$$v_x = -K \cdot (\theta) \cdot \frac{\Delta\phi}{\Delta x} \qquad [2.7]$$

where θ is volumetric soil moisture.

A further equation to describe subsurface flow is the Richards equation. It combines Darcy's law with the continuity or mass balance equation which may be written with capillary potential ψ as the dependent variable as follows

$$C(\psi) \cdot \frac{\mathrm{d}\psi}{\mathrm{d}t} = \nabla[K(\psi)\nabla \psi] + \frac{\mathrm{d}K(\psi)}{\mathrm{d}z} - E_T(x, y, z, t) \qquad [2.8]$$

where ψ is the local capillary potential,
$K(\psi)$ is the unsaturated hydraulic conductivity which is now expressed as a function of ψ rather than θ,
$C(\psi)$ is a function of ψ defined as the rate of change of moisture content θ with change in ψ called the specific moisture capacity,

$E(x, y, z, t)$ is the local uptake of water by plant roots to satisfy evapotranspiration.

An equivalent equation with soil moisture as the dependent variable can also be used (BEVEN, 2001a).

Subsequent research has shown that DARCY's law is not valid under conditions where the flow matrix is fine textured. Hence, adsorptive forces become significant or where hydraulic gradients are so steep that either turbulent flow dominates (HUNT *et al.*, 1996; RICHARDSON *et al.*, 2001) or water movement is mainly driven by gravity (BEVEN & GERMAN, 1982). Numerous wetlands are controlled by macropore flows and thereby

DARCY's law cannot be applied either. Non-wetland studies have shown that models predicting water infiltration into macroporous soils are often based on the concept of a bimodal porosity (HOOGMOED & BOUMA, 1980; BEVEN & GERMAN, 1982; JARVIS & LEEDS-HARRISON, 1987; CHEN & WAGENET, 1992; JARVIS, 1994). Since those models are 1-dimensional and soil deformation by swelling effects is not or poorly accounted for, RYE *et al.* (1999) presented the physical bases of a two-dimensional (2D) numerical model of water infiltration and soil movements in undisturbed swelling clay soils showing macropore dynamics. Since the importance of macropores as a preferential flow mechanism for infiltrating water and transport of solutes is fairly understood, theoretical considerations about different media are given in *inter alia* BEVEN & GERMAN (1982), CHRISTIANSEN *et al.* (2004), German (1990), RITSEMA & DEKKER (2000), STEENHUIS *et al.* (1994).

The measurement of groundwater and soil moisture state is intensively discussed in the literature. A variety of groundwater monitoring techniques is described in detail for non-wetland areas (FREEZE & CHERRY, 1979; TODD & MAYS, 2004) and for wetlands (CONLY *et al.*, 2004). Soil moisture can be measured using gravimetric techniques (ERBACH, 1983), nuclear techniques (STAFFORD, 1988), electromagnetic techniques (DRUNGIL *et al.,* 1989; FREELAND, 1989; HEIMOVAARA & BOUTEN, 1990; STEIN & KANE, 1983), tensiometric techniques (ERBACH, 1983), hygrometric techniques (PHENE & HOWELL, 1984) and remote sensing techniques (DOBSON & ULABY, 1998; SCHMUGGE, 1996). In situ measurement techniques for soil moisture have been evaluated by WALKER *et al.* (2004). The authors point out that connector-type TDR sensors give the most accurate measurements of soil moisture content out of the sensor types tested. In addition HANSCHKE & BAIRD (2001) report about time-lag errors associated with the use of simple standpipe piezometers in wetland soils.

Groundwater dynamics in wetlands are primarily controlled by geological and geomorphological conditions. Depending on their position and underlying materials, wetlands can have a discharge, flow-through or recharge function (LABAUGH, 1998: MITSCH & GOSSELINK, 2000; PRICE *et al.*, 2005; VAN DER KAMP & HAYASHI, 1998). Groundwater inflow appears when the surface water level of a wetland is hydrologically lower than the water table of its tributary watershed (*discharge wetland*) (MITSCH & GOSSELINK, 2000). The incoming groundwater will then be evaporated (no outflow) or discharges as excess water downstream as surface (springs) or groundwater flow. Groundwater will flow out of the wetlands (*recharge wetlands)* when the wetland water table is higher than the water table of its tributary catchment (MITSCH & GOSSELINK, 2000). Those wetlands often occur in depressions or in marshy environments and can be hydrologically isolated. They are usually characterized as being perched due to their impermeable soils and therefore loose water only by slow infiltration into the ground and evapotranspiration. However, the extent and type of groundwater dynamics influence the amplitude and duration of baseflow and water level fluctuation, which are linked to surface saturation, runoff processes as well as sediment redox, biogeochemical processes, and the vegetation pattern within the wetland (e.g. TÓTH, 1999; HAYASHI & ROSENBERRY, 2001).

As shown by numerous studies (e.g. LA BAUGH, 1986; HUNT *et al.*, 1999) soil and groundwater are the most critical components of wetland water budget studies because of their spatio-temporal dynamics. Basically, this is due to a lack of detailed studies addressing wetlands subsurface flow (CARTER, 1986; DAGAN, 1997; HUNT *et al.*, 1996; MANN & WETZEL, 2000; SMITHERS & SCHULZE, 1995) and the extensive operating expense for data acquisition (COLE *et al.*, 1997).

Based on empirical studies EULISS & MUSHET (1996) evaluated the fluctuation dynamics of water levels with specific respect to land use management (grassland, agriculture) in temporary, seasonal and semi-temporary wetlands. They emphasized that the groundwater dynamic is the primary driving force of the hydrology within investigated study sites. Similar results are presented by GONTHIER (1996) who studied the groundwater dynamics of forested wetlands in Cache River watershed (Arkansas, USA) and related them to the phiysographic basin characteristics. Moreover, CASTELLI *et al.* (2000) examined the temporal and spatial relationships between hydrologic gradients, vegetation, and soil morphological and physical properties in order to identify plant species and environmental variables that can be used as key indicators to enumerate groundwater status in riparian meadows. The impact of land use on ground water level dynamics is furthermore confirmed by SUN *et al.* (2000) who studied the impact of commercial forestry on groundwater fluctuation in coastal plains.

STEIN *et al.* (2004) evaluated the influence of geologic settings on slope wetland hydrodynamics in 20 slope wetlands in southern California. The authors concluded that wetlands in alluvial/colluvial deposits respond quickly to precipitation and subsurface water levels stay near the surface for long periods. In contrast, bedrock landslide slope wetlands respond significantly slower to rainfall events, show greater variation over time, and decrease more quickly after the cessation of recharge events.

Analysis of long-term records of hydroperiods has been carried out by LONG & NESTLER (1996) to identify factors responsible for immense hydroperiod alterations within the Cache River basin. The authors proved that those changes are caused by increased withdrawal of groundwater since the early 80s. In addition NUTTLE (1996) used harmonic analysis to characterize hydroperiod dynamics quantitatively and therefore found a relationship between water-level fluctuation and water management decisions in the Everglades. HUNT *et al.* (1999) discussed the potential of hydrograph analysis for groundwater dynamic assessment in natural and constructed wetlands, while MOON *et al.* (2004) formulated a statistical relationship between precipitation and groundwater level fluctuations and therewith evaluated the spatial variability of recharge in river basins. Moreover, GUNDUZ & ARAL (2005) introduced a new approach based on the simultaneous solution of coupled channel and groundwater flow systems. The solution technique is coupling a one-dimensional channel network flow model that uses the complete form of the ST VENANT equation with a two-dimensional vertically averaged groundwater flow model. BAKKER (1999) studied errors in discharge that needs to be considered when analytic DUPUIT-models are used to describe groundwater flow in multi-aquifer systems. As a result the author found a certain cell size and domain size that give accurate results when the DUPUIT solution is approximated with the finite difference method. A system identification approach was introduced by VON ASMUTH & KNOTTERS (2004) to characterize groundwater dynamics. Therefore the dynamics of the input parameters being the mean and annual amplitude of the precipitation surplus for univariate time series have been linked to the spatially variable system properties, and result in a new set of parameters describing groundwater dynamics.

Groundwater inflow (36%) and outflow (<50%) was quantified by water budget studies in a southern Ontario, USA wetland utilizing long-term measurements of hydraulic conductivity related to hydraulic gradients (GEHRELS & MULAMOOTTIL, 1990). Moreover, KORENY *et al.* (1999) evaluate the potential of laboratory and field-based methods to measure hydraulic conductivity, which were combined with measured vertical gradients to estimate seepage loss to groundwater and travel times of groundwater in a constructed wetland in Ohio.

An approach using *'interaction indices'* derived from water budget indices was introduced by LENT *et al.* (1996) and successfully applied to 19 wetlands to estimate water budget components. GERLA (1999) estimated groundwater rates by linking a Digital Elevation Model (DEM) with transient numerical model algorithm. By knowing the hydraulic conductivity and using the model water-table configuration, groundwater flow from and to each discretized area unit can be estimated from DARCY's law and the DUPUIT approximation.

Research review has shown that water transport dynamic in the unsaturated soil zone found less consideration in wetland studies in the past. Although the importance of interflow due to its function for the landscape water cycle and basin water budget is widely re-cognized (BARSCH & FLÜGEL, 1988; SCHAAR, 1988; FLÜGEL, 1991), only a few detailed studies have been published looking at vertical and lateral flow in unsaturated wetland soils (DUEVER, 1988; GEHRELS & MULAMOOTTIL, 1990; PRICE *et al.*, 2005; SKAGGS *et al.*, 1994; TODD *et al.*, 2006). DUEVER (1988) and WOHLRAB *et al.* (1995) refer this fact to problems regarding the measurement of water fluxes in unsaturated conditions as well as to the complex interaction of interflow influencing variables (e.g. microtopography, soil properties, hydraulic gradient, hydraulic conductivity, vegetation, and land use impacts).

Vertical transfer of soil water has been simulated using DRAINMOD by FOUSS *et al.* (1987) in the lower Mississippi Valley, USA. REEVE *et al.* (2000) revealed that the extent of vertical flow in the Hudson Bay Lowland wetland is limited by low-permeability mineral substrate, promoting lateral flow through the acrotelm. Moreover, FRASER *et al.* (2001) found reversals between recharge and discharge to and from the deeper peat layers during wetting and drying periods respectively. Transfer of water from deeper peat layers to the surface is important in sustaining soil moisture in the surface layer, and changes of soil moisture in this layer should be taken into account for in the water balance (LAPEN *et al.*, 2000). As found by KENNEDY & MAYER (2002) vertical redistribution of peat pore-water has also been shown to occur from the saturated zone to the soil-moisture zone during peat consolidation (LANG, 2002). They may be enhanced by pressure caused by methane generation (PRICE, 2003). These exchanges have implications for water quality (FRASER *et al.*, 2001).

Considerable progress has been achieved regarding lateral flow dynamics in non-wetland areas. Intensive studies on experimental test sites (ANDERSON & BURT, 1978; BARSCH & FLÜGEL, 1989; FLÜGEL, 1979) and in micro- and meso-scale humid, polar and semi-arid basins (KOSUGI *et al.*, 2001; FLÜGEL & SCHWARZ, 1988; FLÜGEL, 1989, 1990, 1991, 1993 a,b,c) have shown that spatio-temporal variability of hillslope water fluxes can be primarily seen as a function of soil moisture, clay content, texture and topography. The difficulties of the physical understanding of hillslope process dynamics and associated modeling problems are summarized in KIRKBY (1978) and ANDERSON & BURT (1990).

In a case study, TODD *et al.* (2006) compared vertical and lateral water fluxes and their importance for the wetland hydrology. They concluded that vertical water movement in response to rainfall, evapotranspiration and recharge of deeper groundwater was more important than lateral groundwater fluxes in explaining the wetlands hydrologic behavior. Furthermore, the problem of piping and pipeflow in deep peat layers has been studied by HOLDEN & BURT (2002). The contribution of pipeflow to streamflow volume is assumed to vary between 10% and 30% depending on type of pipe and rainfall intensities.

Several approaches have been presented to model hillslope hydrological processes and interflow considering topography (BEVEN *et al.*, 1988; CORRADINI *et al.,* 1986; GUPTA *et al.*, 1986), macro-pore flow (GERMAN, 1990), infiltration and soil moisture (BOUMA, 1986; CLAPP*,* 1983), and evapotranspiration and interception (BRADEN, 1991; FLÜGEL, 1988; HERRMANN, 1992; HOYININGEN-HUENE, 1983; WEIHE, 1977). In addition SAMPER-CALVETE (1997) emphasized the potential of geostatistical methods to evaluate process parameters of the unsaturated soil zone. Stochastic descriptions of hillslope dynamics considering the heterogeneity of slope systems and water cycle components are given by FREEZE (1978). The presented concepts have been implemented in physically-based models like HYDRUS (KOOL & VAN GENUCHTEN, 1991), HILLFLOW (BRONSTERT, 1994) or HILLS (HEBBERT & SMITH, 1992) and were thereby used to analyze and quantify lateral flow dynamics (e.g. LORENTZ *et al.,* 2004; FLÜGEL & SMITH, 1999).

A few studies consider the affects of groundwater on soil moisture and its distribution. A soil hydrological model was developed to include groundwater effects by allowing water exchange between the unsaturated zone and groundwater (CHEN & HU, 2004). The model uses a vertically varying saturation hydraulic conductivity, and is evaluated using observations at a monitoring station in the Nebraska Sand Hills. WISE *et al.* (2000) introduced an approach called Wetland-Aquifer Interaction Test (WAIT) to identify and determine the hydraulic connection between an isolated wetland and the underlying aquifer.

2.2.2 Modeling Concepts in Wetland Hydrology

In recent years considerable work was done in terms of model development and application in environmental research in general and hydrology in particularly. Summarizations of published work regarding hydrological models and its concepts, classification, function and structure are given e.g. in BEVEN (2001a, b), GRAYSON *et al.* (1992), BECKER & BRAUN (1999) and SCHULZE (1995).

Principally, environmental models describing natural processes are either conceptual or deterministic. Conceptual hydrological models involve the interaction of hydrological processes by using simplified approximations and assumptions. A deterministic model can be developed from a conceptual model. They are physically-based in the sense of having a theoretical structure based on definite physical laws of conservation of mass, energy or momentum. They specify initial and boundary conditions and transfer model inputs to a uniquely definable output (SCHULZE, 1995).

According to LEWIS (1995) there are two major approaches to integrate deterministic models in wetland hydrology. One involves the evaluation of the hydrologic condition of a specific wetland site in relation to defined hydrologic thresholds for wetlands. Since they are spatially limited, they can only be used for descriptive and assessment purposes of one specific wetland. Such models are developed for constant boundary conditions and therefore are not linked to their tributary basin. A second trend is to use models to estimate effects of cumulative wetland loss or increase on regional hydrologic characteristics like flood flows, sediment retention and others in order to assess watershed response functions. Therefore wetland models are usually embedded in regional model applications and are considered to interact with the surrounding system. Following sections give an overview of presented wetland models (Section 2.2.2.1) and watershed-response simulation models to assess wetland hydrology in a basin perspective (Section 2.2.2.2).

2.2.2.1 Wetland Modeling

The potential of wetland models was firstly discussed by COSTANZA & SKLAR (1985) who reviewed 87 models utilized in 59 wetland studies. The authors introduced three indices, namely articulation (size and complexity of the model), accuracy (measures of goodness of fit) and effectiveness (explanatory power as a combination of articulation and accuracy). For the reviewed models it was shown that accuracy was seen to fall with increasing articulation resulting from increasing complexity and cost, while effectiveness rose to a maximum at intermediate articulation (COSTANZA & SKLAR, 1985).

While COSTANZA & SKLAR (1985) classified models in linear and non-linear categories depending on their theoretical background, LEWIS (1995) and REFSGARD (1996) considered wetland models as being functional (lumped parameters) or discretized (distributed parameters).

Functional models are mainly based on the assumption of relatively uniformed soil systems with defined boundary conditions, but in some cases layers with specific hydraulic properties are considered (LEWIS, 1995). Water budget estimations for the wetland are restricted to algebraic equations and analytical algorithms are used to calculate water fluxes as a function of water level, depth, drainage and evapotranspiration (LEWIS, 1995). Functional models like DRAINMOD (SKAGGS *et al.*, 1994) and PHIM (GUERTIN & BROOKS, 1986; GUERTIN *et al.*, 1987) were successfully applied in drained wetlands. MIKE 21 was used to model flow hydrodynamics in a constructed wetland (SOMES *et al.,* 1999) and in lowland wet grassland (THOMPSON *et al.*, 2004). FENNEMA *et al.* (1994) developed a two-dimensional coupled surface/ground water model called Natural System Model (NSM36) which was used to estimate surface water flows in selected areas of the Everglades. The modular-structured Wetland Dynamic Water Budget Model (WALTON *et al.*, 1996a) integrates several model concepts and has been used to model the water budget in the Black Swamp wetlands of Cache River basin, Arkansas. The authors found that the wetland hydrological system is evidently dominated by the runoff dynamic of the river and associated overbank flooding at certain times of the year. Moreover, COPPOLA *et al.* (2003) utilized artificial neural networks for groundwater management purposes. They concluded that the proposed technique was successfully applied to reproduce groundwater dynamics with varying groundwater pumping and climate scenarios and provide an alternative to the application of physically-based models. All studies emphasized that functional models can be effectively applied for water balance studies of wetlands, but also reveal that such models are often limited given the spatial inhomogeneities within such wetlands.

Distributed-parameter models are usually used for estimating detailed subsurface groundwater flow and to estimate flood flows (LEWIS, 1995). They are complex in nature and require a variety of empirical parameters to describe the hydrological system. Since detailed descriptions of the properties of unsaturated soil and boundary conditions throughout the flow domain are limited, such models are usually considered for groundwater studies. That kind of groundwater models were successfully used to evaluate major drivers of wetland ground water hydrology in many settings (SIEGEL, 1983; SIEGEL & GLASER, 1987; WINTER, 1988; MCNAMARA *et al.*, 1992). Where subsurface water movement is primarily horizontal in the saturated zone, numerical solutions to the BOUSSINESQ equation can be easily used for wetland modeling (LEWIS, 1995). Models like GERGAM-A (DELAAT *et al.*, 1981) and WATCROM (PARSONS *et al.*, 1991 a,b) were applied to simulate spatially distributed water table fluctuations. BRAVO & BROWN (1998) reviewed several models and presented a 3-D model (HST3D) that integrates piezometric heads, vertical piezometric gradients, estimates of groundwater inflow, and eventually temperature distribution within a groundwater wetland model. MANSELL *et al.* (2000) introduced a multidimensional model describing water flow in variably saturated soil and evapotranspiration to simulate local hydrologic dynamics for a cypress pond within a pine forest landscape. Other 2-D wetland models using the diffusion flow assumption include the WETFLOW model by FENG & MOLZ (1997). A weighted implicit finite volume model was successfully applied by (LAL *et al.* (1998) aiming to simulate both overland and groundwater flow in the Everglades National Park. Moreover, LAL (1998) supplemented his research by the assessment of numerical errors and run-times of 1-D and 2-D wetland models in order to identify the impact of spatial and temporal discretizations on model results.

A distinctive extension of MODFLOW (MCDONNALD & HARBAUGH, 1988) developed by RESTREPO *et al.* (1998) allows simulating three-dimensional wetland flow hydroperiods and wetland interactions with aquifers and slough channels. It can be used to reproduce surface water flow processes through wetland bodies, and then to simulate new flow rates and values using MANNING's equation. Moreover, REEVE *et al.* (2000) applied MODFLOW to evaluate the main drivers controlling vertical flow dynamics in large peatlands. The authors concluded that the vertical groundwater flow in peatlands is primarily controlled by mineral soil permeability.

A generic wetland ecosystem model WETMOD was introduced to simulate floodplain wetlands in South Australia (CETIN *et al.*, 2001). The model was shown to predict the response of degraded wetlands to feasible restoration measures by simulating five qualitatively different wetland ecosystems. Since it was restricted to open water wetlands, further developments are needed to consider subsurface processes (CETIN *et al.*, 2001).

2.2.2.2 Catchment Modeling and Wetland Implementation

According to KALMA & FEDDES (1993) and BEVEN (2001b) catchment modeling aims to transfer spatio-temporal variable precipitation into a system output considering the 3-dimensional, interlinked geohydrological and plant-physiological processes within a watershed. Hereby, physically-based or conceptual models link lateral and vertical flow dynamics of the water cycle. Lateral water fluxes represent the spatial distribution of soilwater dynamics and therefore are considered as drivers controlling runoff mechanisms (KLEEBERG *et al.*, 1999). While process-driven and physically-based SVAT-models (Soil Vegetation Atmosphere-Transfer) are often utilized for microscale applications (FLÜGEL & SMITH, 1999; KALMA & FEDDES, 1993), simplified storage-process models which cascade water storages are usually applied in meso- and macroscale studies (LEAVESLEY *et al.*, 1983; SCHULZE, 1995).

The importance of distributed, physically-based catchment models for general and hydrological system analysis and in particular process research is constituted, since such models consider the spatial heterogeneity of a landscape and physical laws described by measured parameters (BEVEN, 2001a; FLÜGEL, 1995; BECKER & BRAUN, 1999). Nevertheless, the concept, potential and scale issues are controversially discussed in numerous publications (e.g. BEVEN, 2001a; GRAYSON *et al.*, 1992; REFSGAARD, 1996; REFSGAARD *et al.*, 1996).

A number of catchment models are available to the research community. Common models that were successfully applied for catchment modeling are SHE – Systéme Hydrologique Européen (ABBOTT *et al.*, 1986); J2000 (KRAUSE, 2001); IHDM – Institute of Hydrology Distributed Model (CALVER & WOOD, 1995); PRMS – Precipitation-Runoff-Modeling System (LEAVESLEY *et al.*, 1983); TOPMODEL (BEVEN & KIRKBY, 1979), and ACRU - Agrohydrological Modelling System (SMITHERS & SCHULZE, 1995). Those models differ in their structure, model design and application potential. Example application, highlighting the potential and limitations of these models, have been extensively performed (e.g. BEVEN, 2001a; SINGH, 1995; LEAVESLEY & STANNARD, 1995; MICHL, 1999; BONGARTZ, 2001).

With the exception of ACRU (SMITHERS & SCHULZE, 1995), those models do not take specific algorithms to model wetlands into account. The wetland module implemented in ACRU is based on a lumped approach utilizing the hydrological mass balance equation (SCHULZE, 1995). This approach has been used by HAMMER & KADLEC (1986) and HUFF & YOUNG (1980) as the nucleus of wetland models, and is expressed as

$$dS_w = P_g + I_s + I_{gw} - E - O_s - O_{gw} \quad [2.8]$$

where dS_w is the change in storage [mm],
P_g is the gross rainfall [mm],
I_s is surface inflow [mm],
I_{gw} is the groundwater inflow [mm],
E is the total evaporation [mm],
O_s is the surface outflow [mm],
O_{gw} is the groundwater outflow [mm].

In ACRU, the wetland module simulates a wetland separately as a reservoir located at the outlet of the basin (SCHULZE, 1995), whereas a wetland is routed to the channel using MANNING's equation (SCHULZE, 1995). The model was applied to the Ntabamhlope catchment in South Africa (SMITHERS, 1991). Results indicated that the simulation of the volume of water was correct, but with a lagged daily time distribution. Consequently only monthly totals of daily observed flow were obtained and thereby showed the limitation of the model.

STAUDENRAUSCH (1996) discussed the application of MMS/PRMS to model rainfall-runoff relationships in semi-permanent saturated environments. He applied the concept of distributed HRUs (FLÜGEL, 1995) and concluded that better results could be achieved by implementing the modul '*fixroute*' which originally was developed to be used for reservoirs. Nevertheless, he suggested enhancing PRMS by improving routing techniques. In addition, a more flexible soil zone routine which allows filling and emptying soil water storage within an infinite subsurface reservoir needs to be developed to improve the model performance.

The Soil and Water Assessment Tool (SWAT) model was used for wetland water budget studies by ARNOLD *et al.* (2001). Thereby they applied the model to assess whether the sustained flow from the Walker Creek, Texas could maintain the proposed bottomwood wetland ecosystem. The basic model was modified by allowing ponded water within the wetland to interact with the soil profile and shallow groundwater. The results based on a 14 years time series indicate that the wetland does not dry out as long as the creek continuously provides inflow to the wetland. Moreover, the authors emphasized that the presented model approach can be used to assess hydrological wetland functions under varying climatic condition and long-term impacts of land use and management changes (ARNOLD *et al.*, 2001). ZACHARIAS *et al.* (2004) presented an integrated approach to model land use changes and associated hydrological impacts on a semi-mountainous subcatchment of Trichonis Lake basin in Western Greece using MIKE SHE. As shown on a 40 year time span, significant variations in the hydrologic regime, including a 6% increase in the annual evapotranspiration and a 10% increase in the soil water deficit have been simulated to indicate their substantial impact on wetland hydrology.

The spatial and temporal transformation of basin relevant parameters and processes among different scales is known as regionalization (up- and down-scaling) and is considered to be a fundamental research field in catchment hydrology (BEVEN, 2001b;

BLÖSCHL, 1996; GUPTA *et al.*, 1986; LEIBUNDGUT *et al.*, 1999; KALMA & SIVAPALAN, 1995). Summarizing numerous case studies, it was shown that enormous progress in terms of the scale-dependent identification of hydrological parameters and processes as well as their spatial aggregation and disaggregation was achieved within the last two decades (e.g. BERGSTRÖM & GRAHAM, 1998; BLÖSCHL, 1996; BONGARTZ, 2001, KAVVAS, 1999; MERZ & BLÖSCHL, 2004). As shown by BECKER (1992) regionalization in hydrological modeling requires the consideration of different scales, since environmental processes and parameters are usually associated with respective scales. There are a number of studies considering different scale concepts in hydrology and discussing their potential and limitations (e.g. BECKER, 1992; BOGENA & DIEKKRÜGER, 2002; RATKOVICH, 2000).

Several regionalization approaches were introduced for physiographic parameters in wetland studies. Such can be found for soils e.g. the Hydric Soil List (LEWIS, 1995) or for biological parameters as shown by the Hydrophyte List (TINER, 1991) and wetland vegetation studies in Nebraska (HENSZEY *et al.*, 2004) and South Africa (KOTZE & O'CONNOR, 2000). As shown in Section 2.2 a number of concepts and methods exist to describe wetland systems and its driving forces in a hydrological context. But the literature review also reveals that their regionalization is investigated inadequately (LEWIS, 1995). In summary, this is related to the immense requirements for parameterization on a basin scale as well as the difficulties resulting from the transformation of existing models for mesoscale applications. Nevertheless, some studies adumbrate the potential of regionalization concepts applied to wetland modeling within a basin perspective as shown by studies in the Everglades (FENNEMA *et al.*, 1994).

Since physically-based models are often related to distributed model approaches, the parameterization of the spatial variability of environmental parameters and processes needs to be based on the spatial discretization of the catchment. As a consequence, a variety of discretization concepts have been established in recent studies such as Hydrological Response Units (FLÜGEL, 1995; LEAVESLEY *et al.*, 1983), Grouped Response Units (TAO & KOUWEN, 1989), Hydrotopes (LEIBUNDGUT, 1984) and Representative Elementary Area (WOOD *et al.*, 1988). A detailed discussion of those concepts is given e.g. in BEVEN (2001b), BONGARTZ (2001) and SINGH (1995). KALMA & SIVAPALAN (1995) emphasized that the spatial discretization of environmental properties is strongly linked to the development of Geographical Information Systems. Thus, GIS technology and its potential to store, transform, analyze and visualize digital information are considered to be an integral part of hydrological catchment modeling in future research (BEVEN, 2001a). In addition, the application of GIS in environmental research offers the possibility to integrate information provided by remote sensing and the coupling to Decision Support Systems (FEDRA & JAMIESON, 1996; FRYSINGER *et al.*, 1993).

2.3 Wetland Research in South Africa

Starting with some base studies in the early 60s, wetlands are assumed to be a relatively young research field in South Africa. Nevertheless, wetland research also found consideration in a hydrological context in water resources management studies in South Africa's river systems over the last two decades (DAVIES *et al.*, 1993). A compendium of knowledge and experiences provided by South Africa's wetland research community was published by COWAN's '*Wetlands of South Africa*' in 1995. COWAN (1995) provided a synthesis of individual contribution of accredited scientists and managers in terms of the type and distribution as well as the eco-hydrological functioning, conservation and management of South African wetlands. It was shown that with the exception of some detached wetland studies, wetland research in South Africa is strongly linked to inventory and conservation initiatives. Based on selected publications the following sections give a basic overview on wetland research and management issues in South Africa.

2.3.1 Wetland Inventory and Conservation

A first overview of wetlands in South Africa considering types and distribution as well as research needs concerning wetland function assessment was provided by NOBLE & HEMANS (1978). According to BEGG (1986) legislation that firstly announced wetland conservation in South Africa was introduced by the Physical Planning Act, No. 88 in 1967. For example it was utilized to protect parts of the Lake St. Lucia wetland (BEGG, 1986). The author furthermore concluded that wetlands found considerations in a number of regulations, but numerous factors have prevented this from being effective and applicable aiming at wetland conservation.

As emphasized by BREEN (1985) wetland inventory are a prerequisite to provide a base for wetland conservation. As a consequence, BEGG (1986) published a thorough report describing the extent, role and present status of wetlands in Natal. Although the report considers types, characteristics and functions of wetlands in Natal, the report is descriptive in nature and rarely based on empiric research studies. The report has been completed by three further parts focusing on wetlands in the Mfolozi catchment (BEGG, 1988), the importance and delineation of priority wetlands in Natal (BEGG, 1989) and policy proposals (BEGG, 1990). The status of conservation of Southern African wetlands in the late 80s have been summarized by BREEN & BEGG (1989).

In recent years, South Africa's wetlands have received more attention by researchers and federal authorities, since their hydrological importance in terms of water resources management has been recognized. As highlighted by Cowan (1995), wetlands are among the most threatened aquatic habitats in South Africa, and it is estimated that up to 50% of wetlands may have been lost country-wide in the past. KOTZE *et al.* (1995) found that loss appearing to be greatest in the coastal belt and inland margin zones, but the authors also highlighted that a general lack exists concerning wetland inventory and losses in South Africa. Thus, noticeable efforts have been undertaken to classify, inventory and assess South Africa's wetlands and its losses. It was shown, that the first South African classification system utilized descriptive characterization of soils based on hydromorphic soil properties (KOTZE *et al.*, 1994). Moreover, KOTZE *et al.* (1996) improved the classification system by considering variables which characterize soil moisture dynamics (degree of saturation, frequency, etc.). Nevertheless, KOTZE *et al.* (1996) emphasized that more detailed studies are needed to evaluate the applicability of the introduced classification approach and the potential of quantitative-qualitative soil parameters in order to provide a better understanding of the soil water dynamics in wetlands.

The status of wetland inventories for Southern African countries has been evaluated by TAYLOR *et al.* in 1995. The authors reviewed aims and strategies as well as methods used for inventory purposes and found that more effort is necessary to develop consistent criteria for wetland delineation and to explore existing data sets more effectively.

Since 1998 the conservation and maintenance of wetlands in South Africa have been regulated by laws resulting from of the adoption of the National Water Act 36 (1998). The regulatory was merely designed to identify and delineate South Africa's wetland habitats on the base of descriptive parameters. As a consequence, DUTHIE *et al.* (1999) published a set of documents on Resources Directed Measures (RDM) for protection of water resources with a special section regarding wetland ecosystems. In this context, MARNEWECKE & KOTZE (1999) introduced a guideline for nationwide wetland delineation utilizing criteria for wetland boundary conditions. As emphasized by the LAND-USE AND WETLAND/RIPARIAN WORKING GROUP (1999), the principle applicability of the manual could be demonstrated, but the guideline was assumed to be ineffective in the field. Consequently, a simple, effective and affordable procedure for field-based delineation of wetlands was published by LAND-USE AND WETLAND/RIPARIAN WORKING GROUP (1999). Since both manuals are based on descriptive parameters, they need to be improved regarding their scientific background.

Due to the requirements for the adoption of the National Water Act (1998), DINI *et al.* (1998) published a first draft of a classification system for wetlands in South Africa which was widely based on COWARDIN's system. It was replaced by a revised version in 2000 (DINI & GOWAN (2000).

A tool called WETLAND-USE was introduced by KOTZE *et al.* (2000) to assist agricultural and nature conservation staff, working closely with local resource users and managers, in promoting the wise use of palustrine wetlands. It describes the biophysical features of the wetland, predicting the likely environmental impacts of alternative land-use options and makes ongoing management decisions for particular land-use options. Although WETLAND-USE is designed primarily for use in commercial agriculture, forestry and rural communal areas, it may also be used in areas protected specifically for biodiversity conservation.

Summarizing the initiatives that are associated with wetland inventory, conservation and management in South Africa, it was shown that wetlands are considered to be important features of the landscape. Nevertheless all presented concepts are widely based on descriptive parameters and are theoretical in nature. As expressed by most authors, field-based detail studies are needed to provide a better understanding of wetland processes and to improve existing concepts. Moreover, most of those studies are restricted to wetlands and thus research is required to evaluate wetland functioning from a landscape perspective.

2.3.2 Case Studies in South Africa's Wetland Research

Wetland research in South Africa started with some detached, but noteworthy studies in the 60s of the last century. JACOT GUILLARMOD (1962, 1963) and VAN ZINDEREN BAKKER (1965) gave initial descriptions of bogs and vleis of the high-altitude regions of Southern Africa. Those studies were merely based on vegetation characterization, but effects of land use on wetland species composition have also been considered (JACOT GUILLARMOD, 1968). As a consequence, the authors assumed that wetlands in upper reaches need to be conserved, since they are understood as integral part of the landscape and important in terms of flood attenuation, water purification, water storage, etc. PEGRAM (1983) introduced the modeling aspect in wetlands research in South Africa and formulated the need for better data availability to understand wetland hydrology.

SCHWABE (1989) presented a comprehensive wetland study that was carried out in the eastern highlands of the Drakensberg Mountains. Based on field surveys, remote sensing analysis and a literature review the author discussed the distribution, biotic structure, function, use and importance for rural communities. Furthermore he found out that the total area of high-altitude wetlands has decreased by 2.8 % and vegetation composition has been changed by the replacement and thinning of natural grasses over a 20 years time period. As a result of this development, he concluded that flood attenuation and sediment retention was reduced, while erosion dynamics increased dramatically.

Considerable work on wetland hydrology has been done in the Ntabamhlope catchment. CHAPMAN (1990) focused his work on the investigation and quantification of water loss by evaporation from vegetated wetlands and open water bodies. He utilized a wetland evaporimeter, continuous water stage recorder and energy budget techniques to estimate evaporation rates for the wetland and found that the energy budget methods were assumed to be most appropriate for evaporation quantification. DONKIN (1994) continued the studies on wetland evaporation which were initiated by CHAPMAN (1990) and extended it by modeling of the water budget. As discussed by DONKIN (1994) the diurnal fluctuation methods for determining evaporation in different environments (redbeed, sedge meadow) was proved to be effective and provides realistic total evaporation rates but was limited to water tables below the ground surface. Nevertheless, distinct seasonal trends are found to be evident for redbeed and sedge meadow sites. Based on intensive work by evaluating errors provided by water budget studies, he emphasized that groundwater and associated change in storage seemed to be the most critical component in water budget studies of wetlands. SMITHERS (1991) and SMITHERS & SCHULZE (1993) used the ACRU wetland sub-model to simulate water dynamics of the Ntabamhlope wetland. It was shown that the model provides acceptable simulation of monthly totals of daily observed flow, and thus the model simulated the correct volume of water, but with a lagged daily time distribution. The temporal lag of daily discharges is addressed to groundwater recharge which is not considered in the model as well as possible errors in the observed data (SMITHERS, 1991). Nevertheless, the model seemed to be very useful to evaluate streamflow dynamics. It was also highlighted that more data are necessary for further understanding and better modeling of wetland process dynamics. STAUDENRAUSCH (1996) used the PRMS model in the Ntabamhlope catchment to evaluate the model performance for the southern hemisphere in general. In addition, he studied the model potential to simulate wetlands in a semi-arid environment using the standardized '*fixroute*' routing method and found that the model principally provides good results for wetland modeling purposes, but needs to be enhanced in terms of soil water dynamics.

Although floodplain wetlands are understood as important features of South Africa's river systems, they have been little studied in the past. An initial study by TOOTH *et al.* (2002) has been conducted to investigate the geological influence and erosion dynamics on the formation of alluvial meanders and floodplain wetlands along the Klip River, Eastern Free State. The authors found out that resistant dolerite outcrops directly influence river response in the immediate reach. It also forms local base levels influencing river response in the upstream, dominantly alluvial valleys. In the upstream valleys, the geological base also affects the fluvial dynamics, since lateral erosion of the river bed by migrating meanders is facilitated by the largely horizontally bedded and weakly cemented sandstone (TOOTH *et al.*, 2002).

Little attention has been given to the impact of land use changes on wetland hydrology, even though a few studies evaluated the effect of afforestation on streamflow response in South African basins. Studies at Cathedral Peak, Natal have shown that pine afforestation of former grassland reduced annual streamflow by 440 mm (BOSCH, 1979), while VAN LILL *et al.* (1980) calculated a reduction of annual flows by 300-380 mm, with 200-260 mm occurring during the wet summer season, for a small catchment in Transvaal after the afforestation with *Eucalyptus grandis*. More recently, SCOTT & SMITH (1997) analyzed results from five catchment studies and concluded that the percentage reductions in low (dry season) flow as a result of afforestation were actually greater than the reduction in annual flow. Evaluating the long-term effects of afforestation, SCOTT & LESCH (1997) found that the streamflow completely dried up in the ninth year after planting *Eucalyptus grandis* in a small catchment in the Transvaal. The eucalypts were harvested after 16 years but perennial streamflow did not return for another five years. The authors attribute this lag time as being due to very deep soil moisture deficits by the eucalypts which require many years of rainfall before field capacity conditions can be re-established and recharge of the groundwater aquifer and perennial flows return. GRENFELL *et al.* (2005) carried out an initial study to investigate the impacts of changes in catchment land use from natural grassland to commercial forestry on distribution of vegetation and hydrological regime in a small slope wetland in the KwaZulu-Natal Midlands. Based on the analysis of direct runoff response to rainfall using the SCS-based Design Model (SCHMIDT & SCHULZE, 1987), the authors simulated the impact of afforestation on the wetland hydrology. Without providing a substantial background of their modeling approach, the authors calculated a reduction of stormflow volumes which is available as wetland water input from 16.62 m^2 (grassland) to 2.33 m^3 (grassland and forest). However, GRENFELL *et al.* (2005) concluded that this reduction will alter plant community structure and allow the enrichment of alien and invasive species within the most of the identified plant communities.

Only a few studies were carried out in the former Transkei and Eastern Cape area respectively. ROWNTREE (1993) presents a hydro-geomorphic survey of wetlands in the North-Eastern Cape forest area. The main objective of this study was seen in the classification and distribution of wetlands. Above that an estimation of hydrological impacts by forest activities within the forested areas should be provided. It was shown that 55 wetlands have been mapped from aerial photographs and about 35 % (20.5 km^2) of these wetlands are surrounded by afforested areas. The wetlands were grouped into five classes according their size and have been characterized in terms of land use, alien vegetation, saturation status, drainage, degree of disturbance, etc. Three major wetlands (Gatberg Vlei, KuNtombizininzi Vlei, and Little Pot Vlei) were identified for water budget analysis. As a result an indication was given that the wetlands will be affected by afforestation. Model applications also revealed that the impact depends on the size of the catchment relative to the wetland area. Even though the study is considered as being preliminary, neither the wetland identification and distribution map nor the water balance study was supported by field-based mapping or measurements. In addition, the author provided little explanation about the assumptions the model is based on and its physical background. Thus, the model results of the study need to be considered as incoherent.

The study presented herein is part of a multidisciplinary project which was initiated in 1995 in order to investigate the impact of afforestation on the hydrological system dynamic in the North East Cape Forest areas with specific considerations to the hillslope and regional scale. Although the wetland water dynamics found less consideration within the initial phase, results obtained from intensive hillslope studies (ESPREY, 1997; LORENTZ & ESPREY, 1998) indicated that the hydrology of common wetlands is significantly influenced by hillslope processes and the wetlands are functioning as water storage within the basin. The discussion has also revealed that the wetland inflow from hillslopes either occurs as surface flow or rapid lateral flow benefiting from a macroporous matrix of the soils. Since the assumptions are based on hillslope models, the authors emphasized the investigation of wetland water dynamic from a basin perspective and to transfer knowledge to a regional scale (LORENTZ *et al.*, 2004). Hence, a detailed discussion of the outcome of the hillslope processes studies that was completed by own analyses is given in Chapter 6.

2.4 Landscape-related Research in the Eastern Cape

This study is based on the assumption that the formation and functioning of palustrine wetlands in the Eastern Cape is strongly linked to the landscape and land use dynamic during the Holocene. For this reason, the palaeoclimatological and palaeoecological research as well as historic land use studies which are assumed to be related to the landscape development have been reviewed.

2.4.1 Palaeoclimatological Research

Landscape development in general and wetland genesis in particular are significantly driven by climate dynamics, but only a few studies have been published about palaeoclimatic conditions. TYSON (1986) reviewed the most important of those studies and presented a state-of-the-art report on the climatic change and variability in Southern Africa within a palaeo-climatologic context. Despite the sparsity and varying reliability of data, a spatially-coherent picture seems to be emerging for Southern Africa. In general, little evidence is available for a significant climate change in Southern Africa during the Holocene affecting rainfall variability and intensity, and thereby vegetation distribution remarkably. Nevertheless, a few studies indicate that longer periods of the Holocene seemed to be slightly wetter and cooler than at present. Based on an oxygen isotope temperature curve for the Southern Cape (see Figure 2.1) it was found that there were two identifiable cooling phases during the last 5 000 yrs. (TYSON, 1986).

The first started around 4 700 yrs. BP reaching a minimum temperature at 4 300 yrs. BP. An intermediate warm phase found its maximum at 3 500 yrs. BP. A second cooling phase set in abruptly after 3 000 yrs. BP and showed a temperature minimum at about 2 000 yrs. BP (TYSON, 1986). Likewise, about 2 000 yrs. BP temperatures rose in Southern Africa. The maximum temperature increased until about 1 000 yrs. BP. This period is followed by a phase of decreasing temperatures reaching the minimum experienced during the 'Little Ice Age' (LIA). Even though data records seemed too sparse to correlate African and global data sets to get a confidential analogy, TYSON (1986) hypothesized that the cooling phase (2 000 – 3 000 yrs. BP) rarely coincided with neo-glacial advance throughout the world, while the end of the warming period was related to the Medieval Warm Epoch (MWE).

In contrast, SCOTT & LEE-THORP (2004) summarized numerous palaeo-climatological studies from different places in Southern Africa (see black line in Figure 2.1). By reviewing studies which provided results based on $\delta^{13}C$ & $\delta^{18}O$ analysis and dendrochronological analysis, the authors have shown that temperatures principally tended to be higher than reported by TYSON (1986) over the last 6 000 years and climate records indicate higher fluctuation of temperatures. As shown in Figure 4.5 the comparison of climate data presented by TYSON (1986) and SCOTT & LEE-THORP (2004) indicate that discrepancies are evident between 3 500 yrs. BP and 1 100 yrs. BP. While TYSON (1986) indicated a cooling phase (3 500 - 2 000 yrs. BP) and a following warming phase, SCOTT & LEE-THORP (2004) confirmed the cooling period, but assumed it as being shorter (3 500 - 2 500 yrs. BP). Afterwards, a warming phase is assumed by SCOTT & LEE-THORP (2004) that found its maximum about 2 000 yrs. BP. The following period (2 000 - 1 050 yrs. BP) showed a general tendency to be cooler, but also features temperature fluctuations. This indicates an opposite trend as formulated by TYSON (1986).

A more detailed picture of the last 2 000 years is given by HUFFMANN (1996) and TYSON & LINDESAY (1992). HUFFMANN (1996) reviewed archaeological studies in terms of migration dynamics and early farming activities that have been carried out all over southern Africa in order to reconstruct climate conditions during the last 2 000 years. He compared his results to climatic data summarized by TYSON & LINDESAY (1992) who evaluated a number of dendrochronological studies and radiocarbon dates to reproduce climate variability for this period. According to HUFFMAN (1996), a warm and wet phase that motivated early Iron Age people to scatter over a wide area of Southern Africa is highlighted between 1 700 and 1 350 yrs. BP. A second warming phase in the middle Iron Age has been related to 1 050-650 yrs. BP (Medieval Warm Epoch), since comparable migration activities as a consequence of higher rainfalls were proved. The Little Ice Age began at 650 yrs. BP and was interrupted by a warmer and wetter episode between 450 and 275 yrs. BP. Around 1850 AD, the climate began warming up again and the Little Ice Age came to an end with continuously increasing temperatures and higher rainfalls. Phases of cooling and warming in the Iron Age widely coincided with data presented by SCOTT-& LEE-THORP (2004) and are summarized in Table 2.1. Based on studies of wood anatomy of Protea species along a rainfall gradient of the eastern Drakensberg mountains, FEBRUARY (1994) indicated that there was a marginal decrease in rainfall from 2 300 yrs. BP to the present with a slight counter trend to increased rainfalls between 600 and 200 yrs. BP. Nevertheless, he summarized similar rainfall conditions with some fluctuations in terms of variability and intensity over the last 2 000 years.

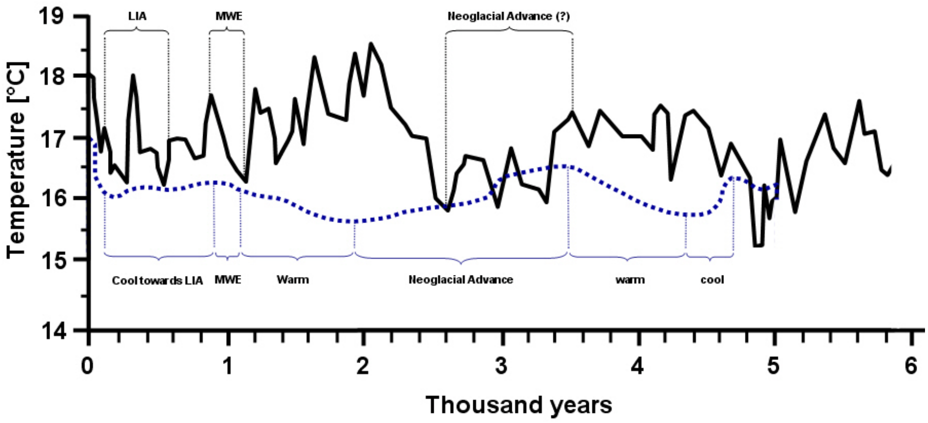


Figure 2.1: Temperature sequence of the Cango Caves stalagmite derived from $\delta^{13}C$ & $\delta^{18}O$ (black curve; mod. after SCOTT & LEE-THORP, 2004) compared to Holocene oxygen isotope temperature for the southern cape from Cango Cave (dotted blue line; mod. after TYSON, 1986).

Table 2.1: Climate history for the past 2 000 years refined by calibrated radiocarbon and dendrochronologial data (mod. after Huffman, 1996; Tyson & Lindesay, 1992).

BP	Conditions
1 850 - 1 750	Cool
1 700 - 1 350	Warm/wet
1 350 - 1 050	Cool
1 050 - 650	Warm/wet
650 - 450	Cool/dry
450 - 275	Warm/wet
275 - 70	Cool
70 - 40	Warm/wet

2.4.2 Palaeoecological Studies

Since wetland formation is mainly influenced by relief position as well as sediment and water input from the surroundings, the Holocene vegetation dynamics on the slopes can be seen as an important component to develop an understanding of wetland formation. Assuming relatively stable climate conditions with little variations in terms of temperature and rainfall, only a reduction in vegetation cover will cause higher erosion rates (i.e. sediment deposition) and water inputs (i.e. positive wetland water budget), and thereby support or even cause wetland formation.

It is being postulated that prehistoric man, particularly early pastoralists and Iron-Age populations, had considerable impacts on the Holocene vegetation (AVERY, 1987, FEBRUARY, 1994; ELLERY & MENTIS, 1992; FEELY, 1987; HALL, 2000; MEADOWS, 2001), soils (MARKER & EVERS, 1976) and fauna (AVERY, 1987) in South Africa. The time and extent of these pre-historic human influences, however, are hard to identify given the incompleteness of the archaeological and palaeo-ecological records. The assumptions of ACOCKS (1988) due to the replacement of indigenous forests by grassland within the Eastern Cape area are controversially discussed by South African ecologists. For example FEELY (1987) hypothesized that no evidence has been presented that farming activities were responsible for more than the diminution of the present extent of forest patches in Transkei, and thereby that grassland is older than 1 500 yrs. BP. But he also concluded that earlier destruction might have been caused by hunters or herders burning down forests to enhance grazing for wild or domestic ungulates earlier than 1 700 yrs. BP. MEADOWS & MEADOWS (1988) found that the cooler and drier late Pleistocene provided the basic conditions for the grassland establishment, but montane forest expanded somewhat in the mid-Holocene from 8 000 yrs. BP as moisture and temperature conditions improved. They also highlighted that the montane forest never dominated the escarpment or the plateaux in the area. ELLERY & MENTIS (1992) summarized a number of archaeological and palaeo-botanical studies and found that the grassland biome as it is presently mapped has been in existence for at least 1 000 years, but probably for much longer.

In contrast, FEBRUARY (1994) analyzed charcoal findings from different shelters and caves along the eastern Drakensberge. He studied the anatomy of recent and archaeological plant samples and compared them to rainfall and temperature regimes. Although no *Protea* and *Podocarpus* forest grow in the immediate vicinity of the sample sites at present, he identified more than 70% of the charcoal as signals of *Protea* species and even *Podocarpus* forest in different depths of the profiles. Thus, he indicates their occurrence for at least 2 000 years. He furthermore concluded that the reason for the absence of other plant species in the modern environment is the veld management practice (annual burning, grazing, etc.) rather than climate variations within the last 2 000 years (FEBRUARY, 1994). Although there is evidence of some environmental shifts during the last 2 000 years (SCOTT & LEE-THORP, 2004), it was shown that climate conditions may have affected vegetation composition, but are not the driving force for recent vegetation patterns.

In addition there are several studies assessing the effects of longterm (ten years up to many decades) burning treatments on species composition of the grassland (EVERSON *et al.*, 1989; EVERSON & TAINTON, 1984; MENTIS & BIGALKE, 1981; SHORT *et al.*, 2003; TROLLOPE, 1974), on shrub regeneration (SMITH & TAINTON, 1985) and canopy recovery in shrublands and woodlands (EVERSON *et al.*, 1985). Those studies give evidence that there is a landscape potential to support higher vegetation like shrubs and trees, which could be verified by own observations (see Figure 4.5). In addition those studies indicate that the significant loss of biodiversity within the high altitude grasslands, shrublands and forests is strongly associated with the type of fire management in terms of frequency (annual, biennial, and quadrennial), intensity (hot or cold) and season as well as grazing management.

2.4.3 Historic Land Use

The literature review has shown that the Transkei and the Lesotho highlands are widely unstudied in terms of historic land use dynamics. Nevertheless, some studies provide information on the behavior of hunter-gatherers and early farmers and their environmental influence. The first indication of early activities in the study area was reported by OPPERMAN (1996) who found out that hunter-gatherers occupied Strathalan caves near Maclear at several times between 29 000 and 26 000 yrs. BP. Archaeological studies at the Sehonghong cave located in south-eastern Lesotho proved its recurrent occupation by hunter-gatherers at ± 6 000, 7 000, 10 000, 11 000, 12 000 – 12 500, 20 000, and 25 000 yrs. BP and in a series of marked pulses within the last 2 000 years (MITCHELL, 1996).

FEELY (1987) reported on farming activities by early pastoralists in the Transkei since 1 700 yrs. BP. As discussed by FEELY (1987) historical information gives evidence that Xhosa speaking farmers settled in areas within woody vegetation formation avoiding grassland, but at later times they were supposed to settle closer, since they utilized the land for grazing. He also found settlement locations occupied by farmers for more than 900 yrs. BP along the middle reaches of the Umzimvubu and the lower reaches of the Mzintlava River. According to FEELY (1987), their extent varied between 1.4 km^2 and 2.9 km^2 in size. Although early farmers primarily practiced live-stock grazing, it is indicated that mixed farming of crops was introduced on the highveld during the 15^{th} or 16^{th} century, since a warm climate pulse created optimal conditions (HUFFMAN, 1996). A further warm pulse at the end of the 18^{th} century contributed to the spread of maize, crops and higher densities of stock and thereby caused increasing populations. Although it is controversially discussed, several studies have shown that the burning of the slopes for grazing and land management has a long tradition in the study area and its impact on vegetation is undisputable (see Section 2.4.2). FEELY (1987) presumed that burning has been utilized for live-stock grazing in the Transkeian areas for more than 1 400 years.

2.4.4 Wetland Formation

As reported by numerous studies the principles of the formation of different wetland types as well as the specific landscape requirements for wetland formation are intensively discussed in the literature (MITSCH & GOSSELINK, 2000; RICHARDSON & VEPRASKAS, 2001; SUCCOW & JOOSTEN, 2001). According to RICHARDSON & VEPRASKAS (2001) the formation of inland wetlands is principally related to the evolution of its surrounding landscape in combination with climate conditions. Therefore, important landscape features controlling wetland genesis are geology, topography, sediment dynamics and vegetation. Usually, two primary processes are necessary for the development of inland wetlands: i) a positive water balance (rainfall excess, subsurface water dynamics or permanent overbank flooding) and ii) either the formation of a hydric soil (availability of sediment depositions) or the accumulation of peat (RICHARDSON & VEPRASKAS, 2001).

While the development of the European and Eurasian mires, bogs and fens (SUCCOW & JOOSTEN, 2001), peatlands and potholes in the US (MITSCH & GOSSELINK, 2000; SIEGEL; 1983) as well as riverine and lacustrine wetland systems (MITSCH &

GOSSELINK, 2000) is intensively studied, little knowledge is available on the formation of palustrine wetlands in South Africa in general, and the Eastern Cape in particular. As reported by LEWIS (1996), there is no evidence that the common wetlands along the Drakensberg escarpment are relics of peri-glacial or even glacial processes. Nevertheless, numerous South African geomorphologists and ecologists assume that the wetlands in this area are older than 10 000 years, and consequently formed during the late Pleistocene (BECKEDAHL, 2004, pers. note). This hypothesis originated from the assumption that wetland soils are very old and because there is no evidence of significant natural or man-induced landscape changes affecting wetland dynamics during the Holocene (BECKEDAHL, 2004, pers. note). Based on vegetation studies, MEADOWS & LINDER (1993) argue that the southern *Afromontane grassland*, and consequently the wetlands are relics from a time, around the last glacial maximum, when the climatic conditions were more suited to the grassland communities. On the other hand, when the pre-historic man reduced or changed vegetation cover during the Holocene, he intensified erosion dynamics in combination with higher lateral water flow, and thereby he certainly supported or even caused wetland formation processes. Further studies, however, are needed to evaluate the effect of vegetation cover dynamics in the surrounds of wetlands and their spatio-temporal impact on the regional water and sediment budgets.

2.5 Conclusions and Research Needs

The literature review has shown that research aiming to understand wetland dynamics and functioning is a relatively young field of research, and thereby subject of ongoing research activities worldwide. Because of their complex nature, wetlands have been usually investigated by research groups of different disciplines with specific research objectives (ecology, hydrology, soil sciences, etc.). The consideration of wetlands within legal regulations in order to provide requirements for wetland conservation and rehabilitation has caused new perspectives and challenges for wetland scientists incorporating socio-economic aspects.

Since the hydrologic conditions affect many biotic and abiotic factors, the hydrology of wetlands is considered as being the most important component for wetland's structure and functioning. Numerous detailed studies have been carried out by means of providing information on hydrological processes and dynamics. Although considerable progress has been made in analyzing and evaluating wetlands hydrologically, the literature review also reveals that certain topical and geographical research deficiencies exist. Thus, research needs have been identified for advanced methods and approaches in wetland research in general (Section 2.5.1) and in particular for regional South Africa wetland studies and landscape-related research (Section 2.5.2).

2.5.1 Research Methods and Approaches

Wetland research aimed at providing advanced approaches and methods for a better understanding and evaluation of wetland systems addresses the following issues

i) Lack of interdisciplinary and holistic wetland research

Although many researchers have highlighted that wetland research is very complex in nature, only a few studies were presented using integrated approaches to characterize, simulate and evaluate wetland dynamics and functioning. Summarizing these studies, it can be concluded that hydrological, biogeochemical and socio-economic investigations are often not satisfactorily convergent. This results in profound uncertainties regarding the impact of environmental changes on wetland hydrological and biogeochemical processes and functions as well as societal values. As a consequence, approaches integrating concepts and methods of various natural and social sciences are needed to provide a better understanding and assessment of wetland functioning within a holistic perspective.

ii) Wetland water budget studies and data problem

The water balance of a given wetland is expressed as the difference between water storage and input (rainfall, surface/subsurface inflow) and output (evapotranspiration, surface/subsurface outflow). Wetland water budget estimates, however, are usually based on the measurement of one or more of the water cycle components. Consequently, the accuracies of water balance estimates are strongly dependent on the quality of the measured or estimated parameters. Data, however, are often spatially and temporally too sparse to characterize and quantify the wetland water balance adequately. Therefore, detailed studies are needed to identify the minimum of hydro-meteorological, vegetation, terrain and soil data which are required to characterize and quantify wetland systems taken its spatial and temporal resolution as well as the measurement technique into account.

iii) Process-oriented, distributed model approaches

Prevalent modeling approaches which are used to simulate wetland dynamics and the lateral connection to their contributing area are usually based on simple 'black box models'. Moreover, regional surface and groundwater hydrological models are not well equipped to represent local phenomena at the interface of groundwater–surface water interactions in wetlands. Little attention is given to the development and application of physically-based models to simulate process dynamics in a fully distributed way taken the wetlands surroundings into account. Hereby the applicability, potential and efficiency of existing models has to be proofed for the identification of dominant hydrological processes controlling wetland and basin hydrology which is of major importance for prognostic modeling, e.g. studying changes of runoff response or water budgets by different management scenarios.

iv) Up- and downscaling in wetland hydrology and regionalization

Wetlands are usually researched as single features of the landscape, and thereby most studies examining groundwater-surface water interactions in wetland landscapes have focused at the individual wetland scale and relatively little consideration has been given to the role of wetlands in the dynamics of complete drainage networks. Although wetland dynamics and processes are assumed to be strongly linked to landscape dynamics, only a few studies investigated wetland functioning within the context of their regional hydrology (streamflow response) and landscape dynamics (management, land use changes). Based on this research it was found, that the combined use of geological and soil data, topography and climate as well as vegetation data provide a reasonable basis for the scale of linkages of the wetland to the surrounding region. Detail studies, however, are needed to improve the understanding of wetland processes at the wetland-upland interface as well as to provide coherent data sets to simulate wetland and basin water budgets in terms of regionalization. Consequently, generalizing site specific studies and scaling up from the upland-wetland boundary to the regional scale is still a major research challenge.

2.5.2 Regional Wetland and Landscape Research in South African

Wetlands in South Africa are recognized as very important areas regarding streamflow regulation, flood reduction water quality amelioration. Because of their natural and socio-economical functions and importance for the water and nutrient cycles as well as an increasing loss of wetland areas, the environmental regulations demand the countrywide protection, conservation and restoration of South African wetland areas.

Little attention has been given to the extent and nature of palustrine wetland systems in the Eastern Cape Province, South Africa. Thus, research needs were identified aiming to provide knowledge on the dynamics and functioning of these wetlands for the regional hydrology, especially, since these wetlands are assumed to be affected by afforestation activities. Specific research needs address the following aspects:

i) Wetland classification, delineation and inventory

The presented approaches and concepts that focus on the classification and delineation of wetlands as well as assessment techniques are usually restricted to those areas where they have been developed. These approaches are hardly transferable to wetlands in South Africa, since climate, landscape evolution and recent hydro-geomorphological conditions are rarely comparable to other parts of the world. Since different types of wetlands have been identified in the area, existing approaches need to be adapted to classify these wetland systems and to develop a method for the delineation and inventory of the wetlands in the upper Umzimvubu catchment.

ii) Wetland system analysis

Presently, regional studies concerning the landscape-related formation and hydro-geomorphological dynamics of wetlands as well as their hydrological importance for the regional hydrology are relatively sparse for the Eastern Cape Province. However, results obtained from intensive hillslope studies in the experimental catchment 'Weatherley' indicated that the hydrology of common palustrine wetlands is significantly influenced by hillslope processes and groundwater dynamics. In addition, it is assumed that the wetlands are functioning as water storage within the basin. A thorough system analysis of these wetlands integrating field work, laboratory analysis and innovative model approaches is needed, to describe the dominant processes controlling wetland hydrology in detail and to quantify water fluxes into, through and from the wetlands.

iii) Assessment of human activities impacts on wetland and basin hydrology

Little research has been done to investigate the impact of human activities on wetland hydrology and its implication for the regional hydrological system. Thus, there is a need to provide knowledge and tools for improved understanding, monitoring and quantification as well as assessment of wetland dynamics, its functioning and prospective change at the catchment scale. This is much more important in areas with substantial landscape changes, e.g. large-scale afforestation in the headwaters of the Umzimvubu. An estimation of their impact on the wetland systems is not presently available.

iv) Holocene landscape dynamics and human impacts on wetland formation

Addressing the research on wetland and landscape formation, it is assumed that the combination of Holocene climate conditions and human influences affected wetland development in the Umzimvubu headwaters. Summarizing the literature, it is being postulated that prehistoric man had much more influence on recent landscapes, especially since little evidence is given for a significant climate change in Southern Africa during the Holocene. It is furthermore indicated that humans had considerable impacts on the Holocene vegetation, soils and erosion dynamics, and thereby supported or even caused wetland formation. Thus, further studies on wetland and landscape evolution are needed to evaluate the effect of vegetation cover dynamics and human activities in the surroundings of wetlands.

Chapter 3

Research Objectives and Methodological Approach

The literature review given in Chapter 2 indicates considerable progress has been made in analyzing and evaluating wetlands hydrologically, but it also reveals that certain methodological, topical and geographical research deficiencies exist in wetland research. Addressing the research deficits identified in Section 2.5, the ***overall objectives*** of this thesis which aim to support integrated wetland research are

- ***the development and application of an integrated research approach to improve the understanding of distribution, functioning and dynamics of palustrine wetlands in the headwaters of the Umzimvubu catchment, South Africa,***
- ***the prognostic modeling and assessment of the impact of land use changes such as afforestation on these wetland systems incorporating a regionalized, landscape-based model approach, and***
- ***the development of a landscape model with regard to the formation of wetlands and human influences on recent landscape dynamics.***

The following scientific and technological aims are proposed to satisfy the overall objectives, and thereby provide the conceptual and methodological background of this study. These specific aims, of course, are interrelated and reflect the interdisciplinary and integrated approach applied. They can be categorized into four main blocks: **Observations and Data Mining (A), Integrated System Analysis (B)**, **Modeling and Assessment (C),** and **Synthesis: The Landscape Model (D)**.

A. Observations and Data Mining: Comprehensive field studies and analysis of existing databases provide empirical observation and information to study multifaceted aspects of the spatio-temporal process characteristics at hillslope, wetland and catchment scale.

A1. Measurement and statistical analysis of hydro-meteorological time series to establish a comprehensive data base for hydrological system analysis (**B1**) at hillslope, wetland and catchment scale; and to provide input parameters for system modeling (**C3**) of the reference basins Weatherley and Mooi.

A2. Detailed soil studies in selected reference wetland and upland areas to provide data on soil-physical properties, soil structure and soil distribution by means of intense field and laboratory work for soil mapping, wetland classification and delineation (**B2, B3**) as well as model parameterization (**C3**).

A3. Geophysical and sedimentological survey to investigate the structure, physical properties and thickness of wetland sediments in selected wetlands complemented by dating and pollen analysis aiming to characterize wetland formation processes (**C5**).

A4. Field-based survey, monitoring and analysis of vegetation to characterize plant composition of wetland and non-wetland vegetation in selected test sites for vegetation mapping (**A5**), wetland classification and delineation (**B3**) as well as to provide significant plant-physiological parameters in wetland, grassland and forested areas for model parameterization (**C1, C2, C3**).

A5. Multi-temporal and multi-scale land use mapping combining satellite-based land use classification, forest stand data and field-based land use maps to provide consistent spatial input parameters for the HRU delineation (**B4**).

B. Integrated System Analysis: Aggregating and integrating the empirical observations lead to an improved generalized understanding of the multi-scale wetland and basin processes. This confluence of information will result in a thorough theoretical framework on hydrological system dynamics, their relationships and regionalization.

B1. Hydrological system analysis integrating time series analysis (**A1**), soil and vegetation analysis (**A2, A3, A4**), land use change analysis (**A5**), relief analysis as well as hillslope studies in order to identify and regionalize dominant processes controlling the hillslope, wetland and catchment (Weatherley, Mooi) hydrology, and thereby to gain information for the HRU delineation (**B4**).

B2. Development of an adapted wetland classification approach to differentiate wetland types according to their landscape positioning, vegetation and soil characteristics (**A1, A2, A3**) as well as hydrological process dynamics (**B1**) taking the variability of wetlands into account.

B3. Delineation and inventory of wetlands in the upper Umzimvubu area based on the wetland classification approach (**B2**) utilizing a GIS-based relief analysis aiming to provide spatial information on wetland distribution for the HRU delineation (**B4**).

B4. Delineation and routing of Hydrological Response Units (HRUs) as distributed, heterogeneously structured model entities representing specific landscape units of similar response in terms of their hydrological process dynamics which are used as spatial input parameters for the hydrological modeling (**C3**).

C. Modeling and Assessment: The empirical studies and the derived theoretical framework will form the basis for the system modeling. The model will be built and evaluated for prognostic investigations and an assessment of water management practices addressing the needs for sustainable development of this highly dynamic landscape.

C1. Analysis and modeling of forest dynamics by means of plant growth modeling utilizing the 3-PG model for pine and eucalyptus stands derived from the HRU delineation (**B4**); and to provide forest-related input parameters for the catchment modeling (**C3**).

C2. Model development and implementation of an advanced algorithm aiming to improve the representation of soil water processes in Precipitation-Runoff-Modeling System (PRMS) with major focus on wetland processes, e.g. dynamics of emptying and filling of soil water storage.

C3. Hydrological modeling of the catchments Weatherley and Mooi by parameterizing, calibrating and validating the PRMS model in order to simulate and analyze runoff response addressing different afforestation scenarios (**C4**).

C4. Evaluation of temporal and spatial impacts of afforestation on the hydrological dynamics of the two catchments (Weatherley, Mooi) in general and changes of runoff dynamics within the different wetland types based on the catchment modeling (**C3**) in particular.

D. Synthesis: Integrating the results of the observations (**A**), system analysis (**B**) and hydrological modeling (**C**), a wetland and landscape model will be developed in order to characterize the wetland formation as well as possible impacts of human activities on past and recent wetland and landscape dynamics.

With respect to the multi-scale nature of these aims, this study needs to be performed by means of a nested catchment approach working at four different scale levels. Dominant runoff generation mechanisms will be studied by event-based monitoring and modeling of soil water dynamics at ***hillslope scale***. Landscape units like wetlands, grassland and forest plantations will be investigated in detail at ***ecosystem scale*** through a thorough system analysis incorporating field-based observation, change analysis and plant growth modeling. Considering the spatial and temporal heterogeneity of their respective scales, the wetland process dynamics and their interrelation with landscape changes will be simulated at ***catchment scale***. Hereby, the fully instrumented, microscale research catchment Weatherley (1.4 km²) will be modeled to bundle knowledge on the dominant hydrological processes controlling the functioning of different wetland types and their response to afforestation in a basin perspective. Processes and parameters derived from the Weatherley case study will be regionalized to quantify the impact of afforestation scenarios on the water budget of the mesoscale Mooi catchment (306 km²). Based on the results provided in the study, an integrated landscape model characterizing wetland formation and human impacts on landscape dynamics will be presented at ***landscape scale***.

Chapter 4

Study Area

In the past, the headwaters of the Umzimvubu catchment have been investigated within large scale studies focusing on geologic-geomorphologic conditions (KARPETA & JOHNSON, 1979; DE DEKKER, 1981; MAUD 1996), climatic pattern (DOLLAR & ROWNTREE, 1995) and vegetation classification (ACOCKS, 1988; LOW & REBELO 1996) of the Eastern Cape Province. Those studies have been complemented by some detailed research activities which have been undertaken in specific parts of the catchment over the last 20 years. The following chapter reviews recent research studies within the basin and provides an overview concerning actual socio-economic developments within the northern East Cape Province. The study area, however, represents the region of the south-eastern Great Escarpment in terms of its physio-geographic conditions, climatic and hydrologic dynamics as well as wetland characteristics.

4.1 Geographic Location

The investigated area comprises the south-western upper reaches of the Umzimvubu basin (20 000 km²), which is located in the SE of South Africa (Figure 4.1). The study area covers an area of about 816 km² and can be separated into the three meso-scale subcatchments Mooi (307 km²), Wildebees (364 km²) and Gatberg (145 km²). It lies approximately between longitudes 27°92‘ and 28°40‘ E and latitudes 31°00‘ and 31°35‘ S, on the southeastern slopes and approaches of the Drakensberg escarpment. The altitude ranges from about 1 200 m asl. at the Mooi weir up to 2 700 m asl. on the catchment boundary at the border to the Kingdom of Lesotho. Major cities are Maclear and Ugie. Within an administrative context, greater parts of the Umzimvubu basin have been managed in earlier days by the administration of the former homeland Transkei, while the farmland around Maclear and Ugie pertained to the Province of Natal at that time. Today the study area belongs to the Eastern Cape Province.

The test catchment Weatherley (Figure 4.2) is located in the eastern part of the Mooi River basin, approximately 6 km south of Maclear. It covers an area of about 1.4 km² stretching from longitude 28°19‘13” to 28°20‘21”E, and latitude 31°05‘42” to 31°06‘53” S. The altitudes vary from 1 257 m asl. at the lower weir up to 1 350 m asl. at the catchment boundary.

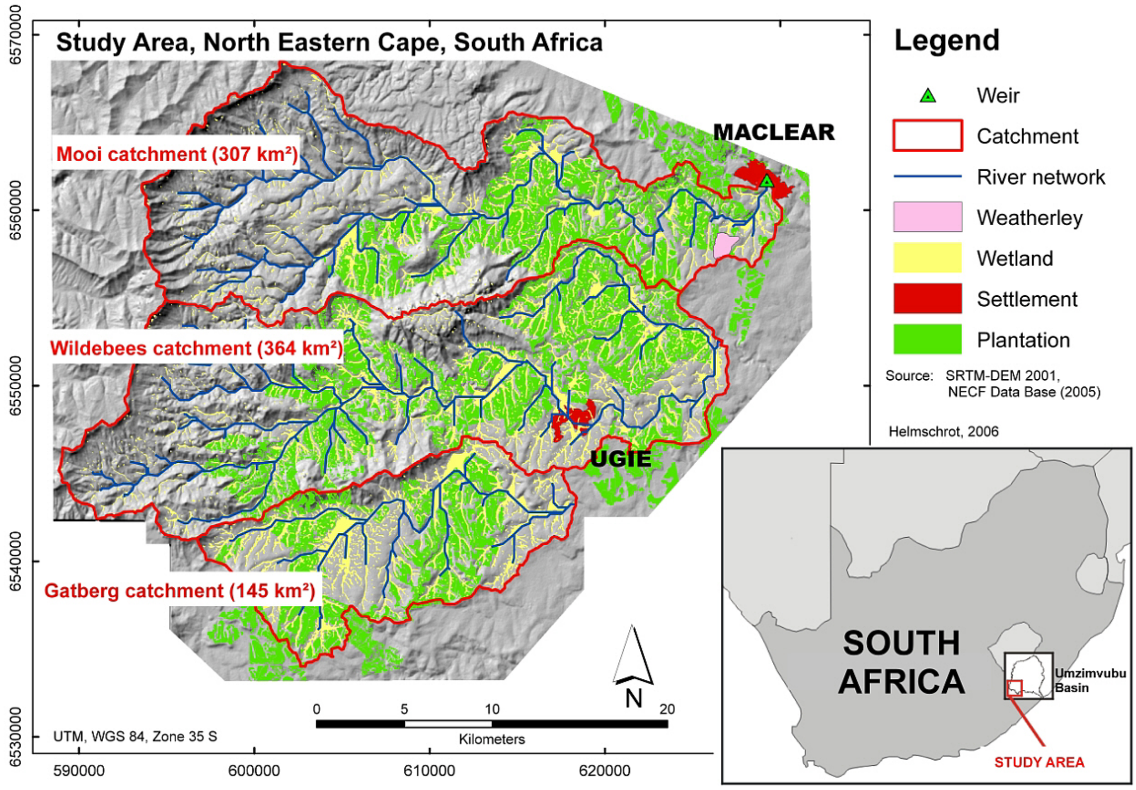


Figure 4.1: Location and characteristics of the study area.

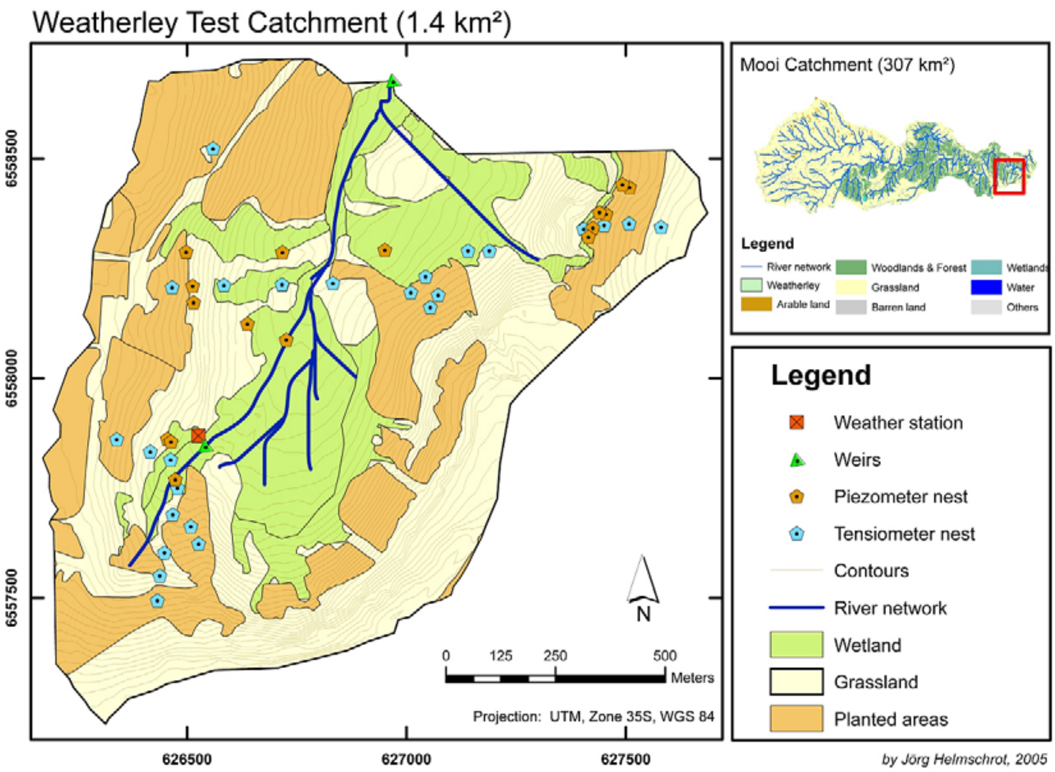


Figure 4.2: Base map of the test catchment Weatherley.

4.2 Geology

According to KARPETA & JOHNSON (1979) and HERBERT (1997) the study area is dominated by Triassic sediments belonging to the Karoo sequence, intruded in places by sills and dykes of Jurassic dolerite (see Figure 4.3). The formations of the Karoo sequence (Molteno, Elliot, Clarens) are mainly characterized by changing layers of sandstone and mudstone, which are in places intruded by siltstone layers and horizons of coal or carbonaceous shales. Basically, there is a gentle dipping of the strata ranging between 1° and 3° towards the west and north-west, i.e. the Drakensberg escarpment. The dipping tends to be higher (up to 7°) in the surrounding of dolerite dykes. In the upper reaches the study area is dominated by basaltic rocks of the Drakensberg Formation.

The geologic base is characterized by sediments of the Molteno Formation, which are predominant in the eastern part of the study area including the test catchment Weatherley. The Molteno Formation varies in thickness from 400 to 500 m and consists of 10-12 upward-fining cycles of alternating quartzitic sandstones and massive mudstone layers (KARPETA & JOHNSON 1979). Each cycle of sandstone to mudstone has an average thickness of 40-50 m. The base of each cycle is sandstone, which is light-grey to yellowish-grey, medium to coarse grained and consists of mudstone pebbles and rounded quartzite, chert and granite clasts. Usually, the sandstone is poorly sorted and characterized by high contents of quartz and minor feldspar (<5%). It is overlayed by cross-bedded and finer-grained sandstone grading into the mudstone layer (ERIKSSON, 1984). In some cases, thin impersistent coal or carbonaceous shale horizons occur at various levels within the Molteno sediments (HERBERT, 1997). The Molteno sandstones have formed conspicuous scarps and plateaus, which are significant features of the landscape. The conformably boundary between the Molteno and Elliot Formations is not very distinct.

The stratigraphy of the Elliot Formation consists of similar, upward-fining cycles of alternating sandstone, siltstone and mudstone, but the cycles are noticeably thicker (60 m). Basically the red to purple sandstone is better sorted and finer-grained and shows higher contents of feldspar and less silicate than the Molteno equivalent (ERIKSSON, 1985).

According to ERIKSSON (1981) the Clarens Formation differs sharply from the underlying Elliot Formation. It consists of layers of pale orange, well-sorted, massive, fine- to very fine-grained feldspathic sandstone or sandy siltstone with minor mudstone intercalations. The layer thickness varies from 25 to 145 m. ERIKSSON (1981) hypothesizes that the structural grading points to deposition of sediments in playa lakes by sheetflow, fluvial and aeolian processes.

Jurassic basaltic rocks of the Drakensberg Group on top of the Clarens Formation have a thickness of up to 700 m. They are characterized by alternating hard, massive, coarsely grained crystalline rock and easier weathering vesicular varieties. Its specific structure gives rise to the stratified appearance of the Drakensberg Mountains.

Intrusions of Jurassic Karoo dolerite appear either as sills or dykes within the Molteno and Elliot Formations showing a NW-SE orientation. Their size varies from decimeters to kilometers, but size and extent tend to decrease towards the north and the escarpment. According to KARPETA & JOHNSON (1979) the Karoo dolerite shows varieties based on their petrographic characteristics, which have been associated with different phases and rates of cooling. Depending on their size, the dykes are either fine-grained dolerite with porphorytic plagioclase or exhibit an ophitic texture. In contact areas the sediments are metamorphosed to either quartzite (sandstone) or Lydianit (mudstone).

Quaternary sediments are restricted to colluvial and alluvial deposits and associated to erosion processes in the valley floors and at the footslopes (HERBERT, 1997; KARPETA & JOHNSON, 1979). Their varying characteristics are specified by their origins and local relief dynamics. Recent studies by HELMSCHROT *et al.* (2005) have shown that the alluvial sediments of the larger valley wetlands are characterized by a fine-grained sandy base, which is overlaid by silty-clay sediments.

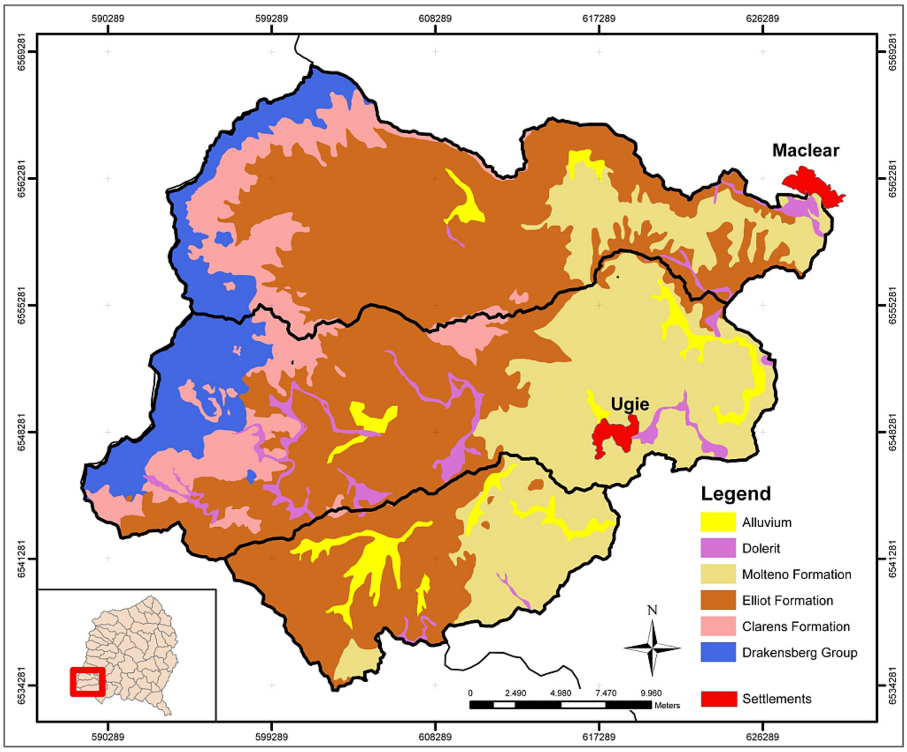


Figure 4.3: Geology of the study area.

4.3 Relief

The relief of the Eastern Cape is predominantly controlled by the regional and local geological basement (MAUD, 1996). The higher parts of the study area are characterized by steep cliffs, which consist of the basaltic rocks of the Drakensberg Formation and the sandstone of the Clarens Formation. The down slope areas tend to be gentler, since they are covered by massive debris rock deposits. Because of the uniform resistance of the basalts, a dendritic drainage system with south-east orientation has been developed (HATTINGH, 1996), which shows results of torrent dynamics in the higher altitudes.

The relief of the lower parts is characterized by a stepped terrain called 'Schichtstufenlandschaft', which is very heterogeneous in terms of its geological base.

Undulating plateaus have been shaped on the quartzitic sandstone. Those were cut through by broad, fluvial-shaped valleys, which in some cases incise sediments of the underlying Tarkastad Formation. The partly steep slopes are characterized by valley-side benches, which have been formed by resistant sandstone layers of Elliot and Molteno Formations respectively. As a result of incision, deep v-shaped valleys were developed, which are presently covered by dense indigenous forests. The down slope areas are characterized by gentle, convex slopes formed by continuous accumulation of debris, which DE DECKER (1981) associates with high erosion dynamics.

While ROWNTREE & DOLLAR (1996) relate the widespread valley asymmetry to the north-northwest dipping, MEIKLEJOHN (1992) and BOULHOEWERS (1988) associate the evolution of steep southern slopes and the flatter northern slope with different intensities of weathering and erosion dynamics. According to BOULHOUWERS (1988) lower insolation causes significantly cooler and moister conditions on southern slopes, which result in diverse and dense vegetation. This leads to drainage conditions dominated by leaching, concentrated interflow and piping. Shallow soils, intense terraceting and soil slips indicate high moisture levels, high clay contents and steep gradients. Consequently, soil creep and shallow soil slipping are the dominant denudational processes. In contrast, the north-facing slopes are significantly drier and relatively warm and show a lower density of grass cover and compacted topsoils. High chemical weathering rates and rapid removal of weathered material by surface flow and creep processes result in gentler north-facing slopes.

In the upper reaches of the Umzimvubu basin, many rivers show evidence of incised meanders, with a meandering course cut into cohesive alluvial deposits of floodplains (ROWNTREE & DOLLAR, 1996). In those areas large wetlands (vleis) have been developed which tend to dry out during dry seasons or periods. Additionally, it is indicated that extent and occurrence of such floodplain wetlands decrease with increasing distance from the escarpment.

4.4 Soils and Soil Hydrology

The pedogenesis is strongly associated with geology, topography and climatic conditions within the study area (HERBERT, 1997). Referring to the South African soil taxonomic system (SOIL CLASSIFICATION WORKING GROUP, 1991), a great variety of different soil forms and families can be differentiated depending on the specific environmental setup within the working area. Although the majority of soil forms show small scale patterns, some basic conclusions can be drawn from soil mapping activities and literature review.

According to HERBERT (1997) the plateau areas of the upper reaches are dominated by shallow *Cambisols* (Glenrosa, Balmoral), which are a result of the quartzitic parent material of the Drakensberg formation. In some cases signs of podzolization have been observed. In contrast, poorly developed, very shallow *Regosols* (Mispah) with very unconstrained textures are predominant on slopes. Those soils characterize initial phases of soil genesis.

Larger parts of the study area are covered by relictic saprolites which vary in thickness and drainage properties. Those saprolites are results of tertiary weathering of the

Mesozoic sediments. The more resistant quartzitic sandstone has formed plateaus on which typically soils with sandy clay loam to sandy loam textures and good drainage characteristics can be found. Depending on the relief situation, clay horizons have developed in the soil profile, which cause moderate to poor drainage in the subsoils. In some cases hydromorphic signs indicate fluctuating groundwater and impounded subsurface water flow respectively. Additionally, aspect effects and associated temperature variations as well as rainfall variability influence the development of soils in those areas. As a result steep southern slopes tend to be cooler and moister than the more gentle north-facing slopes. Nevertheless, higher altitudes receive more precipitation than lower areas and valley bottoms. Consequently, the soil spectra includes hydromorphic *Luvisols* (Cartref, Pinedene), ferric *Podzols* (Bainsvlei, Constantia) and gleyic *Albeluvisols* (Longlands) in higher and moister environments, while *Cambisols* (Hutton, Bloemdal) and shallower soils (Nomanci, Mispah) are predominant in drier areas. Since the finer-grained siltstones and mudstones weather more rapidly, clay loam to silty soils are predominant on underlying slopes. Those soils are usually well-drained, because of the jointing of the underlying rocks. Depending on topography and microclimate the soils show a small-scale pattern of humous *Cambisols* and *Luvisols* (Magwa, Inanda) and lateritic soils (Hutton). The steep midslopes are characterized by shallow soils, while the downslope areas are dominated by sandy and silty, colluvial deposits. In the valley bottoms hydromorphic soils (Katspruit, Westleigh) have developed. Depending on the groundwater dynamics soils with remarkable impermeable clay layers can be found in some areas (HERBERT, 1997).

Jurassic dolerite has formed deep and very productive *Cambisols* (Inanda) with loamy and clay textures and well-drained subsoils (HERBERT, 1997). Their topsoils show a high content of organic carbon (OC). They have a high plant-available water storage capacity. Since dolerite weathers more slowly in drier areas, some soil forms with remained debris and loose boulders have developed (Mispah, Nomanci) consequently.

4.5 Climate

The climate of the study area is classified as temperate-subtropical and is characterized by summer rainfall, with about 75 % of the Mean Annual Precipitation (MAP) falling between November and March. The spatial variability of rainfall is closely associated with macro- and mesoscale topography and its distance to the coast (SMAKHTIN *et al.*, 1997). The area derives its rainfall mainly from oceanic air-streams from east coast highs (TYSON, 1986). At the beginning of the summer, the rainfall is typically orographic in nature. Later in the season, thunderstorm frequency resulting from convectional instabilities increases significantly (SMAKTHIN *et al.,* 1997). Snow only falls during the winter months (May-October), but snow accumulation occurs very rarely and generally has little influence on the regional water balance.

According to WATER RESEARCH COMMISSION (1994) and FORSYTH *et al.* (1997) the MAP of the Northern East Cape Province principally varies from 800 to 1 000 mm/a. In the upstream parts of the basin the MAP increases rapidly with altitude due to orographic effects and reaches annual maxima between 1 000 and 1 500 mm/a. As a result of topographic influences some smaller areas in the middle reaches and some northern parts receive 600 to 700 mm/a, which is less than the annual mean. Figure 4.4 shows the rainfall distribution of the Umzimvubu basin and gives an example of rainfall variability in Maclear over a 100 years period. The MAP of Maclear is about 764 mm/a, but the variability ranges between 350 and 1 150 mm/a. Additionally, Median Monthly Rainfall and Monthly Mean Evaporation are given for specific locations.

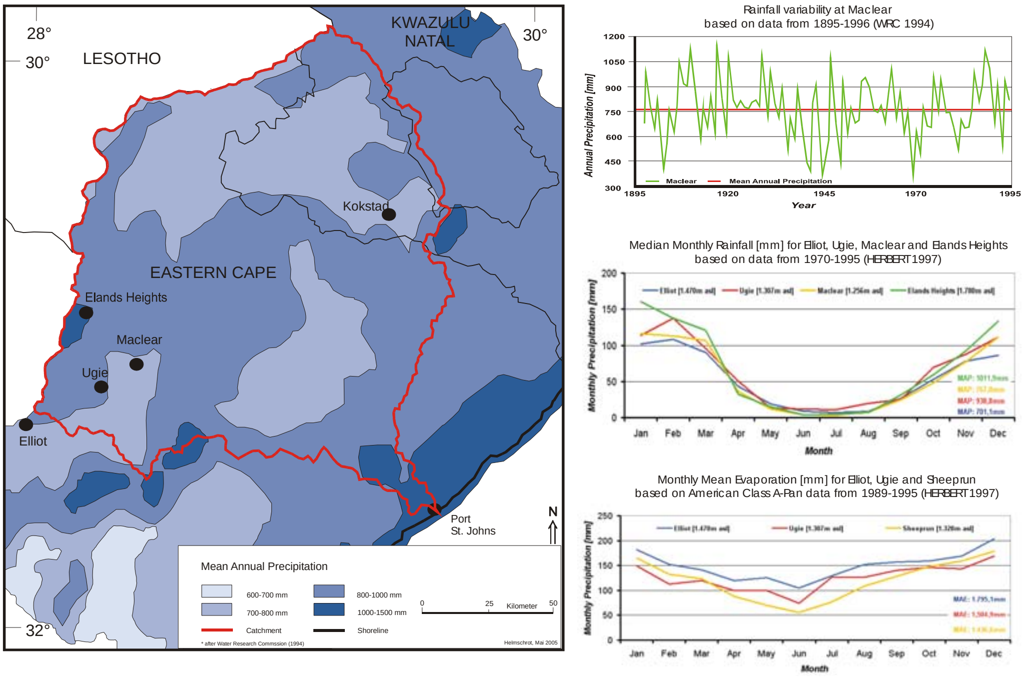


Figure 4.4: Rainfall distribution within the Umzimvubu basin and rainfall variability at Maclear.

As presented by SCHULZE (1997) the Mean Annual Temperature (MAT) of the Eastern Cape Province is 16.1 °C. Since the study area is more influenced by the Drakensberg escarpment, the actual MAT tends to be lower. Hence, HERBERT (1997) analyzed long-term temperature records and calculated a MAT of 15.6 °C for Maclear (1 250 m asl.) and 14.15 °C for Elliot (1 463 m asl.), which is about 60 kms towards the South-West. Because of the differences of means, minima and maxima, HERBERT (1997) found that the temperature regime at Maclear is slightly different to that at Elliot. As a consequence, HERBERT (1997) indicated that temperature distribution varies according to local topography in combination with an average increase in MAT with altitude of 0.42 °C per 100 m and the spatially variable coastal influence. Furthermore it could be shown by HERBERT (1997) that the warmest month is January and lowest temperatures occur between May and July. Frost periods are common during winter months in higher altitudes of the Drakensberg range and have at least an average of 72 days/yr (TYSON, 1986). In colder years frost also appears in lower altitudes depending on local effects like relief conditions, aspect, gradient, etc. According to TYSON (1986) frost periods are mainly initiated by frontal perturbations in the westerlies and are often accompanied by snow falls.

Several studies have been undertaken to estimate loss of water to the atmosphere, either in the form of evaporation from open water bodies or from evapotranspiration from vegetated surface in the Drakensberg area (DONKIN, 1994; EVERSON, 2001; METELERKAMP, 1992; SAVAGE *et al.*, 1997). It could be shown that north-facing slopes experience higher evaporation and evapotranspiration rates due to higher incoming radiation. Based on existing A-Pan data, HERBERT (1997) analyzed Potential Evapotranspiration (PET) rates in relation to elevation. He ascertained that PET increases slightly exponentially with a reduction in elevation. As presented by HERBERT (1997) PET is highest in December and lowest in June, while annual averages range from 1 450 mm/y at 1 800 m asl. and 1 800 mm/yr at 1 300 m asl.

4.6 Vegetation

Vegetation communities and their distribution along the Drakensberg escarpment have been investigated in detail by ACOCKS (1988) and LOW & REBELO (1996). ACOCKS (1988) introduced the so-called Veld type concept. It classifies vegetation units based on similar biotic and abiotic indicators like species richness and composition, water availability, temperature and fauna. As a consequence of the spatial variability of rainfall, relief and soils, the vegetation pattern in the study area is heterogeneously. The upper reaches (> 2 150 m asl.) are characterized by a short, dense grassveld (Themeda-Festucca Alpine Veld), varying from sweet to mixed grass communities, dominated by *Themeda triandra* and different *Festucca* species especially at higher altitudes. Scrub forest, dominated by *Leucosidea sericea*, can be found in sheltered kloofs, while Fynbos species like *Merxmuellera disticha* become dominant on shallow soils and rocky outcrops. The eastern slopes and foothills of the Drakensberg escarpment ranging from 1 350 - 2 150 m asl. have been assigned to the *Highland Sourveld* type (ACOCKS, 1988). Small patches of indigenous forest and scrub forest in v-shaped valleys indicate that the area was originally covered by higher vegetation (ACOCKS, 1988).

Forests are dominated by *Podocarpus latifolius* with *Canthium ciliatum* in the undergrowth and *Leucosidea sericea* at the margin. On the slopes a pure grassveld dominated by *Themeda triandra* and *Tristachya leuctthrix* has been developed, which is reduced to *Eragrostis plana*, *Elionurus muicus* and herbaceous weeds such as *Senecio retrorsus* and *Helichrysum argyrophyllum* in some areas as a consequence of continuous grazing and burning management in the past. Succulent vegetation with *Aloe* and *Crassula* species can be found on shallow, north-facing slopes. According to the classification of ACOCKS (1988), the *Highland Sourveld* type becomes replaced by the *Dohne Sourveld* at lower altitudes (600-1 350 m asl.). Although both types are similar, relics of forests of the *Dohne Sourveld* are larger and better preserved due to warmer and drier conditions. The grassveld is characterized by *Themeda* and *Aristida* species, but it shows more species richness and variations than the *Highland Sourveld* type (ACOCKS, 1988). In remote areas patches of *'Ngongoni Veld* or *Eastern Province Thornveld* are predominant, which can rarely be used for grazing. In some broader floodplains small patches of *Valley Bushveld* are preserved which are characterized by high biodiversity of trees and shrubs (ACOCKS, 1988). In contrast, LOW & REBELO (1996) recognized two predominant grassland types, which are similar to those presented by ACOCKS (1998). The Moist Upland Grassland combines ACOCKS' (1988) *Highland* and *Dohne Sourveld*, while South-eastern Mountain Grassland is synonymous for ACOCKS' (1988) *Themeda-Festucca Alpine Veld*. Studies on the ecology and the management of the grassland biome are published by ELLERY *et al.* (1991), EVERSON *et al.* (1989), EVERSON & TAINTON (1984), MEADOWS & MEADOWS (1988) and SHORT *et al.* (2003).

According to FORSYTH *et al.* (1997) some major rivers are infested with invasive exotic woody species, mostly black and silver wattle (*Acacia meamsii, Acacia dealbata*), grey poplar (*Populus canescens*) and to a lesser extent weeping willow (*Salix babilonica*). The infestation along the rivers has been associated with high loads of plant material in the streams as a consequence of considerable erosion dynamics within abandoned homesteads and surrounding areas during the rainy season.

4.7 Land Use

Presently, the study area is widely characterized by rural land use management. Industries and mining companies are rarely or nonexistent as a consequence of marginal economic potential, insufficient natural resources and an undeveloped infrastructure in the entire region. Settlements and sealed areas are irrelevant in terms of land use, since those areas are characterized by open housing.

The actual land use pattern is caused by two contrary developments in the past. Small scale subsistence farming has developed within the rural areas of the former Transkei. Those areas are often characterized by land degradation of the natural grassveld and by areal soil losses resulting from mismanagement in terms of overgrazing and annual burning over centuries. In addition the significant growth in population, which is mainly caused by people migrating from remote areas of the former Transkei, is a major problem today. An increasing demand for land for housing (urban sprawl) and stock-farming has placed much pressure on the landscape. As shown by ROWNTREE & DOLLAR (1996) those over utilized areas tend to be highly vulnerable to erosion processes. In some areas complete soil degradation is evident. On the other hand a farming economy has been established in regions of former Natal since the beginning of the 20th century. In the past large areas of the region were used as pasture for extensive sheep and cattle farming. Maize and corn (wheat and rye) have been introduced in regions with suitable soils during the 1940s. Recently a crop rotation of maize-corn-grass has been practiced at farms of the western catchment. The majority of the farmers are using their fields for crops during the growing season and stock-farming during the winter months. According to farmer statements this type of land management is a decisive contribution to reduce the process of land degradation by erosion and to preserve the soils.

The potential of forestry development played a secondary role in this region over the last century. This can be traced back to the restrictive economic policy of the former administrative self-government of the Transkei, the underdeveloped infrastructure and the disinterest of investors. Only 1 % of the study area was forested until 1990 (WRC, 1994). In 1989 North East Cape Forests (NECF) as part of Mondi Forests Group began to buy and replant abandoned agricultural lands to initiate economic development based on commercial forestry within the region. Hence, large scale afforestation resulted in significant changes in land use especially in the headwater catchments of the Umzimvubu basin since the establishment of forest industries in 1989. During the last ten years NECF owned 90 000 ha in the area and afforested 31 500 ha of the former range land with various pine species (predominantly *P. patula, P. radiata, P. elliottii*) and eucalyptus. In the future 60 000 ha will be afforested in the NECF area. In addition, the forest potential of agricultural lands within the Matatiele area will be further investigated. As a consequence thereof, another 30 000 ha could be afforested during the next years. Although these activities indicate an enormous socio-economic potential in terms of the job creation, regional development, it is furthermore assumed that those large plantations are influencing a variety of both changes in the hydrological system behavior (runoff reduction, interception losses, etc.) and ecological changes (dry out of wetlands, destruction of natural habitats, etc.). Up to now, a quantitative or qualitative estimate of the environmental effects of these phenomena on the landscape has not been investigated in recent studies (FORSYTH *et al.*, 1997).

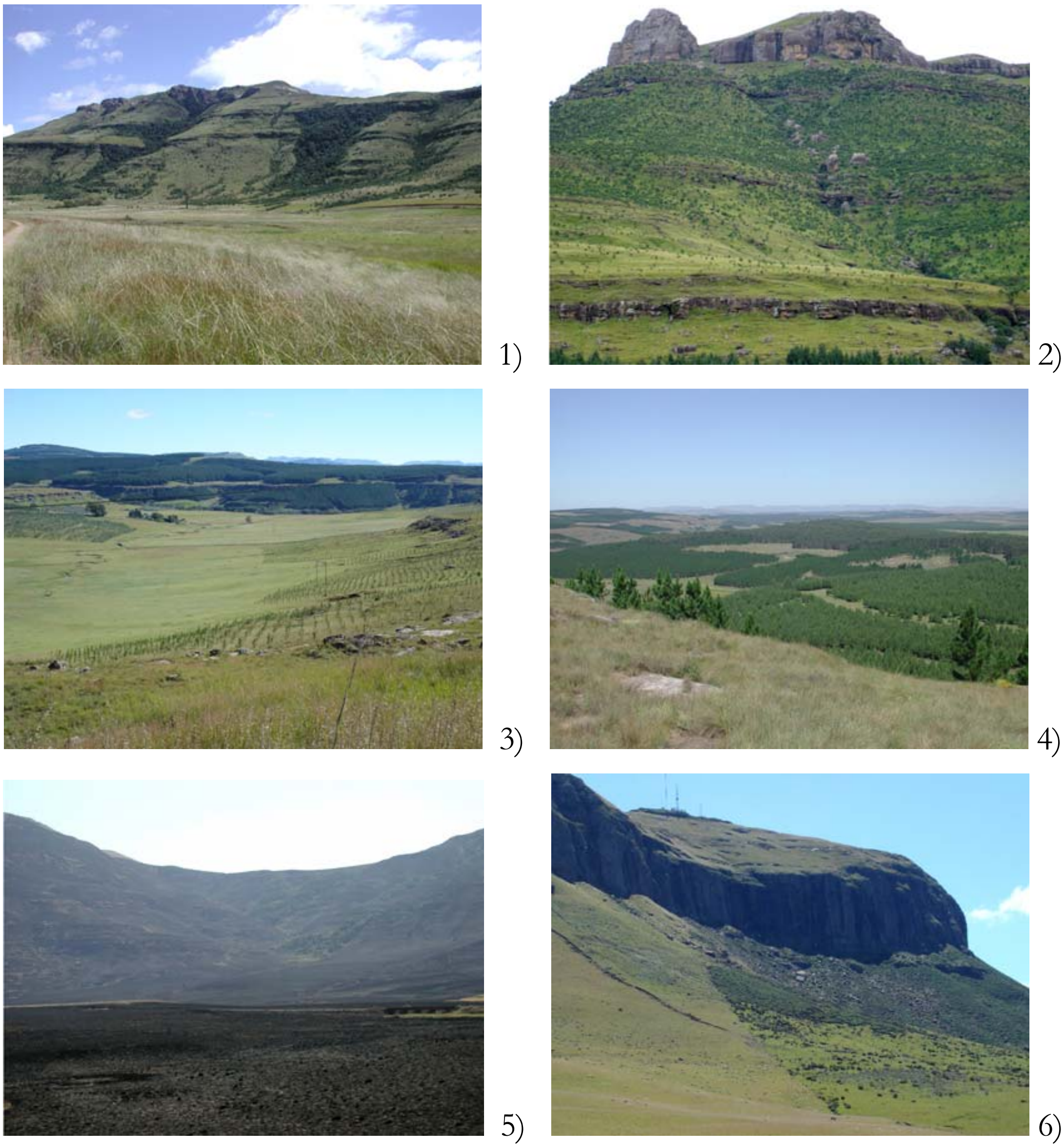


Figure 4.5: Typical landscape features of the study area (Photographs: Helmschrot, 1997-2005).

Photograph 1 shows the southern slope of the Prentjesberg with the typical Highland Sourveld on the open areas and relics of indigenous forests in the steep incised valleys. Photograph 2 shows a north-eastern slope sequence of the Prentjesberg, which tends to support shrub vegetation after two years of non-burning. Photograph 3 shows the research catchment Weatherley 10 months after afforestation. Photograph 4 demonstrates the extent of large scale afforestation, and thereby the transformation of grassland to commercial plantation forests. Photograph 5 shows the effects of burning on slopes and within wetlands, which is done in 2 or 3 years cycles. Photograph 6 shows the impact of burning on vegetation dynamics and cover.

Chapter 5

Data Base

A variety of environmental data such as long-term hydro-meteorological records, digital land use data, vegetation and soil survey data are available from 10 years research within the headwaters of the Umzimvubu basin. Since the project was initiated to model afforestation impacts on hydrological processes and dynamics on several scales (*nested catchment approach*), those data vary in terms of their spatial and temporal resolution. Existing data either were acquired from several agencies, provided by other data bases or measured in the field by continuous monitoring and during several field campaigns. Chapter 5, however, summarizes the data relevant for this study. Data acquisition and data processing are discussed in more detail in LORENTZ *et al.* (2004), ROBERTS *et al.*, (1996), HELMSCHROT & FLÜGEL (2002, 2003), DAHLKE (2002, 2003) and DAHLKE *et al.* (2003, 2005), and in Chapter 6 respectively.

5.1 Hydro-meteorological Data

Hydro-meteorological time series are a prerequisite for environmental model application. In this study climatic records (precipitation, temperature, sun hours, wind speed and direction) of varying spatial and temporal resolution were used as basic input data for both hillslope and catchment modeling purposes, while runoff data were utilized to validate hydrological model outputs. In addition hydro-meteorological data sets were analyzed to provide general information on hydrological system behavior on each scale. Existing time series are summarized in Table 5.1.

The research catchment Weatherley (1.4 km²) has been instrumented systematically since 1995 by the School of Bioresources Engineering and Environmental Hydrology (SBEEH) at University of KwaZulu-Natal (UKZNP) and collaborating partners. Initially, soil moisture status was recorded weekly via neutron probe in 29 stations placed in several transects across the catchment. Twenty one tensiometer nests which are automatically recording soil water tension and 14 groundwater observation wells were installed in 1996. In 1997 the instrumentation has been completed with two full-automated weather stations and two crump weirs measuring runoff at breakpoint intervals. In addition energy balance components like solar radiation, vapor pressure, etc. were measured from 2001 to 2002 by an additional meteorological station installed by the Centre for Scientific Industrial Research (CSIR). The Weatherley data base has been extended by data records obtained from five surface runoff plots. Supplementary water samples were continuously taken at several locations to provide information on water quality. These data were also used for isotope analysis carried out by the Schonland Research Centre (SRC, Johannesburg). Weatherley data can be accessed by the so-called *Weatherley Data Base*, which is developed and distributed by SBEEH at UKZN Pietermaritzburg (LORENTZ *et al.*, 2004).

Long-term climate data from eight weather stations and runoff data from the weir in Maclear are available for the Mooi basin. In addition several hydro-meteorological data sets have been acquired for the Umzimvubu basin. Runoff data on a daily base have been made available by the Computing Centre for Water Research (CCWR) and the Department of Water Affairs (DWAF), while daily rainfall and temperature data were acquired from either CCWR or the South Africa Weather Bureau (SAWB).

Table 5.1: Summary of available hydro-meteorological time series used in this study and selected data characteristics.

Catchment	Data type	NStat	Res	Unit	Time span	Source	State
Weatherley (1.4 km²)	precipitation	3	min	mm	1997-2004	SBEEH	C
	temperature (min, max)	2	h	°C	1997-2004	SBEEH	C
	rel. humidity	2	h	%	1997-2004	SBEEH	O
	sun hours	2	h	Hrs	1997-2004	SBEEH	O
	wind speed/direction	2	h	$m\ s^{-1}$	1997-2004	SBEEH	O
	solar radiation	1	h	$mJ\ s^{-1}$	1997-2004	SBEEH	O,C
	Bowen ratio	1	d	$mm\ d^{-1}$	2001-2002	CSIR	O,C
	water quality/isotopes	1 + div	bp	$^0/_{00}$	2002-2004	SBEEH/SRC	O
	soil moisture	29 + div	2wk	V%	1996-2004	SBEEH	O
	soil water tension	21	12min	mm	1996-2004	SBEEH	O
	perched groundwater	14	12min	m	1996-2004	SBEEH	O
	deep groundwater	5	mnth	m	2004-2005	SBEEH	O
	runoff	2	bp	$l\ s^{-1}$	1997-2004	SBEEH	C
	surface runoff	5	h	$l\ s^{-1}$	2000-2004	SBEEH	O
Mooi (307 km²)	precipitation	8	d	mm	1950-2004	CCWR/SAWB	C
	temperature (min, max)	3	d	°C	1970-2004	CCWR	C
	rel. humidity	1	d	%	1976-1996	CCWR	C
	sun hours	1	d	H	1976-1996	CCWR	C
	runoff	1	d	$m^3\ s^{-1}$	1964-2004	CCWR/DWAF	C
Umzimvubu (19 845 km²)	precipitation	123	d	mm	1970-2004	CCWR/SAWB	C
	temperature, (min, max)	10	d	°C	1970-2004	CCWR	C
	rel. humidity	5	d	%	1976-1996	CCWR	C
	sun hours	5	d	H	1976-1996	CCWR	C
	wind speed/direction	5	d	$m\ s^{-1}$	1976-1996	CCWR	O
	runoff	7	d	$m^3\ s^{-1}$	1949-2004	CCWR/DWAF	C
	soil temperature	3	d	°C	1970-1988	CCWR	O

NStat … Number of Measuring stations; Res ... Resolution; h … hourly; bp … accelerated breakpoint; d … daily; mnth … monthly; wk … week; O … originally; C … corrected; div … divers (several sample sties)

5.2 Soil-physical Data

Soil-physical data are the primary input parameters in physical-based modeling of soil water balance and thereby were measured by extensive soil surveys within the Weatherley and Mooi catchment using standardized field and laboratory methods. The measured parameters are summarized in Table 5.2 for each catchment.

Intensive field work has been done in Weatherley to assess geochemical and soil relevant parameters by sedimentological analyses of soil cores and samples from several cross-valley and wetland transects. Cross-valley transects were made where tensiometer and neutron water tubes were installed (LORENTZ *et al.*, 2004) and thus soil profiles and samples were taken from these open pits. In addition numerous soil drillings using standard augers have been done in selected terrain positions to extend soil information. Those measurements have been completed by extensive soil observations carried out by the ISCW (ROBERTS *et al.*, 1996) as well as by data provided by SBEEH (ESPREY 1997).

Table 5.2: List of soil information available for this study.

	Parameters	NProf	Method	Source	Time
Weatherley (1.4 km²)	soil type	69	SAST (1991), FAO (1998)	ISCW, FSUJ, SBEEH	1996-2004
	grain size	69	Sieve (Atterberg), pipette (Köhn)	SCW, FSUJ, SBEEH	1996-2004
	matrix color	69	Munsell Color System	SCW, FSUJ, SBEEH	1996-2004
	hydr. conduct.(kf)	32	Double ring infiltrometer, tension infiltrometer, Stenzel equip.	ISCW, SBEEH, FSUJ	1996-2004
	field capacity	38	Ceramic plates (Eijkelkamp)	ISCW, FSUJ, SBEEH	1996-2004
	bulk density	28	Core and radiation method	ISCW, SBEEH	1996,1997
	exch. cations	28	LiCl extraction	ISCW	1996
	phosphate	28	Bray 1 method	ISCW	1996
	TOC, N, S	4	Vario EL	FSUJ	2003-2004
	Al, Fe, Na, Mg, K, Ca	4	AAS	FSUJ	2003-2004
	soil moist. tens. (pF)	4	Ceramic plates (Eijkelkamp)	FSUJ	2003-2004
Mooi (307 km²)	soil type	54	SAST, FAO (1998)	ISCW, FSUJ, SBEEH	2001-2004
	grain size	54	Sieve (Atterberg), pipette (Köhn)	ISCW, FSUJ, SBEEH	2001-2004
	matrix color	54	Munsell Color System	ISCW, FSUJ, SBEEH	2001-2004
	hydr. conduct.(kf)	11	Stenzel equipment	FSUJ	2001
	field capacity	11	Ceramic plates (Eijkelkamp)	FSUJ	2001
	TOC, N, S	11	Vario EL	FSUJ	2001
	Al, Fe, Na, Mg, K, Ca	11	AAS	FSUJ	2001
	soil moist. tens. (pF)	11	Ceramic plates (Eijkelkamp)	FSUJ	2001
	dating	2	AMS	AMS Lab Erlangen	2004,2005

NProf … number of profiles; SAST … South African Soil Taxonomy (Soil Classification Working Group, 1991); AMS … Accelerator-mass-Spectrometer; Vario EL … Vario Element Analyzer; AAS … Atom Absorption Spectrometer; ISCW … Institute for Soil, Climate and Water; SBEEH … School of Bioresources Engineering and Environmental Hydrology; FSUJ … Friedrich Schiller University Jena

In addition, seven wetland profiles were selected to represent different types and zones of wetlands in terms of topographic position, hydrological dynamic and vegetation composition. Soil drillings were undertaken for soil profile descriptions along these transects. Finally, almost 70 soil profiles were described in terms of matrix color, soil type, grain size, concretions and hydromorphic indication in Weatherley. Moreover, both disturbed and undisturbed soil samples have been taken at most tensiometer nests as well as in selected hillslope and wetland positions to determine type, grain size, pf-curves, field capacity, exchangeable cations (Ca, Mg, K, Na), pH, TOC, N, S, Al, Fe, hydraulic conductivity, bulk density and others in the laboratory. Analysis methods that were used are either described in ROBERTS *et al.* (1996) and LORENTZ *et al.* (2001) or in Chapter 6 if relevant for system analysis.

Soil moisture has been measured along the seven wetland transects (Figure 4.2) and on a small plateau wetland to provide information about soil moisture distribution in wetlands using a portable TDR (Time Domain Reflectometry) sensor. After calibration, four mea-surements per plot were taken along the transects, while measurements in the wetland were made on a regular grid system with distances of 3 m (core zone) and 6 m (transition zone). As a result, spatial patterns of soil moisture could be related to specific soil properties as discussed in Chapter 6.

The intensive work carried out in Weatherley was complemented by numerous drillings and associated profile descriptions within the Mooi basin. In situ measurements have been made in selected areas to consider different geological situations as well as selected wetlands as described in Chapter 6.

A variety of geophysical data were available for both catchments. A ground penetrating radar (GPR) measurement was carried out to identify soil depth and the topography of the underlying bedrock for one transect in Weatherley (ESPREY, 1997). Refraction seismics have been applied at selected wetland sites to identify sediment thickness, physical properties and sediment structure (see Chapter 6).

Summarizing the soil observations, a comprehensive data base about the dominant soil types in the region, their physical properties and distribution has been developed.

5.3 Plant-physiological Data

Since vegetation plays a significant and dynamic role for the plant and soil water evaporation and interception (regardless if it occurs as natural vegetation or as commercial plantations and agricultural fields respectively), vegetation parameters are critical input parameters for hydrological models. In addition vegetation dynamics are strongly influenced by seasonality and land management.

As a consequence thereof intensive research has been done in several environments to provide information about vegetation characteristics. Vegetation parameters such as species richness, abundance, LAI, density, rooting depth, height, phenological condition, etc. have been provided by *in situ* measurements on regular plots (1x1 m^2) in grassland environment (Weatherley and Mooi) and in different wetland types in Weatherley (DAHLKE *et al.*, 2003).

In addition, plant-physiological parameters for forest plantations have been measured in selected pine stands (heights, DBH, LAI, density, etc.) and were available from a forest data base (stem volume, DBH, basal area stocking rate) maintained by Mondi Forest Ltd. Table 5.3 summarizes the vegetation parameters available for system analysis and for the calibration of the plant growth model as well as the hydrological model.

5.4 Remote Sensing Data

A set of remote sensing data (Table 5.4) have been acquired to provide land use change information and Digital Elevation Models (DEMs) and thereby have been used to delineate basic data for HRU delineation. Landsat TM/ETM data acquired in 1989, 1995,

Table 5.3: List of vegetation parameters measured in the field or provided by remote sensing analysis and from the forest data base.

	Parameter	Vegetation Type	Scale	Resolution	NMeas	Year	Frequency (Season)
Field Measurement	composition	GL	Plot	1x1 m^2	48	1998-2001	1 (Sum) / 1 (Win)
		WL	Plot	1x1 m^2	41	1998-2001	1 (Sum) / 1 (Win)
	height	GL	Plot	1x1 m^2	158	1998-2001	2 (Sum) / 1 (Win)
		PWL	Plot	1x1 m^2	4	1998-2001	2 (Sum) / 1 (Win)
		SWL	Plot	1x1 m^2	65	2001	1 Sum
		WBWL	Plot	1x1 m^2	69	1998-2001	2 (Sum) / 1 (Win)
		Forest	Stand	5 tr/st	19 (E), 83 (P)	1997-2003	3 (Sum) / 2 (Win)
	rooting depth	GL	Plot	1x1 m^2	158	1998-2001	2 (Sum) / 1 (Win)
		PWL	Plot	1x1 m^2	4	1998-2001	2 (Sum) / 1 (Win)
		SWL	Plot	1x1 m^2	65	2001	1 Sum
		WBWL	Plot	1x1 m^2	69	1998-2001	2 (Sum) / 1 (Win)
		Forest	Stand	5 tr/st	19 (E), 83 (P)	1997-2003	3 (Sum) / 2 (Win)
	root density	GL	Plot	1x1 m^2	54	2001	1 (Sum)
		WL	Plot	1x1 m^2	41	2001	1 (Sum)
		Forest	Stand	Tree	21 (P)	1997	1 (Sum)
	LAI	GL	Plot	1x1 m^2	158	1998-2001	2 (Sum) / 1 (Win)
		PWL	Plot	1x1 m^2	4	1998-2001	2 (Sum) / 1 (Win)
		SWL	Plot	1x1 m^2	65	2001	1 Sum
		WBWL	Plot	1x1 m^2	69	1998-2001	2 (Sum) / 1 (Win)
		Forest	Stand	5 tr/st	19 (E), 83 (P)	1997-2003	3 (Sum) / 2 (Win)
	litter	Forest	Stand	1x1 m^2	23 (E), 64 (P)	1997-2003	3 (Sum) / 2 (Win)
	cover density	GL	Plot	1x1 m^2	158	1998-2001	2 (Sum) / 1 (Win)
		PWL	Plot	1x1 m^2	4	1998-2001	2 (Sum) / 1 (Win)
		SWL	Plot	1x1 m^2	65	2001	1 Sum
		WBWL	Plot	1x1 m^2	69	1998-2001	2 (Sum) / 1 (Win)
		Forest	Stand	5 tr/st	19 (E), 83 (P)	1997-2003	3 (Sum) / 2 (Win)
	wet/dry biomass	GL	Plot	1x1 m^2	48	2001	1 (Sum)
		WL	Plot	1x1 m^2	41	2001	1 (Sum)
		Forest	Stand	Tree	21 (P)	1997	1 (Sum)
EO-Data	LAI	GL WL Forest	Basin	W: 5x5 m^2 M: 25x25 m^2	4 (E,P)	1989, 1995 1999, 2001	1 (Sum)
	cover density	GL WL Forest	Basin	W: 5x5 m^2 M: 25x25 m^2	4 (E,P)	1989, 1995 1999, 2001	1 (Sum)
NECF Data Dase	age height LAI cover density DBH stocking management	E. grandis E. nitens P. radiata P. elliottii P. patula	Stand (NECF Property)	m^2	all	since 1996	monthly
	wet/dry biomass	P.patula	Stand	5tr/st	21	1997	1 (Sum)

NMeas … number of measurements; GL … Grassland; WL … wetland; PWL … Plateau Wetland; SWL … Slope Wetland; VBWL … Valley Bottom Wetland; tr … tree; st … stand; Sum … summer; Win … winter; LAI … Leaf Area Index; E … Eucalyptus; P … Pine; Weath … Weatherely catchment; EO … Earth Observation; NECF … North East Cape Forest

1999 and 2001 were primarily analyzed in order to quantify land use change dynamics within the Umzimvubu and the Mooi basin utilizing a Maximum-Likelihood-Classification approach (HELMSCHROT & FLÜGEL, 2002). DEMs were produced by both, photogrammetric analysis of panchromatic SPOT data (HELMSCHROT 1999) and the processing of X-SAR/SRTM data (DAHLKE *et al.,* 2003). The latter have been used to determine wetland distribution based digital terrain analysis (DAHLKE *et al.,* 2005). In addition a selection of aerial photographs taken in 1994 was provided by Mondi Forests Ltd. Satellite images and aerial photographs were of use for visual interpretation as well as field mapping and thereby for validation purposes. All data and products have been georeferenced (UTM, WGS 84, Zone 35S) and implemented into the GIS data base.

Table 5.4: List of available satellite data and selected characteristics.

Platform	Sensor	Acquistion	Resolution [m²]	Processing	Application
Landsat	TM	09 Mar 1989	30x30	Level II	Land use, Mapping, Visual Interpretation
	TM	29 May 1995	25x25	Level II	Land use, Mapping, Visual Interpretation
	TM	09 Apr 1999	25x25	Level II	Land use, Mapping, Visual Interpretation
	ETM	10 Mar 2001	25x25	Level II	Land use, Mapping, Visual Interpretation
SPOT	HRV2	04 Jul 1992	10x10	Level 1A	DEM, relief/basin features
	HRV1	09 Jul 1995	10x10	Level 1A	DEM, relief/basin features
	HRV1	22 Oct 1992	10x10	Level 1A	DEM, relief/basin features
	HRV1	31 Oct 1992	10x10	Level 1A	DEM, relief/basin features
SRTM	X-SAR	Feb 2001	25x25	DTED-2	DEM, relief/basin features, wetland map

5.5 GIS-Data

The HRU concept that was applied for modeling purposes in this study (see Chapter 7) requires a variety of reliable GIS data layers. As listed in Table 5.5 such data were available from previous studies and sources. Multi-scale and multi-temporal land use information have been provided by land use classification from Landsat ETM/TM data and several mapping campaigns (HELMSCHROT & FLÜGEL, 2002). Additionally, data from the forest data base considering specific stand information have been included. High-resoluted Digital Elevation Models (DEM) derived from SRTM data (Mooi, 25 m²) and field-based survey with GPS (Weatherley, 5 m²) have been used to provide catchment-related information (catchment boundaries, river network, etc.) as well as topographic parameters (slope, exposition, etc.) A detailed soil map of Weatherley provided by the Institute for Soil, Climate and Water (Pretoria) was revised, while regional geology was digitized from 1:250 000 geological maps (Department of Mines, 1977). Since data are assumed to be overlaid for the HRU delineation, all data layers were unified in terms of georeference and scale-related raster size.

Table 5.5: List of available GIS data sets that have been utilized for system analysis and the delineation of HRUs on several scales.

GIS data	Scale	Format	Res [m²]	Source	Application	Model parameters
Land use (1989-2001)	Weatherley	RAS	5x5	Mapping, GPS	Land use change analysis, Pre-, post-afforestation, HRU delineation	Vegetation type, rooting depth, sealing, management, rooting depth, interception,
	Mooi	RAS	25x25	Landsat TM/ETM		
	Umzimvubu	RAS	25x25	Landsat TM/ETM		
Forest dynamics (1989-2005)	Weatherley	RAS	10x10	NECF	Afforestation dynamics, HRU delineation, plant growth modeling	Size, age, species, stocking, planting method, pruning, thinning
	Mooi	RAS	25x25	NECF		
	Umzimvubu	RAS	25x25	NECF		
DEM	Weatherley	RAS	5x5	GPS survey	Relief features, HRU delineation	Slope, exposition, altitude, river net, catchment boundary, flow accumulation, flow direction, TWI, SWI,
	Mooi	RAS	25x25	SRTM, SPOT		
	Umzimvubu	RAS	200x200	WRC data base		
Geology	Weatherley	RAS	100x100	Survey, GPS	HRU delineation, hillslope modeling	Transmissivity, groundwater sink, Darcy-coefficient, texture, storage capacity
	Mooi	RAS	500x500	Geological Map		
	Umzimvubu	RAS	1x1	WRC data base		
Soil	Weatherley	RAS	5x5	WRC	HRU delineation, hillslope modeling	Grain size, unsat. hydraulic conductivity, pore volume, field capacity
Instrumentation	Weatherley	VEC	Point	GPS, DWAF, CCWR	Hillslope modeling, interpolation (precipitation)	Hillslope positioning, rainfall distribution
	Umzimvubu	VEC	Point	WRC		
Roads	All	VEC	Line	WRC, TopoMap	Basin characteristics	---

Res … resolution; RAS … raster data; VEC … vector data

5.6 Supplementary Data and Information

Supplementary data such as topographic maps (1:50 000, 1:250 000), geological maps (1:250 000) and numerous detailed maps about vegetation, soils and geology provided by foresters and farmers could be used for field work and interpretation purposes. Habitats were mapped explicitly in non-afforested areas of NECF properties aiming to complete the Environmental Conservation Data Base (ECDB). Those detailed habitat maps were provided by Mondi Forest Ltd. and therefore could be used for validation purposes.

In addition comprehensive system knowledge and information was compiled by continuous interviews of farmers and foresters concerning their management strategies, growth dynamics and water use of crops, pasture and forest plantation as well as socio-economic related issues.

Chapter 6

Methods

To understand and simulate environmental systems an integrated research approach is a prerequisite. This includes evaluating landscape changes and their impact on wetland dynamics. Consequently, field observations, laboratory analysis, hydro-meteorological time series analysis, GIS and remote sensing techniques as well as process-based model approaches have been combined to provide information which can be related to landscape dynamics in general as well as wetland characteristics, distribution and functioning in particular. The aim of Chapter 6 is to describe the methods utilized for the measurement and processing of environmental data.

Section 6.1 summarizes the analytical methods applied to improve the quality of hydro-meteorological time series available from different sources or own measurements. Section 6.2 describes the field-based methods applied to provide empirical observation and information aiming to study multifaceted aspects of the spatio-temporal process characteristics at wetland and catchment scales. These studies were complemented by laboratory analysis in order to provide input data for the parameterization of soil-physical processes and, moreover, to contribute to the development of the landscape model (Section 6.3). Section 6.4 focuses on the GIS-based aggregation and integration of empirical observations to provide spatial data which will be used for system analysis and the delineation of spatial model inputs. A theoretical and methodological background for both the **P**hysiological **P**rocesses in **P**redicting **G**rowth model (3-PG) which was applied to simulate forest growth dynamics and the **P**recipitation-**R**unoff-**M**odeling **S**ystem (PRMS) which was used to model landscape dynamics and their spatio-temporal effects on wetlands is given in Section 6.5.

6.1 Hydro-meteorological Data Analysis

Hydro-meteorological time series of the major water cycle components are essential for water budget studies and system modeling at different scales. Especially in remote areas like the Eastern Cape Province, the availability of spatial data is notably limited by the density of the measurement network. In addition, measured climate variables may be subjected to errors depending on the design and maintenance of the measurement equipment (BEVEN, 2001a; DVWK 1985). For example, FUCHS *et al.* (2001) reported that measurement errors in daily rainfall data can vary between 10 % and 30 %. As a consequence, it was necessary to evaluate and statistically correct hydro-meteorological time series. A variety of hydro-meteorological and runoff data were available at the regional scale. Since these readings were obtained from different sources, statistical analyses have been carried out to harmonize data and to provide long-term records for the Mooi catchment (Section 6.1.1). The following section provides a summary of the hydrometric and hydro-meteorological readings measured in the experimental test catchment Weatherley and efforts undertaken to complete time series (Section 6.1.2). The corrected data sets have been analyzed to provide selected measures characterizing spatio-temporal patterns of the specific parameters at different scales.

6.1.1 Regional Data

Regional daily rainfall (Section 6.1.1.1), runoff data (Section 6.1.1.2) and supplementary climatological data (6.1.1.3) have been acquired and statistically analyzed in order to use it for system analysis and model applications of the Mooi catchment.

6.1.1.1 Regional Rainfall Observation and Data Analysis

Precipitation is the major driving input variable for hydrological model systems but also a parameter showing a high spatial and temporal variability. Hence, data availability, data quality and resolution as well as their analysis aiming to provide information on the temporal and spatial rainfall pattern are of crucial importance for distributed, physically-based model approaches (BEVEN, 2001a).

To evaluate regional spatio-temporal rainfall patterns, long-term rainfall records were available from 121 weather stations, but less information was given regarding their consistency and quality. Although the stations are distributed over the entire Umzimvubu basin, the station density significantly decreases in remote areas towards the escarpment. In South Africa, rainfall data are usually available from different sources and providers, which in turn indicated an inhomogeneous data quality expressed by missing values over long periods or obviously wrong data. Additionally, little information has been given regarding the measurement method. Consequently, the rainfall data needed to be pre-processed using standard statistical methods.

At the beginning, all station data have been extracted from ASCII-files and have been re-written to an Excel-spreadsheet as records in mm values. To identify obvious inconsistencies, all time series were plotted as simple rainfall graphs and visually screened for plausibility tests. Comparing data records, it was shown that some stations provided accumulated rainfall amounts expressed as sums of several days, whilst others were given as daily totals. In addition, monthly and annual sums have been analyzed to exclude stations with inconsistent and erroneous data. The following criteria have been defined for the station and data exclusion.

- Daily values higher than 120 mm[a] have been considered as accumulated values of a two days minimum. These values have been compared and adjusted with data of neighboring stations.
- Daily values of more than 300 mm[1] have been considered as erroneous.

[1] These values have been defined with respect to other rainfall studies (SCHULZE, 1997; WRC, 1994). The amount of 120 mm is an estimate of a potential 2 days maximum. The amount of 300 mm gives an estimate of the highest measured sum of maximal 5 successive days in South Africa.

- Records with erroneous or missing daily values have been excluded for the calculation of monthly sums, i.e. no monthly sum has been provided for these cases.
- Years missing more than 4 monthly sums have been excluded from further processing.
- Stations with gaps over 5 years were excluded.

As a result, 55 stations have been excluded from the further processing due to considerable gaps or erroneous values in the time series. The data of the remaining 66 stations have been statistically analyzed using tests for homogeneity and inconsistency. In a second step, series with missing values have been filled using regression analysis which was usually performed between nearby stations. In cases where the nearest station showed a significant variation regarding the altitude or distance to the coast and escarpment respectively, more remote stations have been considered for regression analysis. An example for regression analysis based on double mass curves is given in Figure 6.1. In this example, sums of the areal means were plotted against rainfall data from the station Ngqeleni. Obvious inconsistencies caused by measurement errors are evident, so that rainfall data have been fitted using the remaining regression equation.

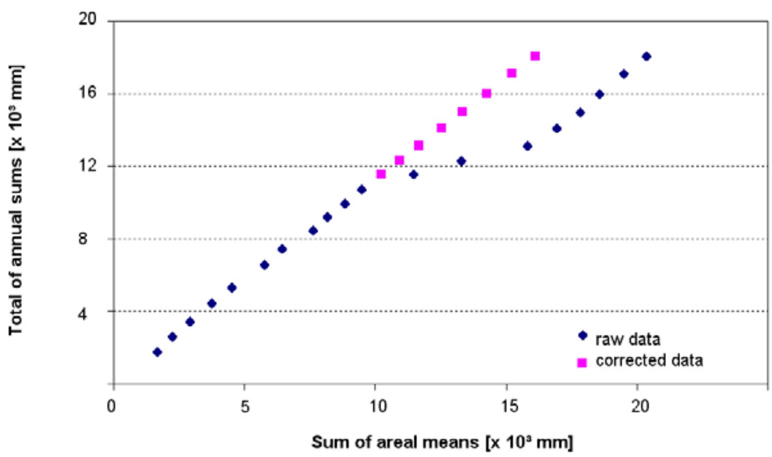


Figure 6.1: Test on homogeneity and data correction using regression analysis based on double mass curve (Station Nqgeleni).

Since the 66 stations provided a consistent data set for the period between 1970 and 1988, standard annual statistics like mean, minimum and maximum, standard deviation, median and skewness have been calculated for this period on an annual and monthly base. Moreover, seasonal dynamics, long-term oscillations as well as driest and wettest years have been identified based on the analysis of selected station data. Finally, the data have been compared to existing data sets for South Africa (SCHULZE, 1997; WRC, 1994).

6.1.1.2 Runoff Data Processing and Analysis

The availability and quality of runoff data is of a crucial importance for hydrological modeling purposes, since it is necessary for the model calibration process (BEVEN, 2001a). Runoff data are often based on water-level measurements that have been converted to water flow expressed as volume per time unit. Because of the wide range of errors in discharge records (BEVEN, 2001a), runoff data need to be evaluated regarding plausibility and faultiness. In South Africa, runoff time series are often incompletely. This is often a result of alterations to stream courses or the temporary loss of gauging stations mainly caused by extreme floods and by insufficient maintenance of the weirs and measurement equipment (SMAKTHIN *et al.,* 1997).

For this study, daily runoff data were available for the Mooi catchment from the weir in Maclear (see Figure 4.1) for the period from 1970 to 2005. The runoff data have been extracted from ASCII-files and were transformed to an Excel-spreadsheet as daily volumes in cubic meters per second. First, the discharge volumes were analyzed statistically to explore inconsistencies and homogeneity. From this effort, missing values could be identified for individual days and several weeks. These gaps were filled using regression analysis with a second data set provided from a downstream weir (Tsitsa Bridge), since a high correlation between both data sets has been determined.

From this effort, runoff data were used to generate runoff hydrographs and to compute measures such as annual and monthly averages, specific basin discharge, discharge coefficient, runoff coefficients and runoff regime characterizing spatial and temporal runoff dynamics of the Mooi River based on a long-term data record. In addition, these data built the base for the analysis of specific events with respect to runoff generation processes.

6.1.1.3 Supplementary Hydro-meteorological Data Processing

A variety of additional hydro-meteorological data could be used to improve system analysis and for modeling purposes. Minimum and maximum temperature data from 8 stations and sun hours, humidity and wind data (speed, direction) from five stations have been extracted from ASCII-files. The extracted times series were re-written to Excel-spreadsheets as daily means. All time series were reviewed to identify missing values, and gaps were filled using regression analysis between neighboring stations similar to the efforts undertaken for the rainfall correction.

Analyzing these data, a variety of statistical measures such as monthly and annual averages were calculated for each parameter aiming to identify seasonal dynamics and long-term trends.

6.1.2 Hydrometric Survey in Weatherley and Data Analysis

Beginning in 1996 the experimental test catchment Weatherley has been systematically instrumented with a variety of observation equipment to provide information on the hydrological dynamics prior to and following afforestation. A detailed description of the instrumentation layout, the functioning of the equipment and data provided is given by ESPREY (1997) and LORENTZ *et al.* (2004). Figure 6.2 shows the upper climate station next to the upper weir and a tensiometer nest installed in Weatherley.

The change in soil water content within a soil profile is an essential value for the characterization of soil water dynamics. In particular in small catchments, its accurate accounting and analysis has a dominant influence on runoff generation assessment. The soil water content can be determined using either direct methods which are destructive, or indirect methods like the neutron moisture meter (BEVEN, 2001a). In this study, soil moisture status was measured weekly via neutron access tubes installed in 29 stations set out in two major transects across the catchment. To consider the soil variability, the stations were established on sites where different soil types have been identified. As discussed by ESPREY (1997), the readings were converted to soil water content using calibration equation developed from field data.

Soil water content can be used for a direct indication of soil water fluxes which can be calculated when the soil water matric pressure of a soil is known (ESPREY, 1997). Thus, automated tensiometers were installed at 21 locations in 1996 to complement soil status observations. A tensiometer is an airtight, hollow tube filled with water. A porous ceramic cup is attached to the end of the tube inserted into the soil and a vacuum gauge is attached to the upper end. The tensiometer measures soil moisture tension, an index of how tightly water is held in the soil. At each location tensiometer nests comprising between 2 and 4 tensiometers have been installed at different depths in the profile recording the matric potential of the soils at a 12 minute interval. As a result, soil moisture retention curves were developed for each soil horizon to determine soil water content. A detailed description of the manufacturing and installation is given by LORENTZ *et al.* (2001).

Figure 6.2: The upper weir and the full-automated weather station in the experimental test catchment Weatherley (Photograph: HELMSCHROT, 2001).

Additionally, perched and deep groundwater have been monitored in the catchment. Based on a Ground Penetrating Radar survey it was recognized that the bedrock topography is irregular and undulating and, as such, is conducive to the development of perched and discontinuous groundwater tables (ESPREY, 1997). Thus, 14 piezometer tubes have been installed to identify the direction and magnitude of saturated subsurface fluxes down the slope. Monitoring data could be used for yield predictions of the movement of perched water tables and interflow (ESPREY, 1997). In addition, six boreholes installed in 2004 allow monitoring of the water table in the fractured sandstone and mudstone rock on the hillslopes and in the wetland.

These observations were supplemented by 2D Resistivity surveys which have been conducted in transects across the catchment to determine the distribution of hillslope water in the subsurface (LORENTZ *et al.*, 2004). In addition, samples have been taken by an ISCO sampler during a number of rainfall events and in the surface, soil and ground waters at different times. These samples were analyzed in terms of natural isotopes of oxygen and hydrogen in order to define the sources and pathways of contributions to streamflow (LORENTZ & VERHAGEN, 2004, not publ.). Five surface runoff plots of 8 m x 22 m were established on several terrain positions providing hourly runoff totals. The design of the plots is described in ESPREY (1997).

One raingauge measuring weekly rainfall data and two fully-automated meteorological weather stations recording precipitation, temperature, wind speed and direction, and radiation were installed in Weatherley in 1996. All hydro-meteorological time series used for model purposes have been reviewed and statistically corrected in order to improve data quality. Continuous rainfall readings were first converted to daily averages in millimeter. Homogeneity and consistency tests were applied to correct and fill rainfall records using identified regressions between the stations within the Weatherley catchment and neighboring stations based on double mass curves. Corrected data sets have been used to compute basin averages characterizing spatial and temporal rainfall pattern.

Daily minimum and maximum temperature data have been compared to temperature measurements in Maclear and surrounding climate stations such as the forest estate offices. Missing values were replaced by using regression analysis. Figure 6.3 shows temperature values of the weather station in Weatherley compared to measurements observed 6 km away at the forest estate office in Glen Cullen. Based on statistical analysis of these data, measures characterizing monthly, seasonal, and annual temperature dynamics have been calculated.

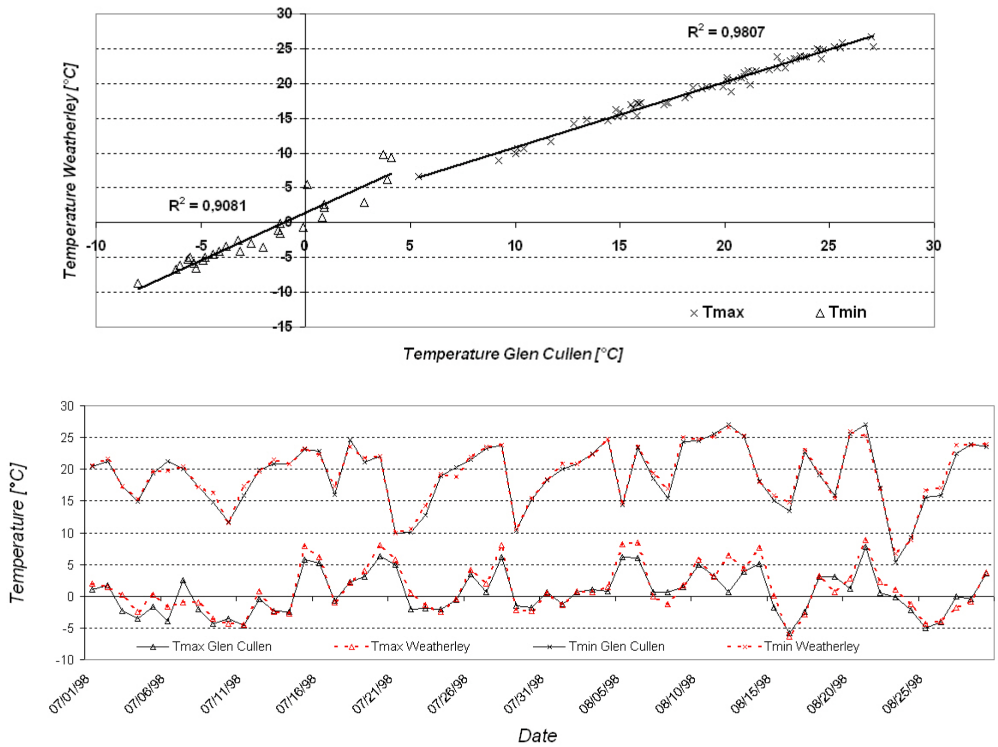


Figure 6.3: Regression analysis for temperature values (min, max) measured in Glen Cullen and Weatherley for the period of July and August in 1998.

Since only a 10 month record of solar radiation was available for the Weatherley catchment, two approaches have been evaluated to complete data records (LORENTZ, 2005, pers. comm.). Initially, a simplified model introduced by BRISTOW & CAMPBELL (1984) has been applied. This model uses the relationship between atmospheric transmittance and daily range of air temperature to account for solar radiation. Model results have been fitted using the measured Bowen ratio data (r=0.84). Furthermore, a model developed by LIU & SCOTT (2001) that included temperatures (minimum and maximum) and rain-day information was explored. This approach showed a significantly higher variability of daily solar radiation. Comparing the results of both models applied to solar radiation records from the Umtata weather station, the approach of BRISTOW & CAMPBELL (1984) seemed to provide more accurate solar radiation. Thus, data calculated after BRISTOW & CAMPBELL (1984) have been used for further analysis in order to provide information on radiation intensities and its temporal dynamic.

Wind data have been evaluated and filled using data from a weather station in Umtata. Also, two fog interceptors were installed close to the downstream weir and on the hillslope crest. These data have been measured as weekly totals.

Two crump weirs provide basin runoff by measuring depths of flow at breakpoint intervals since 1997. First, discharge volumes of both weirs were converted to daily volumes in liter per second. In a second step, missing or overpredicted runoff data have been corrected by regression analysis between the upper and lower weir (r=0.97). In cases of missing records for the upper weir, data of the lower weir have been corrected by correlating and subsequently filling of the data with data obtained from the Mooi weir in Maclear (r=0.94). As a result, consistent runoff data ranging from 1997 until 2004 have been provided for the lower weir. Based on these records, a hydrograph representing the time series and hydrological measures such as monthly and annual discharge, runoff coefficient and specific discharge were computed to describe runoff dynamics. Individual high rainfall events have been studied to identify runoff generation mechanisms by relating runoff to rainfall intensities and soil moisture and groundwater measurements.

6.2 Field Work

Intensive field work has been done during several campaigns between 1996 and 2004. The aim of the field work was to provide the information necessary to develop a thorough system understanding and model input parameters. Therefore, ***soils and sediments*** and ***vegetation*** parameters have been measured at ecosystem, hillslope and catchment scales, but also with respect to a landscape perspective. The investigations were mainly focused on the experimental Weatherley catchment, but work has also been done in selected sites within the Mooi, Gatberg and Wildebees watersheds.

As described in Section 6.2.1, previous soil studies have been completed by additional soil analyses. Section 6.2.2 refers to the geophysical and sedimentological methods which have been applied to provide information for landscape analysis incorporating wetland formation and functioning as well as soil-related model parameters. Since the vegetation is controlling interception and evapotranspiration, grassland and wetland vegetation and commercial forest plantations has been investigated by measuring and analyzing plant-biophysical parameters (Section 6.2.3).

6.2.1 Soil Survey

The available soil data base for the Weatherley catchment (ROBERTS *et al.*, 1996; ESPREY, 1997) has been completed by own soil survey during several field campaigns between 1996 and 2004. Since soil survey provide *i) information on soil distribution, ii) empirical model parameters*, and *iii) information on wetland soil structure and formation*, the profiles of numerous excavated soil pits and soil cores were described from Weatherley and different wetland locations. Furthermore, samples have been taken for laboratory analyses from sites representing typical soil types in the study area.

In Weatherley, 8 open pits and 12 soil drillings along an additional cross-profile and along the refraction seismic transects (see Figure 6.4) have been described in detail. Depending on the depth of the excavated soil pit or the auger used, the depths of the profiles varied between 0.45 m and 2.40m. For soil drilling and sample collection, an extendable soil core sampler with a beveled core tip was used to ensure minimal disturbance. Using the FAO Guidelines for soil description (FAO, 1998), the soil profiles were described according to different horizons, color, root abundance and diameter, stone content, parent material, and moisture (if perceptible). Soil color was determined using the revised MUNSELL Standard Soil Color Chart, while root properties, stone content and moisture were roughly estimated based on AG BODEN (1994). Parent material was taken from the geological survey (ESPREY, 1997). Soil texturewas determined by finger probe with respect to AG BODEN (1994). Summarizing the soil characteristics, the soil type was determined according to FAO (1998), AG BODEN (1994) and SOIL CLASSIFICATION WORKING GROUP (1991) for comparison purposes. To provide a relative idndication of soil wetness at different sites, *in situ* moisture content of the soil was determined addressing three classes: *i) dry* (soil was friable, crumbled easy between fingers), *ii) moist* (soil was pliable, no signs of discharge water), and *iii) saturated* (when squeezed in hand, a soil/water slurry passed through one's fingers). In addition, soil samples were collected for laboratory analysis according to diagnostic horizons.

Addressing the objectives of this dissertation, wetland soils have been more intensively studied in six wetlands. The studies were focused on a smaller slope wetland in Weatherley as well as the larger valley bottom wetlands Gatberg Vlei and Ku'Ntombininzinzi Vlei (Figure 6.4). Existing wetland soil profiles from the Weatherley catchment (ROBERTS *et al.*, 1996; ESPREY, 1997) have been verified by 18 soil drillings during field campaigns in 2000, 2003, and 2004. There, drilled soil profiles have been described by the same procedure as presented above. In addition, soil profiles of 38 excavation pits and soil drillings have been described in detail in the Gatberg Vlei and Ku'Ntombininzinzi Vlei. Moreover, undisturbed and disturbed soil samples have been taken at 10 cm intervals from 11 profiles and were analyzed in the laboratory regarding soil physical and chemical properties (Section 6.3.1).

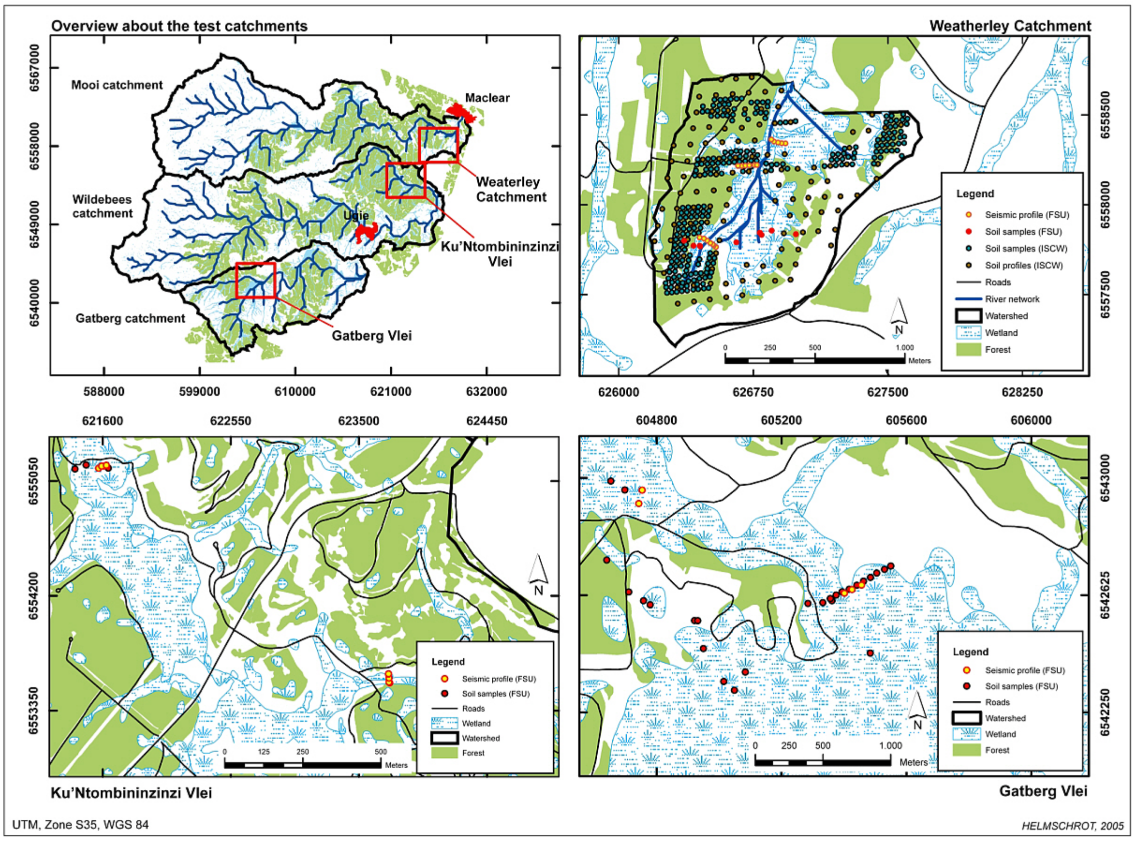


Figure 6.4: Location of the test sites which were selected for detailed soil studies.

6.2.2 Refraction Seismic Measurements

Refraction seismic surveys can be effectively utilized to provide information on depth of bedrock, depth of water tables, thickness and subsurface structures of unconsolidated sediments and underlying bedrock surface as well as type of sediments or bedrock (BURGER, 1992; PULLAN & HUNTER, 1999). Thus, refraction seismic measurements were applied along representative cross and longitudinal profiles in selected wetlands in Weatherley, Ku'Ntombininzinzi Vlei and Gatberg Vlei (Figure 6.4). In addition, measurements have been used to verify and regionalize soil information obtained from point measurements in the field (Section 5.3.1; Section 6.2).

6.2.2.1 Principles of Refraction Seismics

The principle of refraction seismics is based on the analysis of measured traveltimes of direct and refracted seismic waves in subsurface materials. Traveltime is a function of propagation velocity and can be used to determine depth to a refractor such as bedrock. Since the propagation velocity of seismic waves is strongly influenced by specific material properties, mainly by their density, a change of velocities indicates differing subsurface layers or discontinuities (BURGER, 1992). Refracted waves can only be detected at the surface for situations in which lower velocity material (sediment) overlies high velocity material (bedrock). The velocity of wave propagation of refracted signals changes along the path, traveling at relatively slow speeds in the sediment, at higher speeds along the bedrock interface, and slow speeds again as they return to the surface. In seismic refraction surveys two kinds of waves are generated by seismic energy source. For refraction seismic analysis, P-waves (compressional or longitudinal waves) and S-waves (transversal or shear waves) can be analyzed, but usually characteristics of compressional waves are used for refraction seismic surveys. This is because of their higher velocity in solid materials (BURGER, 1992).

Physically, energy from the seismic source (sledge hammer) is radiated downwards with a constant velocity v_1 assuming relatively homogenous overburden. At subsurface interfaces wave velocity changes due to refraction of the wave (v_1 to v_2), whereas the refraction angle i_2 is greater than the incident angle i_1. When velocity v_2 is greater than v_1 there is a critical angle of incidence i_c, where the angle of refraction is $i_2 = 90°$ and sin $i_2 = 1$. According to SNELL'S law, i_c is calculated using

$$i_c = \arcsin \frac{v_1}{v_2} \qquad [6.1]$$

where i_c is critical angle of incidence [°]
v_1 is velocity in layer 1 [m s^{-1}]
v_2 is velocity in layer 2 [m s^{-1}]

Consequently, energy that is critically refracted travels along the interface at a velocity v_2 and is radiated back to the surface continuously and therefore can be measured at the source receivers.

Basically, seismic waves triggered by the energy source (hammer blow) penetrate the overburden and refract along an interface and travel back to the surface, where they are detected by a series of equally spaced receivers (geophones). The signal recorded at the geophones can be plotted in a traveltime curve (seismogram). The first arrival time of P-waves at the geophones is the most important data for the delineation of a subsurface layer model.

As shown in Figure 6.5, traveltimes of direct waves are recorded first at the geophones. Refracted waves (*Mintrop* or Head waves) are usually generated at a critical distance x_c from the source. As a consequence, first arrival times at the receiver are only measured when refracted waves overtake direct waves at a critical distance x_C, induced by their higher velocity in the underlying bedrock (GEBRANDE & MILLER, 1985; PULLAN & HUNTER, 1999). Reflected waves are neglected, since they propagate at slower velocities and thereby are recorded at later times at the receivers.

According to HECHT (2001) the seismic velocity of a material can be determined directly by refraction seismics, since the rise of the traveltime vector is equal to the reciprocal velocity of the refractor. As a consequence of the relation between the material-specific density and its seismic velocity, the depth of the interface and thereby layer thickness can be estimated by traveltime analysis, while measurements of seismic velocities are used to derive information on physical properties of the sediments (DRESEN *et al.*, 1985; HILBICH, 2003). Summaries of material-specific p-wave velocities are given in HECHT (2001) and PULLAN & HUNTER (1999).

Numerous analysis methods are available to derive subsurface models from data provided by seismic surveys. Today, most methods are implemented in computer-based analysis systems. While kinematic approaches are limited to the analysis of traveltime data, dynamic approaches offer possibilities to consider effects like amplitudes and frequency dynamics during data processing (HECHT, 2001). Kinematic approaches can be differentiated into direct inversion methods (standard inversion method), methods of iterative forward (progressive) modeling and refraction tomography including tomographic inversion of transmission traveltime data (HECHT, 2001).

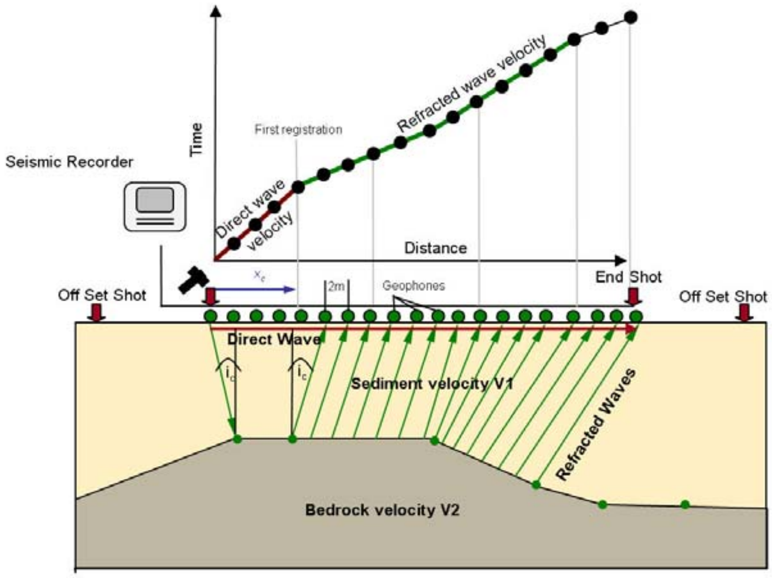


Figure 6.5: Generalized diagram illustrating basic principles of refraction seismics and associated traveltime curve for a 2D-layer model (after Burger, 1992; Hecht, 2001).

6.2.2.2 Field Measurement and Data Processing

Refraction seismic surveys have been undertaken during field campaigns in 2003 and 2004 (dry season) utilizing a 12- and 24- channel system (*Bison 5000, Bison Instruments Inc., Smartseis*-Seismograph by *Geometrics*). A total of 21 single sequences have been measured along 7 selected transects representing different types of wetlands (see Figure 6.4).

GEBRANDE & MILLER (1985) have shown that higher densities of shot points cause a better resolution of subsurface structures. Thus, the geophones were arranged using equal distances of 2 m along a linear sequence. Offset shot points need to be set up depending on both local topography and expected sediment depths and therefore varied between 5 m and 30 m. As recommended by HILBICH (2003) two offset shot points were set at the beginning and end of the profile to enhance the signal densities of deeper layers and thereby the vertical resolution (forward/reverse shot method) as well as to reduce effects caused by inhomogeneous interfaces (DRESEN *et al.*, 1985). According to HECHT (2001) such a set up can also be used to improve forward and reverse modeling of traveltimes which is necessary for optimization purposes. Since the profiles were taken as several consecutive sequences, overlapping sequences were achieved by using the end point of one sequence as starting point of the following one.

The data processing was performed using the modules *2D Data Analysis* and *Refraction Traveltime Analysis* of the analysis software *ReflexW* (Version 3.5) introduced by SANDMEIER (2001). Thus, first arrival times of seismic waves were delineated delineated by sequential picking of each shot point at each geophone interactively. In the next processing step all resulting traveltime plots of each shot location within one profile were combined to one traveltime diagram as a whole, showing vectors of differing velocities. These were analyzed to identify several layer boundaries. Since break times give an indication of vertical or lateral velocity changes in the subsurface, they were interpreted as interfaces between differing materials. An assessment of the quality of the traveling time analysis is given by the correlation between shot and reverse shot data (HILBICH, 2003). Topographic corrections of the data are needed when topographic induced effects are assumed to distort first arrival times of refracted waves. Topographic correction is done by transforming the z-values of the topographic coordinates measured by GPS into a two-way travel time, i.e. an apparent shift in the position of the equally spaced geophones relative to their topographic position.

Once the data are picked and layers identified, the wavefront inversion method allows migrating the combined forward and reverse traveltimes into layer-specific depth using a Finite Difference approximation of the eikonal equation (SANDMEIER, 2001). In addition 2-D subsurface model and seismic layer velocities can be delineated from the complete forward and reverse wavefronts (SANDMEIER, 2001; BURGER, 1992; GEBRANDE & MILLER, 1985).

The derived seismic profiles have been validated using measurements from soil drillings and outcrops. Therefore, soil data from ROBERTS *et al.* (1996), ESPREY (1997) and own observations have been reviewed for evaluation of received seismic profiles.

6.2.3 Vegetation Studies

Since only two dominant vegetation types were identified in the study area, studies concerning vegetation have been focused on grassland, including wetland areas which are predominantly covered by grassy vegetation (Section 6.2.3.1), and afforested areas (Section 6.2.3.2).

6.2.3.1 Grassland and Wetland Vegetation

The vegetation of grassland and wetland areas was intensively investigated during field campaigns in 1997, 1998 and 2001. These studies aim to characterize the distribution and dynamics of grassland and wetland vegetation and to delineate empirical parameters for the hydrological modeling.

There are a variety of sampling techniques used in studies of grassland and herbaceous plant communities (SORRELS & GLENN, 1991). In this study 1 m^2 plots have been investigated which were either set up along selected cross-valley and longitudinal profiles (transects) or randomly distributed in selected grassland and wetland sites. The wetland studies were mainly focused on several wetland types in the Weatherley catchment as well as the larger valley bottom wetlands Gatberg Vlei and Ku'Ntombininzinzi Vlei, while the grassland studies have been carried out in the Weatherley, Mooi and Wildebees catchments (see Figure 4.1). Finally, 11 transects (incorporating 178 plots) and 32 single plots have been selected in Weatherley and 8 transects (64 plots) and 28 single plots in grassland and wetlands areas of the Mooi, Wildebees and Gatberg catchments. The intervals between the plots within transects varied between 10 and 60 m according to the topography, underlying bedrock, soil distribution and visible environmental changes. Plots were selected in areas that seemed to be in optimal condition in terms of growth, composition and density. In addition, only such areas were chosen which were assumed to be not burned for about 2 years before the vegetation analysis.

First, dominant species and their individual occurence were recorded for 89 plots (DAHLKE *et al.*, 2003) using field guides (GIBBS RUSSEL *et al.*, 1991; HILLIARD, 1996). Second, abundance and dominance analyses were carried out by DAHLKE *et al.* (2003) to identify indicator plants for different environmental conditions within wetlands and grasslands. Third, a selection of plant-biophysical parameters (vegetation height, root length and density, cover density, LAI, and wet and dry biomass) and plot-related parameters (slope, aspect, and soil moisture) were measured (see also Table 5.3).

Vegetation height and root length were determined as averages of 10-16 plants measured at each plot, while root density was described according to 5 classes (very sparse, sparse, medium, dense, and very dense). The cover density of each plot was estimated using a procedure described by USDI National Park Service (2001). The LAI was directly measured using the Digital Plant Canopy Imager Model CI-100 (GENEQ Inc.). The Plant Canopy Imager calculates LAI and other canopy structure attributes from radiation measurements made with a "fish-eye" optical sensor (148° field-of-view). Six measurements made above and below the canopy of each plot were used to determine canopy light interception at 5 angles, from which the mean LAI is computed using a model of radiative transfer in vegetative canopies. Moreover, LAI has been determined from its close relationship to dry biomass. The wet biomass was measured by cutting and weighing samples from a 20 cm^2 subarea of each plot. The dry biomass has been determined from the wet biomass samples after two days of drying in an oven at 80°C.

Slope and aspect were determined for each plot to evaluate topographic impacts on vegetation composition and structure. In addition, soil moisture was measured at all plots utilizing portable *Time Domain Reflectometry* (TDR) equipment (Section 6.2.4).

6.2.3.2 Forest Plantations

Since the afforestation activities which started in 1989 are assumed to impact the water budget in general and the wetland dynamics in particular, growth dynamics of several forest species were surveyed during field campaigns from 1997-2005. In addition, model parameters were provided for the parameterization of 3-PG and PRMS and to validate the model results.

Plant-biophysical data were provided by measurement of Diameter at Breast Height (DBH), crown diameter, tree height, rooting depths, wet and dry biomass, cover density and LAI, and stocking in selected pine and eucalyptus stands within the NECF area. In total, 152 forest stands of different ages have been demarcated and measured, including 133 pine (87 *P. patula*, 32 *P. radiata* and 14 *P. elliottii*) and 19 eucalyptus stands (12 *E. nitens* and 7 *E. grandis*). Since approximately 70 % of the afforested areas are covered by *P. patula*, more detailed studies were focused on growth dynamics of those stands. Therefore they were grouped into four age classes (2-5 yrs., 5-10 yrs., 10-15 yrs., and 15-22 yrs.). The measurement of litter thickness in 42 selected stands (*P. patula, P. radiata* and *E. nitens*) completed the parameter pool of stand-related data.

Forest stands of each species were pre-selected on the forest map delineated from the NECF data base. In the field only those stands were selected, where consistent stocking and little variation in growth and stem quality was found. The size of sample sites established in the inspected stands varied depending on the designated parameter and therefore ranged from single trees to groups of four trees and 30 trees (6x5). For each sample site species, estate name, stocking, forest management practice (planting method, pruning, thinning etc.), altitude (GPS), location (GPS), slope, aspect, terrain unit and when available, soils were recorded. The measurement strategy was designed in order to provide time series of stand-related parameters on an annual basis for each forest species. All measured values within a sample site were averaged and thereby considered as representing the stand mean at a defined tree age.

All sampling sites were located at altitudes between 1 165 and 1 512 m asl. and showed a low to moderate slope (0-12%). Although ZWOLINKSI *et al.* (1997) pointed out that south-facing slopes receive less rainfall and show lower temperatures than north-facing slopes; stands of all aspects were selected, since the rainfall analysis (Section 7.2.2.1) indicated that the rainfall intensity is neither significantly influenced by altitude nor by aspect.

Parameters were measured using following methods:

- Diameter at 1.3 m height (DBH) was measured over bark with the diameter tape for 30 trees in each selected stand.
- Crown diameter was measured for 30 trees in each stand using a standard method developed by the UNITED STATES DEPARTMENT OF AGRICULTURE (USDA, 1992). The method is described in detail in HELMSCHROT (1999).
- Tree height was obtained by either direct measurements (smaller trees) or estimations using a technique introduced by the USDA (1992) for 30 trees per stand.
- Rooting depths were determined for up to 5 years old *P. patula* trees. Five trees per stand were dug out and root diameter and lengths were measured (HELMSCHROT 1999).
- Biomass data were available from studies carried out by HELMSCHROT (1999).
- Cover density was calculated as described by HELMSCHROT (1999) using the crown diameter data and stocking information from the NECF data base.
- Leaf Area Index was directly measured using the Digital Plant Canopy Imager Model CI-100 (GENEQ Inc.). Hereby, 30 measurements were made randomly in each of the selected stands.
- The litter thickness was measured at 15 sites within each selected stand. The 15 measurements were averaged and considered as mean litter thickness of each stand at a defined age.

Besides own measurements, additional data were used from studies by ZWOLINSKI *et al.* (1997) who investigated mature pine stands in the NECF area as well as data which were available from the NECF data base (Mondi Forests Ltd.).

6.2.4 Field-based Soil Moisture Measurements

TDR (Time Domain Reflectometers) measurements were carried out by measuring soil moisture at irregular intervals supplementing the hydrometric, soils and vegetation monitoring efforts in Weatherley. TDR equipment measures the difference in capacity of a non-conductor (soil) to transmit high-frequency electromagnetic waves or pulses, which is related through calibration to soil moisture content. Physically, the TDR measures the traveltime for an electromagnetic wave through the soil between two or more probes. After calibration, the TDR equipment provides direct readouts of volumetric, plant-available soil moisture percentages which can be directly used for further processing.

Selected sites have been surveyed during the field campaign in March 2001 utilizing portable TDR equipment (TRIME-FH, IMKO Mikromodultechnik GmbH). The Trime-system is a specially designed TDR technique for moisture content measurements in various depths of the soil profile. It consists of a read-out unit and various two-pin probes. The probes have a recording range of 0 - 95 volume percentage moisture. Since no extensions for the probes were available for this study, soil moisture measurements were limited to the upper 26 cm of the soil, i.e. the length of the probes.

One survey was carried out in a small wetland site (60 m x 90 m) on the crest in Weatherley. Herein, 128 measurements were taken on a 6 m x 6 m grid. These readings were interpolated to provide spatial distribution pattern of soil moisture. Furthermore, soil moisture was measured at each vegetation plot in Weatherley (described in Section 6.2.3) to identify relations between species composition and soil moisture status. Thereby, each plot was surveyed four times. These readings were averaged for further analysis.

6.3 Laboratory Analysis

A variety of soil samples were analyzed in the laboratory to provide soil-physical model parameters (Section 6.3.1), age estimates (Section 6.3.2) and pollen analyses (Section 6.3.3). Standard soil analyses were conducted in the Soil Lab of the University of KwaZulu-Natal in Pietermaritzburg, South Africa and the geo-ecological laboratory at the Department of Physical Geography in Jena, Germany. The latter also provided pollen analysis. Hydrometric analyses (pF, K-values) were carried out in the pF-Laboratory at the Department of Geoinformatics in Jena, Germany. Samples for dating were analyzed by the AMS (Accelerator-Mass-Spectrometry) Laboratory of Erlangen.

6.3.1 Soil Analysis

The importance of soil-physical parameters for watershed model applications is intensively discussed by SINGH (1995). In this study, soil-physical analyses were carried out to retrieve both information on soil characteristics and model parameters for process modeling at hillslope and catchment scale. Hence, the samples were analyzed to determine grain size, pH, total organic content (TOC), N, S, Al, Fe exchangeable cations (Ca, Mg, K, Na), pf-curves, field capacity and hydraulic conductivity.

The grain size was determined using the pipette method according to DIN 19683 – 2 (DEUTSCHES INSTITUT FÜR NORMUNG e.V., 1997). Hereby, the proportions of medium silt (63-20 µm), fine silt (2-63 µm) and clay fraction (< 2 µm) were measured in a pipette apparatus after KÖHN. The sand fraction was determined by sieving under running water with sieves of 63 µm for the fine sand, 200 µm for the middle sand and 630 µm for the coarse sand.

pH was measured in both water and a KCl-solution, since water pH frequently does reflect all of the acid ions (ratio soil:fluid as 1:4). TOC, N and S were quantified using an Element Analyzer *(Vario EL)*, whilst Al, Fe, Na, Mg, K and Ca were measured with an *Atom Absorption Spectrometer* (AAS).

Soil water suction curves relate the soil suction to its moisture content. In this study they were used to identify soil moisture movement and the soil moisture available for plant growth. They can be used to determine an index of the available moisture in soil (the portion of water that can be readily absorbed by plant roots) and the drainable pore space (effective pore space, effective porosity, specific yield) for drainage design as well as to identify changes in the soil structure, e.g. caused by tillage, mixing of soil layers etc. Additionally, the relation between soil moisture tension and other physical properties of a soil (e.g. capillary conductivity, thermal conductivity, clay and organic matter content) can be ascertained from such curves. In the present study, pF-curves and field capacities were determined in the range pF 2.0 - 4.2 (0.1 - 7 bar of suction) by a method utilizing ceramic plates equipment (Eijkelkamp). Thereby, soil moisture is removed from completely saturated soil samples by raising air pressure in an extractor. Equilibrium is reached when water flow from the outflow tube ceases. At equilibrium, there is an exact relationship between the air pressure in the extractor and the soil suction (and hence the moisture content) in the samples. The saturated hydraulic conductivity (k_f) was determined according to the DIN 18130 (DEUTSCHES INSTITUT FÜR NORMUNG e.V., 1983) using the Stenzel equipment.

6.3.2 ^{14}C Dating

As shown in several studies, dating techniques are widely used to provide depth-age relationships of unconsolidated sediments that were related to sediment deposition and thereby landscape dynamics (BROWN, 1975; TURETSKY *et al.*, 2004; WIEDER *et al.*, 2005). For that reason, ^{14}C dating was utilized to analyze organic samples collected from two wetland sites in the study area.

6.3.2.1 Theoretical Considerations

A variety of dating techniques like radio-carbon dating, dendrochronology, Electron Spin Resonance, Fission Track, Optically Stimulated Luminescence (OSL), Oxidizable Carbon Ratio (OCR) and Thermoluminescence dating are well-described and successfully used in numerous studies (AITKEN, 1995; GOKSU *et al.*, 1991; WALKER, 2005). For cost and time reasons, radio-carbon dating was assumed to be the most appropriate method to derive age information from organic samples found in several wetlands in this study.

Radio-carbon dating is a method to obtain age estimates on organic materials and has been used successfully to provide age determinations in archaeology, geology, and natural sciences. Radiocarbon determinations can be obtained on wood, charcoal, marine and fresh-water shell and bone, peat and organic-bearing sediments, carbonate deposits such as tufa and marl, and dissolved carbon dioxide and carbonates in ocean, lake and groundwater sources.

Naturally, carbon appears with 3 isotopes – two non-radioactive isotopes (^{12}C, ^{13}C) and ^{14}C, as unstable isotope. Principally, the method of radiocarbon dating is based on the assumption that ^{14}C is continuously produced at a constant rate that assures a constant proportion of radioactive to non-radioactive carbon within the atmosphere. Plants incorporate atmospheric carbon dioxide during photosynthesis and contribute it to the biosphere. Thus, every living organism is continuously exchanging ^{14}C with its environment. With the termination of this exchange, i.e. the die back of an organism, the proportion between ^{14}C and ^{12}C changes since the amount of ^{14}C gradually decreases through radioactive decay with a constant rate. The proportion of carbon-14 to carbon-12 will reduce according to the exponential decay law:

$$R = A \cdot \exp\left(-\frac{T}{8033}\right) \qquad [6.2]$$

where R is $^{14}C/^{12}C$ ratio in the sample, A is the original $^{14}C/^{12}C$ ratio of the living organism and T is the amount of time that has passed since the death of the organism. By measuring the ratio, R, in a sample, the age then can be calculated by:

$$T = -8033 \cdot \ln\left(\frac{R}{A}\right) \qquad [6.3]$$

6.3.2.2 Sampling and Analysis

Samples of organic material were taken from two wetlands in the study area during field campaigns in 2002 and 2003. Two probes of organic material, which were assumed to be decomposed roots, were found near the base of an open soil pit in the Gatberg Vlei 28°05’56”E, 31°14’33”S, 1 363 m asl.). Since the soil profile of the pit showed a typical structure of wetland building sediments, it was assumed to be representative for valley bottom wetlands of the region in general. The overall soil depth was about 240 cm and showed higher fractions of clay in the upper part at 130 cm depth and increasing contents of fine sands at the base. The profile was described in detail in Section 7.1.2. The samples were extracted from depths between 220 and 240 cm at the bottom of the profile, i.e. the above the gravel overlaying the sandstone. Consequently, the age provides a minimum age for wetland evolution.

Furthermore samples were taken from a soil core acquired in a bog nearby Diepfontein farm (28°13’ E, 30°51’ S, 1 730 m asl.). Based on test drillings, it was found that hydric soils in this area are basically characterized by very high organic material. The wetland survey indicated permanent saturation in some parts of the bog site. Since the bog differs from other wetlands in the region because of its exceptional position (altitude) and formation (organic content), it was not considered to be representative for widespread wetlands in lower areas. However, two undisturbed soil cores of 1 m length were taken at different locations of the bog site. A detailed profile description at those places was not possible, since the soil structure did not remain intact when the core was opened. Once the cores were taken, they were sealed immediately. In the laboratory, two samples of one core were extracted at depths of 42 cm and 92 cm and prepared for ^{14}C dating. In addition the respective core was analyzed for soil texture, CNS, AAS, pH and hydraulic conductivity.

All samples were analyzed by the AMS Laboratory of Erlangen. According to KRETSCHMER *et al.* (1997a), the AMS facility can be used to determine the age of carbon-containing samples measuring the ratios between different carbon isotopes ^{14}C, ^{13}C and ^{12}C directly. A detailed description of sample preparation requirements, the AMS facility itself and related errors are given in KRETSCHMER *et al.* (1997a,b).

The results of the ^{14}C dating were related to the rarely existing climate records and anthropological studies and thereby were used to provide supplementary information on wetland formation.

6.3.3 Palynological Studies

The study of pollen and spores (palynology) is a common method to reconstruct past environmental conditions (MOORE *et al.*, 1991b). Pollen grains are the microscopic male reproductive particles released from flowering plants. As these grains are vital for the survival of flowering species, evolution has ensured that individual species produce different types of pollen grains. Pollen grains are also made of a resistant organic material (*sporopollenin*) what means they are often remarkably well-preserved in sediments which are many thousands of years old. Pollen grains and spores are assumed to become incorporated and preserved in lake sediments, floodplains, peat bogs, or other sediments. Accordingly, pollen assemblages preserved in such sediments reflect the surrounding vegetation. Vegetation is often sensitive to changes in environmental conditions; thus, the types of pollen grains and spores produced in a region vary through time. Analysis of the pollen content of sediments deposited over time therefore has the potential of recording vegetation dynamics and environmental change of a region from a landscape perspective (ROBERTS, 1999). Nevertheless, problems with pollen analysis occur, since some plant species naturally produce more pollen, some grains are transported more effectively and other grains are more delicate and are poorly preserved. These taphonomic considerations have to be considered in any interpretation of a pollen sequence. Results of pollen analysis are usually presented on both relative (percentage) and absolute (influx) pollen diagrams. In percentage diagrams, the number of grains of each pollen taxon is expressed as a percentage of the total pollen sum for a given sediment sample.

Basically, wetland sediments provide ideal conditions for pollen preservation and storage. Saturated soils have a reduced oxygen content which aids organic preservation. Wetlands are often characterized by low-energy depositional conditions, and thereby act as a natural trap for pollen grains transported by rivers, the sea and the atmosphere. Consequently, in this study pollen analysis was assumed to be useful to identify past species composition of wetlands and surroundings, and thereby to relate this information to wetland formation and succession.

A total of 23 soil samples were collected from 12 open soil pits along the Mooi River and the Gatberg River during the field campaign in 2002 for pollen analysis. The samples were taken at several depths of the profiles. Referring to standardized methods of sample preparation (MOORE *et al.*, 1991b), the samples were treated with potassium hydroxide (KOH), hydrochloric acid (HCl), hydrofluoric acid (HC) and a mixture of acetic anhydride and concentrated sulphuric acid (*Erdtman's acetolysis solution*) to remove redundant chemicals and substances. Silicon oil was finally added to prepare the samples for microscope analysis.

6.4 Spatial Data Modeling

Accurate spatial quantification of landscape characteristics is of fundamental importance for the delineation of spatial model input parameters. In this study, point data from a reference site which are assumed to be statistically representative regarding the spatial variability were used for the estimation of spatial patterns. In addition, land use information was provided by classifying satellite data.

6.4.1 Spatial Rainfall Modeling

With respect to the information offered by sparse gauging networks, observed precipitation patterns usually show high variability (BEVEN, 2001a, WATSON, 1999). In addition, catchment characteristics like topography and geographic position often substantially affect precipitation distribution, intensities and variability. In this study precipitation data were spatially interpolated aiming to provide information on generalized rainfall pattern and their dependency on local phenomena like altitude, distance to the coast, and aspect.

Since rain gauge measurements are point data, the analysis of spatial rainfall pattern depends on interpolation. Although a wide range of techniques are available for spatial modeling of rainfall, there is no consensus on the best method (BEVEN, 2001a). Herein, the precipitation records were interpolated using the Inverse Distance Weighted (IDW) and Kriging interpolation algorithms of the GIS - program ArcView 3.2. IDW is a simple distance weighted estimate of the value at the target station. The assumption here is that surrounding stations are related to the target station by their proximity to the target station. Kriging procedures are more rooted in statistics, whereby a surface is calculated as a weighted sum of the input data points with the weights adjusted to minimize the variance of the prediction error at each data point.

The precipitation data set used to create the interpolated areal coverage consists of monthly and annual average values from 66 stations. The number of stations providing complete data was highest between 1970 and 1988. Figure 6.6 represents the distribution of the stations which have been used for the spatial modeling and for the analysis of annual means (blue), individual years (yellow) and for validation purposes (red). Using both interpolation techniques, areal precipitation maps were created for each year and for the 19-year average. Since seasonality affects rainfall, supplemental precipitation maps representing dry winter and rainy summer conditions were created for both the 19-year average and annual measures. The created maps were compared to identify spatio-temporal rainfall dynamics. Moreover, the quality of the interpolation was evaluated considering statistical measures like root mean square error (RMSE), differences maps and cross validation. The results were verified based on existing data sets for South Africa (SCHULZE, 1997; WRC, 1994).

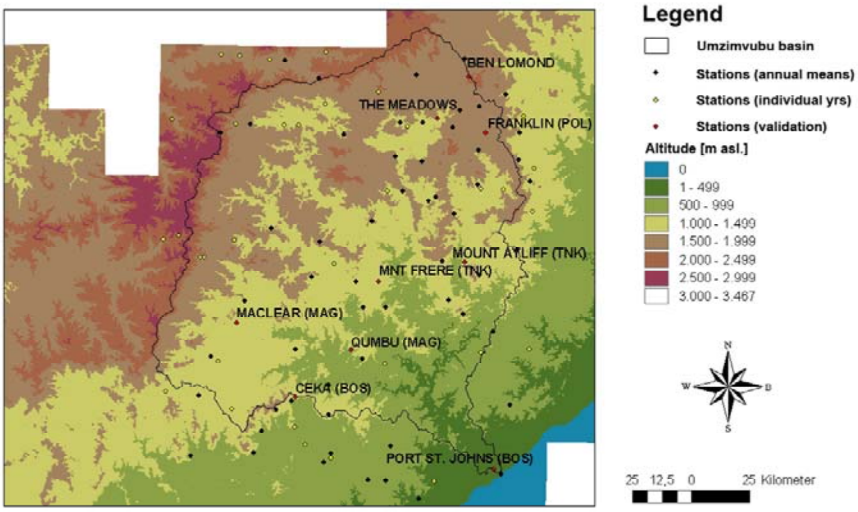


Figure 6.6: Distribution of the rainfall stations used for the spatial modeling of rainfall pattern and hydrological modeling (Cartography: Bäse, 2004).

6.4.2 Relief Analysis

Digital Elevation Models (DEMs) are becoming increasingly important in environmental modeling, since such models attempt to a greater or lesser degree, to incorporate the spatial variation of significant environmental characteristics within watersheds. For hydrological model applications, this requires that information is available for a number of watershed properties. While the specific parameters needed may vary between individual models, integrated model approaches require information on watershed topographic properties such as basin size and boundary, aspect, surface gradient and overland flow length of subcatchments, and topological information on the structure of the channel network and its contributing subcatchments.

Traditionally, such parameters have been manually derived from maps, aerial photographs and field surveys, but such efforts are tedious, costly, time consuming and they depend on the specific operator skills. In recent years, GIS technology has increasingly been utilized to assist scientists' work with the task of model parameterization from operational relief analysis (BEVEN, 2001a). Following a pre-processing of the elevation information (Section 6.4.2.1), standardized relief analysis algorithms included in ArcGIS 9.0 have been used to calculate hydrologically relevant basin parameters (Section 6.4.2.2). In addition, the program extension namely ArcTopo 3.0.2 (BEHRENS, 2003) was implemented in ArcView 3.3 to explore specific morphometric parameters for system analysis and wetland delineation (DAHLKE *et al.*, 2005).

6.4.2.1 DEM Pre-processing

A DEM is a raster representation of a continuous surface, usually referring to the surface of the Earth. The accuracy of this data is determined primarily by the resolution (the distance between sample points). Other factors affecting accuracy are data type (integer or floating point) and the actual sampling of the surface when creating the original DEM. DEMs may also contain noticeable horizontal striping, which results from systematic sampling errors when creating the DEM.

For this research, DEMs of varying resolutions and from different sources were available (Table 5.5). High-resolution SRTM data (25x25 m²) were processed for regional studies covering an area of 815 km² (Figure 6.7). Due to the acquisition technique, SRTM data are addressed as a Digital Surface Model (DSM) including the height of vegetation and buildings (KOCH & LOHMANN, 2000). Additionally, the radiometrically corrected and calibrated DSM contains different types of errors resulting from the interferometric technique and the data processing, which mainly can be found in areas of open water bodies and rough surface terrain. Consequently, an intensive preprocessing was performed to reduce the vegetation effects and to eliminate these artifacts.

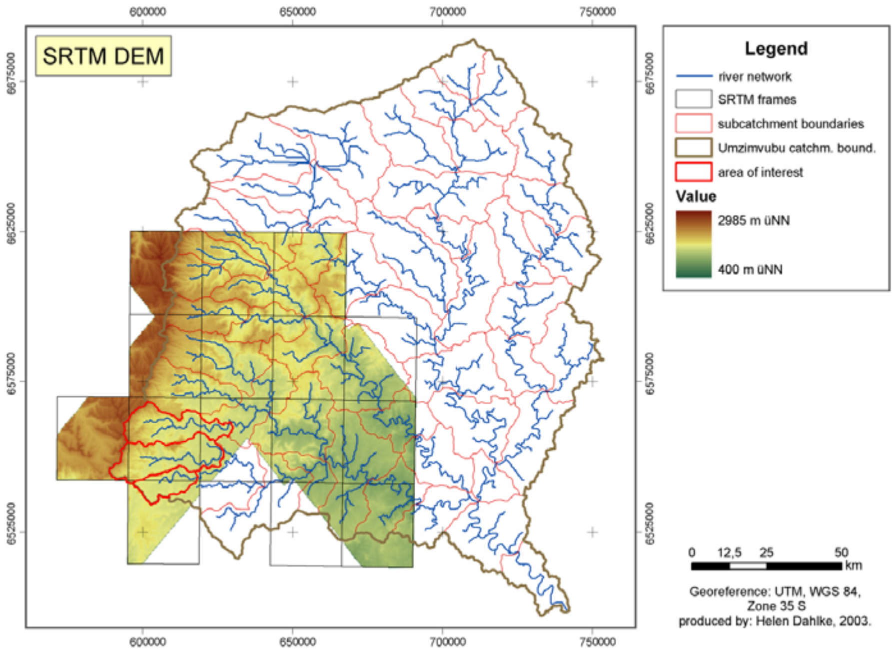


Figure 6.7: Area covered by the SRTM-DEM used for this study and the area of interest for further analysis (mod. after DAHLKE, 2003).

Initially, data were rectified to a reference system (UTM, Zone 35, Spheroid: WGS 84) using a projection algorithm in ERDAS/Imagine 8.7. Since the land use within the study area is dominated by grassland and plantation forestry, efforts to minimize the effect of vegetation heights were limited to the afforested areas. According to the age and the planted species, the trees rarely exceed heights of 20 m. Based on field measurements and information taken from the forestry data base, the mean vegetation height for the plantations can be classified as shown in Table 6.1. Indigenous woodlands given by land use maps have been considered with an average height of 16 m.

Table 6.1: Mean heights of Pinus and Eucalyptus stands within the afforestation areas of NECF.

	Pinus spp.			*Eucalyptus spp.*	
age [yrs]	plantation period	height [m]	age [yrs]	plantation period	height [m]
< 3	03/1997 - 03/2000	0	< 1	03/1999 - 03/2000	0
3 – 6	03/1994 - 03/1997	5	1 – 2	03/1998 - 03/1999	3
6 – 10	03/1990 - 03/1994	9	2 – 4	03/1996 - 03/1998	9
10 – 20	03/1980 - 03/1990	15	> 4	before 1996	15
> 20	before 1980	22			

Summarizing Dahlke (2003), a vector layer containing polygons with the different height classes obtained from field observation was converted to a raster file in order to subtract the tree heights from the SRTM DSM in the forest areas. According to spatial uncertainties and buffer zones in the boundary areas of the plantations, a method for a stepwise adjustment of the tree heights was developed. As schematically shown in Figure 6.8, the tree height was increased from 0 m up to the stand specific tree height using linear steps from the plantation boundary to the base zone. The optimum numbers for the height steps as well as the overall distance of the buffer were iteratively tested by checking the resulting DEM using height profile tracking. Small remaining artifacts which could not be corrected by calculating height buffers were smoothened by applying a low-pass filter. As a result the DSM has been corrected and a Digital Elevation Model (DEM) was calculated.

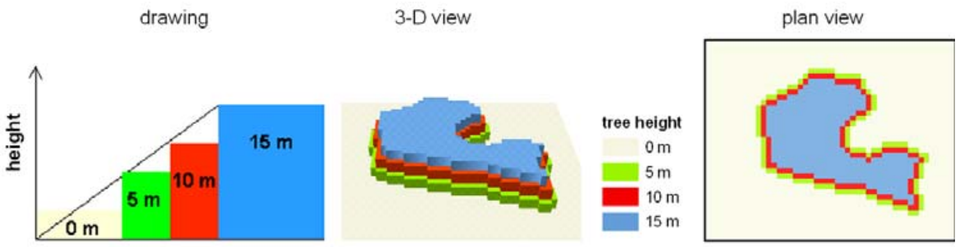


Figure 6.8: Stepwise adjustment of buffer zones in the boundary areas of the plantations to subtract vegetation height from the SRTM DSM (mod. after DAHLKE, 2003).

The elimination of artifacts concerning the surface roughness and small pits of the DEM was realized by using a limit-filter with a 3x3 pixel window (BEHRENS, 2000 [ConFit; ESRI/ArcScripts]). Furthermore, local random errors within the range of open water bodies or steep slopes were detected by the calculation of the local standard deviation of the DEM. By setting a threshold value to the standard deviation only those areas with height differences of more than 130 m have been identified. These areas were revised by interpolating new height values or filling the gaps. Finally, phenomenon-based approach developed by BEHRENS (2002) wasapplied to remove depressions and flat areas, and thereby to eliminate indefinite downslope drainages. At first this algorithm locates all sinks in a DEM and burns small segments of a calculated stream network into the DEM in a predefined circle around the located pits. Consequently, the refilling of the known depressions in the DEM is reduced to minimum extent by burning-in these segments with a specified depth. The final product was verified by comparison with a DEM derived from SPOT data (HELMSCHROT, 1999) and topographic maps. As discussed by DAHLKE (2003), the comparison showed that a highly accurate DEM was processed for further analysis.

The DEM of the Weatherley catchment was automatically generated from GPS survey. First, the DEM was rectified and re-sampled to a resolution of 5 x 5 m². In a second step, sinks were automatically identified and filled to generate a depressionless DEM as described above.

6.4.2.2 Parameter Mapping

Further processing of the pre-processed DEMs generates spatial landscape information and parameters which are of importance for system analysis, wetland delineation and model parameterization.

- **Flow direction and accumulation**

For each DEM, the direction of overland flow at each cell was derived using the method as described by JENSON & DOMINGUE (1988), also known as D8. It is based on the calculation of a flow direction matrix, in which the gradient of each raster cell to its eight direct neighboring cells is determined. If the descent to all adjacent cells is the same, the neighborhood is extended until the steepest descent is found. When the processing cell is smaller than its neighbors, it will be filled by the lowest value of its neighbors having a flow direction towards this cell. If two cells flow to each other, they are sinks, and have an undefined flow direction. Next, flow accumulation was calculated to represent the accumulation of water flow into each DEM cell from surrounding cells. This was done via the method of deriving accumulated flow from a DEM as described in detail by JENSON & DOMINGUE (1988). Multiple flow algorithms are assumed to be more accurate than the D8 method. Thus, the method introduced by QUINN *et al.* (1991) was explored regarding its potential to improve the representation of flow accumulation. It was found that this method provided more precise values for steep slopes. It also revealed that inaccurate flows were determined especially in broad valleys, since it does not allow the computation of drainage lines. Consequently, the single flow algorithm was finally used for the computation of flow accumulation.

- **Catchment boundary, subbasins and stream network**

Once the flow direction and flow accumulation of each raster cell was calculated, catchment boundaries, subbasins and the river network could be derived. The watershed delineation was based on the identification of outlet points in the drainage network which could be taken from the grids of flow direction and flow accumulation. Assuming that all the cells upstream flowing to the specified outlets, the drainage divides were determined by tracing the cells to a selected set of outlets (JENSON & DOMINGUE, 1988), which could be set automatically or manually.

Subbasins were delineated from DEM by identifying ridge lines between basins. Therefore, the flow direction raster was analyzed to find all sets of connected cells that belong to the same subbasin. The subbasins were computed by locating the pour points at the edges of the analysis DEM (where water would pour out of the raster) and sinks, and then by identifying the contributing area above each pour point. This resulted in a raster output representing the subbasins.

The stream network was defined as the set of all the cells in the terrain with flow accumulation value larger than a user-defined threshold. It was necessary to identify the threshold iteratively. An analytical method for determining an appropriate threshold value for stream network delineation is discussed in TARBOTON *et al.* (1991). Values of 500 (Mooi) and 1000 (Weatherley) contributing cells were finally considered as being representative for the stream networks of both catchments after the verification with the river network derived from topographic maps (Mooi) and GPS survey (Weatherley).

- **Slope and aspect**

Classified grids of slope and aspects are necessary input data for the delineation of HRUs. Both parameters were computed for the catchments as continuous values using the *slope* and *aspect* functions of ArcGIS. Conceptually, the slope function fits a plane to the z-values of a 3-x-3 cell neighborhood around the center cell. The slope for the cell is calculated from the 3-x-3 neighborhood using the average maximum technique. An output slope raster can be calculated as percent slope or degree of slope. Aspect identifies the down-slope direction of the maximum rate of change in value from a center cell to its 8 neighbors. The values of the output raster are considered as the compass direction of the aspect in degrees.

- **Topographic indices and morphometric parameters**

According to BEVEN & KIRKBY (1979) the Topographic Wetness Index (TWI) is a measure integrating flow accumulation and slope to predict an index of soil moisture for each cell. It is also often termed the "steady-state wetness index", for it is correlated with zones of moisture convergence (MOORE *et al.*, 1991). Its determination is premised upon two basic assumptions (BEVEN, 2001a): i) the dynamics of the saturated zone can be approximated by successive steady-state representations of the saturated zone on an area a draining to a point on a hillslope; and ii) the hydraulic gradient of the saturated zone can be approximated by the local surface topographic slope measured with respect to the plane distance tan β. According to MOORE *et al.*, (1991), these assumptions result in a simple relationship expressed as ln (a/tan β) which represents the propensity of any point in the catchment to develop saturated conditions. The TWI was computed for each basin implementing an avenue script file into ArcGIS 9.0.

Furthermore, morphometric parameters were determined to delineate wetland areas based on DEM. The supplementary parameters and the delineation procedure are discussed in detail by DAHLKE (2003). Table 6.2 summarizes the terrain-based parameters used for this study.

Table 6.2: Terrain-based parameters used in this study.

Parameter class	Relief parameter	Application	Source
Local geomor-phometric relief parameters	slope, aspect	hydrological model parameterization, system analysis, wetland delineation	BURROUGH & MCDONELL (1998)
	relative profile curvature	system analysis, wetland delineation	BEHRENS (2003)
	relative planform curvature	system analysis, wetland delineation	KLEEFISCH & KÖTHE (1993)
Regional geomor-phometric relief parameters	flow direction	river network delineation and as-sessment, topological HRU routing, hydrological model parameterization,	JENSON & DOMINGUE (1988)
	flow accumulation	basin delineation, river network de-lineation, topological HRU routing, hydrological model parameterization,	JENSON & DOMINGUE (1988), QUINN *et al.* (1991)
	relative slope posi-tion	system analysis, wetland delineation	BEHRENS (2003)
Combined geo-morphometric relief parameters	height above drain-age channel	system analysis, wetland delineation	BEHRENS (2003)
	compound topog-raphic index	system analysis, wetland delineation	BEVEN & KIRKBY (1979), MOORE *et al.* (1991a)
Secondary geo-morphographic relief parameters	floodplains based on flood simulation	system analysis, wetland delineation	BEHRENS (2003)

6.4.3 Terrain-based Wetland Mapping

Addressing the main objective of this dissertation, intensive work was done to provide information on wetland distribution. Utilizing a GIS-based terrain analysis (DAHLKE, 2003), wetlands were delineated with respect to the classification approach developed in this study. Based on field survey and the resulting hydro-geomorphic classification approach discussed in more detail in Chapter 7, wetlands were distinguished into ***i) valley bottom wetlands, ii) slope wetlands*** and ***iii) plateau wetlands*** and several associated subtypes. These types were delineated regarding their spatial distribution using combinations of specific geomorphometric and geomorphographic parameters.

6.4.3.1 Wetland Delineation Approach

According to the hydrological and geomorphic characteristics of wetlands, the terrain attributes listed in Table 6.2 characterize geomorphometric and moisture differences within the landscape. Since the reclassification and combination of these attributes provide a reasonable potential to delineate different types of wetlands, a hierarchical, rule-based delineation approach (Figure 6.9) was used (DAHLKE, 2003). Hereby, each wetland type was delineated on the base of its specific terrain features by sequential processing of the DEM.

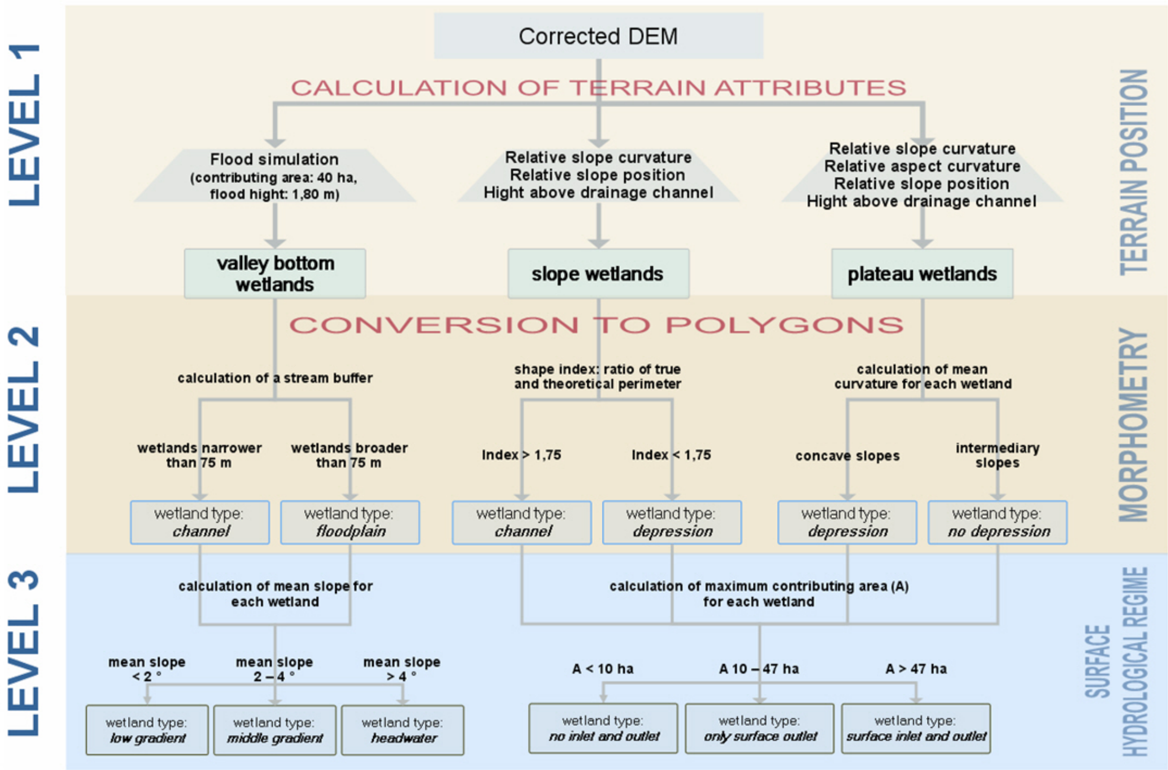


Figure 6.9: Methodology of terrain based delineation of different wetland types (mod. after DAHLKE *et al., 2005).*

- **Valley bottom wetlands**

Valley bottom wetlands are connected to the stream network and are situated in areas of depth contours within a landscape. Thus, they can be delineated calculating a flood simulation of the DEM which is based on the terrain attribute "height above drainage channel". This terrain attribute calculates terrain height of the surrounding terrain area of a stream network in relation to terrain height of the stream itself. By setting the height level of the stream to zero all surrounding areas have positive heights above the stream. The spatial extent of the flooded areas can be limited within the simulation process by setting values for flood height as well as for the contributing area. That means that the size of the hillslope or the catchment area is calculated for each cell of a DEM using the flow accumulation. It was found that best results for the delineation of all possible valley bottom wetlands were achieved using a value of 40 ha for the contributing area and a flood height of 1.80 m. These values showed a good correlation to wetland areas mapped in the field.

After delineating all potential valley bottom wetlands the resulting raster map was converted to a polygon-format to identify the classes "depression" and "channel" wetlands. Therefore the valley bottom wetlands with a large spatial extent were separated from wetlands with a small linear shape. The differentiation was based on a buffer around the stream network with a predefined width of 75 m on both sides of the stream. All wetlands that are lying completely within the predefined buffer are "channel" wetlands, all others were classified as "floodplain wetlands".

The "surface hydrological regime" of all valley bottom wetlands was classified within the third level of hydro-geomorphic classification. According to the classification scheme the hydrological characteristics of valley bottom wetlands show a close relation to the slope of the terrain. The mean slope for each polygon of the valley bottom layer had been calculated using a zonal statistic algorithm. Now the wetland type "headwater" could have been classified by selecting all polygons with a first stream order and a mean slope of more than 4 degrees. Wetlands with a mean slope value of 2 – 4 degrees were classified as "middle gradient" wetlands and those with slope values less than 2 degrees as "low gradient" wetlands.

- **Slope wetlands**

The terrain-based delineation of slope wetlands was based on a combination of the four terrain attributes "*relative profile curvature*", "*relative planform curvature*", "*compound topographic index*" and "*height above drainage channel*" (DAHLKE *et al.*, 2005). First, the basins and depression on the slopes were delineated by reclassifying both curvature attributes. The curvature attributes show a range between -100 (concave areas) and 100 (convex areas). Since wetlands are assumed to occur at concave slope shapes, only these areas with values less than -20 for both attributes were considered for further processing. The results were combined to locate all possible depressions within the slopes. Small sized depressions could have been classified using the profile curvature while the planform curvature primary localizes linear depressions on slopes. In a next step the reclassified curvature map was combined with a reclassified map of the compound topographic index (values = 3.25), because moister areas at the downslopes were not identified sufficiently by the reclassified curvature map. Additionally, the maximum slope was set to 9 ° (15.8 %), because wetlands have never been found on steeper slopes in this area.

The raster map with all potential slope wetlands was converted to a polygon file to differentiate these wetlands with regard to their morphometric characteristics. This differentiation was based on shape information (round or oblong) of each polygon. Assuming that a round object shows a different ratio to its perimeter than an oblong object, a quotient of theoretical (circle) and true perimeter was calculated using the determined area of each wetland polygon. According to DAHLKE (2003) a threshold of 1.75 can be used to differentiate all slope wetlands based on their shape into the types "depression" (quotient $\leq$ 1.75) and "channel" (quotient > 1.75).

To delineate the surface hydrological regime, surface inflow, throughflow, and outflow were determined for each wetland based on calculating the maximum flow accumulation for each wetland polygon. Therefore the contributing area, i.e. number of upslope cells draining into a polygon multiplied by grid size, was calculated. Based on field investigations it was found that a flow channel starts to develop at a contributing area of at least 10 ha (160 grid cells). That means that wetlands with a hydrological catchment smaller than 10 ha do not have a surface inflow and outflow channel and therefore belong to wetland type "no surface inlet and outlet". Wetlands larger than 10 ha were classified as wetlands with "surface outlet only" while wetlands with a maximum inflow value of more than 10 ha in the upslope position and a value of more than 47 ha in the downslope position show a typical throughflow hydrological regime and are classified as wetland "with surface inlet and outlet".

- **Plateau wetlands**

According to the hydro-geomorphic classification, plateau wetlands are found on both hilltops and plateaus within the study area. To delineate these wetlands, a combination of the terrain attributes "relative hillslope position" and "height above drainage channel" was applied (DAHLKE *et al.*, 2005). Whilst the "relative hillslope position" parameter is convenient for dividing stretched slopes, it shows limitations in areas with low relief because of small scale artifacts. Combining both attributes, all plateau areas were delineated using values of more than 15 m for "height above drainage channel" and more than 1.2 for "relative hillslope position" (0.0 is midslope). All potential plateau wetlands were localized by delineation of depressions based on calculation and reclassification of the terrain attribute "relative profile curvature". As described above this parameter is very sensitive to local changes in terrain. Thus small depressions with a minimum size of 4 pixels (2 500 m^2) could be delineated, based on a threshold of -10.

At the second classification level each wetland polygon was reclassified into the two wetland types "depression" and "no depression" based on the "depth" of the depression. Wetlands located in deep concave depressions (curvature values $\leq$ -15) were assigned to the class "depression" while wetlands positioned in concave to intermediary shaped areas with curvature values ranging from -10 to -15 were classified as "no depression".

The differentiation of "surface hydrological regime" was performed in the same way as for slope wetlands. All plateau wetlands smaller than 32 pixels were classified as "no surface channel inflow or outflow" confirming field observations within the study area.

6.4.3.2 Accuracy Assessment

A comprehensive accuracy assessment of the created wetland map was performed. Herein, the map was compared with detailed land use information given by the Environmental Conservation Database (ECDB), remote sensing data and field survey.

First, the wetland map was overlaid with a wetland map received from the ECDB mapping. Using confusion matrices, the extent and the position of main wetland types were evaluated. In addition, delineated wetlands were visually compared with Landsat TM data acquired on 9 April 1999. Since remote sensing data reflect soil moisture and vegetation conditions on a specific date, those data can only be used as supplement information for accuracy assessment. Nevertheless, the comparison showed that especially for the large valley bottom wetlands a high agreement could be confirmed overlaying satellite data with the wetland map.

Since these efforts provided insufficient information on the spatial distribution of each wetland type, a supplementary field-based verification was conducted, producing maps with test areas for all wetland types. These wetland maps were verified by field mapping utilizing GPS survey and vegetation and soil analysis as described in Section 6.2. From these maps, 27 wetlands were selected and surveyed aiming to measure their extent, perimeter, diameter, and terrain features such as slope and aspect. These data have been compared to the wetlands map using difference maps performed from GIS overlay analysis.

6.4.4 Land Use Mapping

Multi-scale and multi-temporal land use information was inferred from different sources. As shown in Figure 6.10 land use was provided by merging classified multi-temporal satellite data with wetland maps created from terrain analysis (DAHLKE, 2003), field maps and forest stand data (Section 6.4.4.1). Land use of the Weatherley basin was provided by field mapping (Section 6.4.4.2).

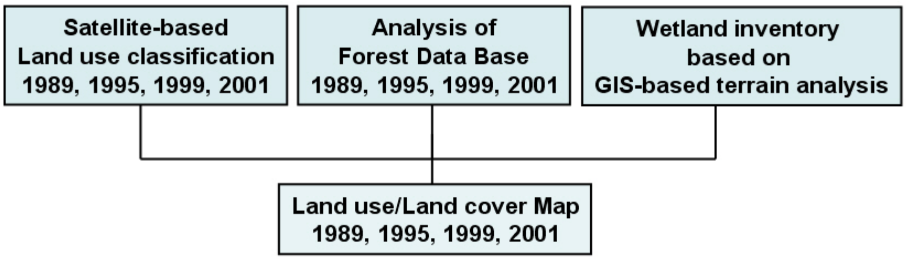


Figure 6.10: Methods used to provide land use and land cover data for the Mooi basin.

6.4.4.1 Land Use Classification for the Mooi Basin

Based on the methodological approach presented by HELMSCHROT (1999), Landsat TM-scenes from 1989, 1995, 1999 and 2001 were classified using Erdas/Imagine 8.3 in order to provide land use classifications at the catchment level. Addressing experiences from former studies (HELMSCHROT, 1999), a simplified hierarchic 3–level scheme (Table 6.3) was developed with respect to the needs for the subsequent HRU-delineation (FLÜGEL, 1995). In this scheme, forest plantations were classified in order to differentiate different species and ages which are related to different canopies, growth rates and rooting depths. Additionally, deforested or harvested areas were separately considered, since these areas are usually characterized by dense litter layers with fairly high interception storage capacities (PUTUHENA & CORDERY, 1996). Moreover, clearcuts are usually replanted as soon as possible. Indigenous forest class combines natural forests and alien vegetation like wattle which usually has similar closed canopies like natural forests. Grassland areas were differentiated in terms of their densities. Highly eroded grassland (more than 60 % degraded) is considered as being open grassland, while moderate grassland is characterized by a degradation of 20 – 60 %. Closed grassland (less than 20 % degraded) is very dense grassland in very good condition. Agriculture was divided into cultivated (i.e. planted areas) and non-cultivated areas. The latter are areas which are prepared for planting or plowed areas. Bare rock is defined as rocky outcrops, while bare soil areas are characterized by less vegetation. Wetlands were classified according to the wetland classification approach developed in this study. Consequently, wetlands show similar vegetation pattern, but differ in terms of their relief position, size and hydrological functioning. The water class comprises all open water bodies.

Initially, necessary rectification to a unique geodetic system (UTM, Zone 35, Spheroid: WGS 84) was carried out by 98 GPS-measured ground control points using a polynomial second order transformation with nearest neighbor resampling. Mean RMS errors less than one pixel resolution were achieved. This resulted in homogeneous data sets with a spatial resolution of 25 x 25 m². In a second step, data enhancement was done by extended preprocessing procedures including atmospheric correction, terrain correction, filtering and contrast stretching in order to avoid misclassifications due to illumination and relief effects.

Table 6.3: Level-based Classification Scheme.

ID	Level 1	ID	Level 2	ID	Level 3
1	Forest Plantations	11	Pine	111	< 3 years
				112	3 – 6 years
				113	7 – 10 years
				114	11 – 15 years
				115	16 – 20 years
				116	> 20 years
		12	Eucalyptus	121	< 1 year
				122	1 – 2 years
				123	3 – 4 years
				124	> 4 years
		13	Poplar		
		14	Deforested		
2	Ind. Woodlands				
3	Grassland	31	Closed (< 20% degraded)		
		32	Moderate (20-60% degraded)		
		33	Open (> 60% degraded)		
4	Agriculture	41	Cultivated		
		42	Non-cultivated		
5	Bare rock				
6	Bare soil				
7	Wetlands	71	Plateau Wetlands		
		72	Slope Wetlands		
		73	Valley Bottom Wetlands		
8	Water				

A hybrid classification approach was chosen for the land use classification. The approach considered an unsupervised ISODATA clustering to get an overview of the spectral contents of the images. This information was used to produce class signature files. Based on a complex signature analysis this catalogue and the information derived from the land use mapping were utilized to define training areas with unimodal spectral characteristics. Capability approval was carried out at all stages of the signature evaluation using covariance matrices and mean vector analyses. The classification procedure was performed by using a Maximum-Likelihood-Classifier using 6 bands in the visible, infrared and short wave infrared spectra. Classification results were verified by statistical comparison with class-weighted reference areas for each object class. Hereby, data from the forest data base as well as from field mapping during several campaigns provided a reliable validation data base. Finally, a post-processing of the classification result was done by reclassifying inaccurately classified or „mixed“ pixels utilizing several filter algorithms to improve the classification accuracy.

The classification accuracies were evaluated at two levels, i.e. after the Maximum Likelihood Classification and at different stages during the post-processing. This was done by comparing the percentage of pixels correctly labeled with those incorrectly classified for each class using confusion matrices. Then the overall accuracy for the level one classification was determined to exceed 90% and the accuracies for the level two and three classifications were determined to exceed 85%. Finally, the accuracy of wetland and forest plantation classes have been significantly enhanced by merging the classification results with the wetland distribution map and age-related stand data from the forest data base in order to obtain the most accurate classification results.

More details on the methods used for the classification and accuracy assessment and a discussion of their potential and limits can be found in HELMSCHROT (1999).

6.4.4.2 Land Use Information for Weatherley

Distributed models need detailed digital spatial information on land use dynamics, in particular in cases where the effect of land use change should be simulated. As a consequence, land use and vegetation maps for Weatherley have been delineated based on the digitization of field information mapped in 1997 and 2000. In the field, several types of wetlands and non-wetland areas were differentiated using indicators such as vegetation composition, hydromorphic signs found in soil drillings and degree of saturation. Therefore, a field guide incorporating descriptions of common grass and wetland species, indicator assessment and wetland delineation techniques was developed.

To evaluate afforestation dynamics, areas which are considered for planting have been extracted from the forest data base and were overlaid on the created map. The extent of these areas and planted species was verified by field observations utilizing GPS equipment. In addition, scenarios have been developed addressing the planting of all grassland areas which have the potential to be planted with pine or eucalyptus. As result, four layers representing different scenarios of land use could be used for the delineation of HRUs (Section 7.2.4).

6.4.5 Delineation of Spatial Model Entities

As discussed in the literature, even the most physically-based models cannot represent the heterogeneity and complexity of the processes occurring in a catchment (HORNBERGER *et al.*, 1985). Consequently, the model theory provided different perspectives on the spatial discretization of model entities for hydrological modeling purposes (BEVEN, 2001a). A promising approach was seen in the concept of hydrological similarity of model units which describe hydrological units with a similar water balance or similar runoff generation processes, whether by surface or subsurface water flows. Hereby, the model is used based on a distribution of functional hydrological responses in the catchment. As emphasized by BEVEN (2001a) these distributed function models are limited due to their accuracy, since they are clearly an approximation of fully realistic distributed models. Nevertheless, they offer the possibility to delineate spatially distributed model entities which can be hydrologically modeled separately. Moreover, their conceptual storages and process dynamics can be linked to each other by water flux routing. One of these approaches utilizing distributed model entities is known as the **H**ydrological **R**esponse **U**nits (HRUs) approach (FLÜGEL, 1995). Since the approach of HRUs was utilized for this study, it is discussed in more detail in the next sections.

6.4.5.1 Conceptual Approach of Hydrological Response Units (HRUs)

The original concept of HRUs treats them as homogeneous areas which are characterized by topographic parameters like elevation, aspect, and slope and physiographical parameters like geology, soil, land use, vegetation type, and rainfall distribution (LEAVESLEY *et al.*, 1983). According to MICHL (1999), this HRU concept is considered as being deterministic, but he also emphasizes that little attention is given to the spatial variability within an HRU. Although landscape attributes are incorporated, these parameters only represent an integral value of the landscape unit. For example, a given Leaf Area Index (LAI) for a specific HRU is only representing an averaged LAI for a specific vegetation type, even though the LAI is assumed to be variable within specific vegetation types. A further deficit of the HRU concept by LEAVESLEY *et al.* (1983) is recognized, since the delineated HRUs need to be directly connected to a stream channel segment, so that water fluxes from one HRU to another HRU are not possible.

An enhancement of the HRU concept has been introduced by FLÜGEL (1995) who considered HRUs as being homogenous with respect to their hydrologic response, and thereby as representing specific landscape units with a similar hydrological process dynamics. According to FLÜGEL (1995) a thorough system analysis approach is essential to identify dominant process dynamics in the heterogeneously structured soil-vegetation-atmosphere (SVAT) interface, and as a consequence thereof to analyze and simulate processes by preserving the three-dimensional physiographic heterogeneity of a hydrological system such as a river basin. FLÜGEL (1995, 1997), MICHL (1999), BONGARTZ (2001) and others found that topography, soils, geology, rainfall, vegetation and land use provide the most appropriate physiographic basin properties to describe process dynamics within a catchment. Thus, HRUs are defined as *"distributed, heterogeneously structured (model) entities having a common climate, land use, and underlying pedo-topo-geological associations controlling their hydrological dynamics"* (FLÜGEL, 1995). The variation of the hydrological process dynamics in a specific HRU is assumed to be relatively small compared with the dynamics in a different HRU. As a consequence, each HRU is characterized by a set of parameters representing the conceptual storages and runoff generation dynamics. As pointed out by BEVEN (2001a), the identification and characterization of processes and storages controlling the hydrological dynamics are strongly related to the temporal and spatial scale, i.e. as the HRU element scale and the temporal resolution respectively become finer, the description of hydrological processes and storage functions become more physically-based (BEVEN, 2001a). In contrast, the spatial homogeneity of an HRU gets poorer as the HRU gets larger. For that reason, the modeler has to consider the scale dependence of the parameter values which are used for the model application.

FLÜGEL (2000) emphasizes that spatially distributed HRUs need to be topologically routed applying GIS-based tools to cascade flow components from the upper areas down to an underlying HRU or a river reach. In this context, STAUDENRAUSCH (2001) developed, implemented and validated an enhanced, topological HRU concept. As a result, STAUDENRAUSCH (2001) introduced a GIS-based toolkit which can be used to combine the advantages of the scale-independency of process dynamics with detailed topological routing techniques.

6.4.5.2 GIS-based Delineation of HRUs

HRUs are typically delineated by overlaying different types of information using a Geographical Information System. Since HRUs can be based on regular elements where grids are used or irregular in shape when vector files are overlaid, data are usually stored as either raster or vector data layers. As shown in Figure 6.11, each data layer, represents a specific type of information such as topography, soil distribution, geology, rainfall distribution, vegetation types, and landuse. Based on a thorough system analysis and literature review, each data layer can be attributed to a set of parameters in order to represent specific properties within one specific class (see Figure 6.11). For example, a specific soil type is assumed to be homogeneous, and thereby can be associated with a specific texture or unsaturated conductivity that is derived from soil analysis.

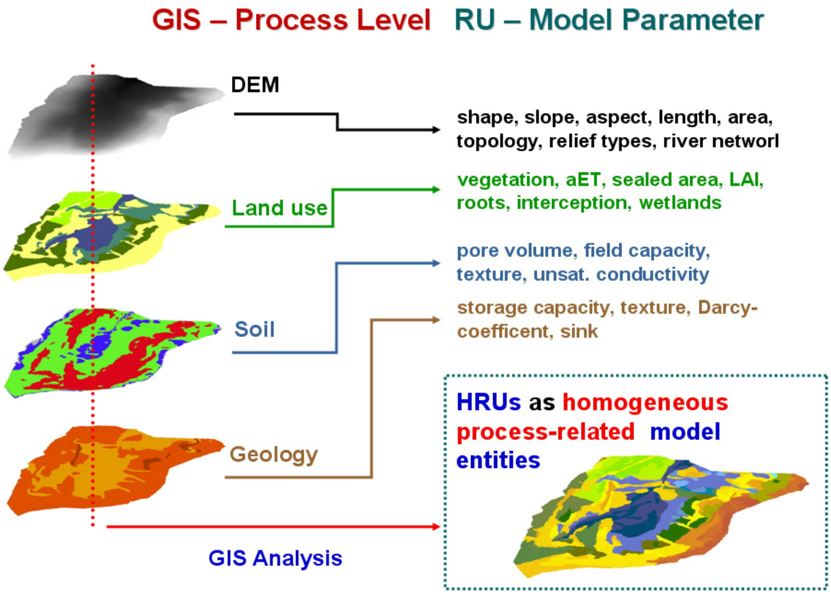


Figure 6.11: Schematic representation of the HRU delineation process.

Once those data layers are identified which are assumed to be important for the hydrological process dynamics, these are overlaid with respect to the modeler's specific needs. The resulting HRU distribution map then represents HRUs in which each HRU incorporates the prospective parameters of each specific class provided by the single layers. As shown by numerous studies (BONGARTZ, 2001; FLÜGEL, 1995; MICHL; 1999) the number of HRUs is strongly controlled by the number of input data layers and their respective classes. According to these authors, the total number of HRUs should be reduced by merging similar HRUs depending on their size and physiographical properties.

Since a comprehensive system analysis is essential to delineate HRUs which are preserving the three-dimensional physiographic heterogeneity of a drainage basin, the prospective catchments of the Weatherley Creek and the Mooi River have been intensively studied with respect to their hydrological system dynamics during several field campaigns between 1997 and 2005. Therefore, soil analysis and vegetation studies at plot and catchment scales and the monitoring and modeling of subsurface flow at hillslope scale (LORENTZ *et al.*, 2004) have been combined to derive scale-related information on dominant hydrological processes within the catchments. In addition, time series of hydro-meteorological data and discharge hydrographs have been analyzed to identify hydrologically relevant parameters at a catchment scale. From these efforts, it was found that land use, soils, geology and topographic features are key parameters influencing streamflow generation, evapotranspiration and storage dynamics. Thus, the HRUs were delineated by GIS overlays for each basin utilizing data layers of land use including different wetland types and forests, slope, exposition, soils and geology as well as a topographic unit. Since land use information was available for different stages, scenarios of landscape dynamics were considered in the HRU delineation process in order to satisfy the pre- and post afforestation conditions.

6.5 System Modeling Approach

The modeling is an essential part of the integrated research approach presented. This section refers to the model approaches used in this study. Section 6.5.1 relates to the concepts, processes and parameterization of the plant growth model (3-PG) which was applied to simulate forest growth dynamics of pine and eucalyptus in the study area. Section 6.5.2 provides a theoretical and methodical background regarding the structure, the implementation of hydrological processes, the model building procedure and parameterization of the hydrological model PRMS which has been applied to model landscape dynamics and their spatio-temporal effects on catchment and wetland hydrology.

6.5.1 Plant Growth Modeling

According to WHITE *et al.* (2000) climate driven, process based models of primary production provide a framework to estimate biomass accumulation and forest productivity over resource gradients. Such models regionalize conventional point estimates of biomass over large areas by indicating where field data is inadequate or potentially biased. In this study, the physically-based **P**hysiological **P**rocesses in **P**redicting **G**rowth model (3-PG), version 2.0, was applied to simulate forest growth dynamics of forest plantations within the North Eastern Cape, and thereby to derive parameters that have been used to calibrate and validate the catchment model for forest scenarios. Section 6.5.1.1 reviews the conceptual structure of the model considering basic features and components and Section 6.5.1.2 describes processes and their mathematical implementation in 3-PG in detail. The basic principles of model parameterization are discussed in Section 6.5.1.3.

6.5.1.1 Conceptual Design of 3-PG Model

The 3-PG model introduced by (LANDSBERG & WARING, 1997) is a process-based model that has been developed to simulate growth and productivity of commercial forest plantations. The model has been successfully applied to forest plantations in Australia and New Zealand (LANDSBERG & WARING, 1997; SANDS & LANDSBERG, 2002; WHITE *et al.*, 2000), South America, South Africa and North America (ALMEIDA *et al.*, 2004; COOPS *et al.*, 2001; DYE *et al.*, 2004) and thereby has shown its great potential to be used for different environments, scales and forest species. Based on these studies the developers were able to improve the model continuously by implementing new algorithms and extensions. DYE (2001) improved the model by integrating forest management practices like thinning as well as day length prediction based on latitudes and time of year. The potential of parameter estimation methods like PEST (**P**arameter **EST**imation; DOHERTY, 2002), a free software package based on the MARQUARDT algoritm (MARQUARDT, 1963) has been studied by SANDS (2004). ESPREY *et al.* (2004) performed a thorough sensitivity analysis to verify the integrity of model parameters used in 3-PG. A modified version, 3-PG Spatial, has been developed to study forest productivity across landscape areas (COOPS *et al.*, 1998; COOPS & WARING, 2001). In addition several studies have shown the potential of linking 3-PG and remote sensing data analysis to estimate forest growth capacities (COOPS & WARING, 2000) and productivity (COOPS, 1999) on a regional scale.

Conceptually, the model is based on a number of established biophysical relationships and constants that can be derived from literature or standard field measurements. Generally, the model requires site and species related parameters as well as basic climate data to predict the time-course of stand development in terms of biomass production, tree water use and available soil water. 3-PG can be applied to all kinds of relatively homogeneous forests including commercial forest plantations, even-aged stands and closed natural forests. It is a generic stand model since its structure is neither site- nor species-specific, but it must be parameterized for individual species. The model, however, works with the assumption of optimal growth conditions for each species.

3-PG is based on five interlinked sub-models simulating: ***i)*** the assimilation of carbohydrates (biomass production); ***ii)*** the distribution of biomass between foliage, roots and stems (biomass allocation); ***iii)*** the determination of stem number incorporating stem mortality); ***iv)*** soil water balance and ***v)*** conversion of biomass into variables representing stand characteristics. Figure 6.12 shows the structure of 3-PG and the interrelation of its variables and processes schematically.

6.5.1.2 Process Implementation in 3-PG

This section summarizes the basic processes and their implementation in 3-PG. This description is primarily based on model specifications published by LANDSBERG & WARING (1997), SANDS (2004) and SANDS & LANDSBERG (2002).

6.5.1.2.1 Basic symbol Description

The model requires monthly means of daily total radiation (Q in MJ m^{-2} d^{-1}), mean air temperature T_a (°C), day-time atmospheric vapor pressure deficit VPD (mbar), monthly rainfall R (mm $month^{-1}$) and frost days d_F ($month^{-1}$).

The state variables of 3-PG are biomass of foliage (WF), stem (WS), and root (WR) as dry matter (t_{DM} ha^{-1}), stem numbers or stocking (N in ha^{-1}) and available soil water (θ_s in mm). Stem biomass WS includes bark and branches, but 3-PG is able to reduce this by the implemented age-dependent branch-and-bark fraction (p_{BB}). 3-PG considers a day as a basic time unit (t), and the rate of change of the state variables with respect to time can be written as a set of coupled differential equations. Nevertheless, 3-PG is usually utilized by a set of difference equations with a default time step of one month, since several relationships implemented in 3-PG are performed on a time step of a month rather than a day. The following description considers difference equations, and parameters with time in their units that are conveniently given with the month as the temporal unit.

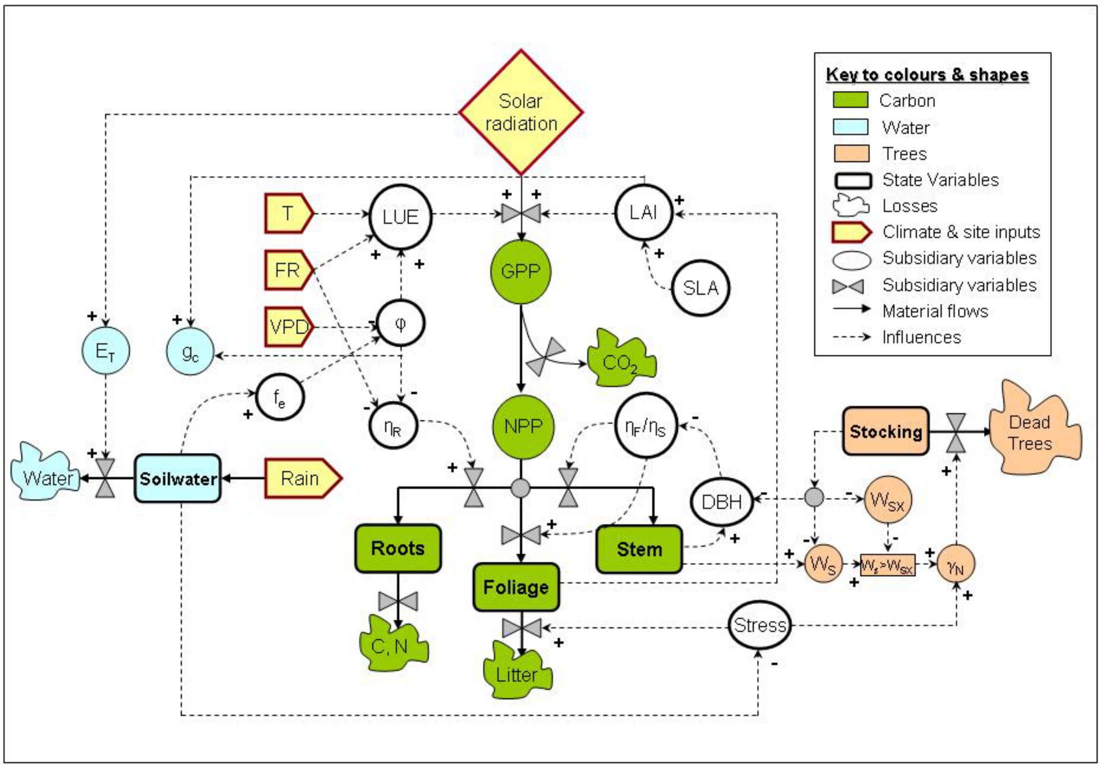


Figure 6.12: Schematic structure representing variables and processes considered in 3-PG model (based on SANDS, 2004).

Internal variables are either derived from the state variables or are explicitly age-dependent (SANDS, 2004). Stand averages of the biomass pools w_i are expressed as

$$w_i = \frac{1000 \cdot W_i}{N} \qquad [6.4]$$

where the index i denotes foliage (F), stem (S) or root (R).

Stand leaf area index (L in m^2 m^{-1}), and the measure B (cm) of tree size are important stand attributes used for the estimation of interception, and biomass productivity. The measure B can be either the arithmetic mean DBH or the corresponding quadratic mean diameter (qDBH), where qDBH is preferred. In 3-PG, B is derived by inverting an allometric relationship between mean stem mass per tree w_S and B. The choice of B as DBH or qDBH depends on which of these observations is used when 3-PG is parameterized. Other stand-level variables of significance to the forest manager are calculated from the state variables as described in Section 6.5.1.2.8.

6.5.1.2.2 Carbon Balance

The carbon-balance is calculated in 3-PG using a modified equation introduced by MCMURTRIE & WOLF (1983). Using dx as the change in any quantity x over a time interval of dt days, the 3-PG carbon balance equations are expressed as

$$\mathrm{d}W_F = \eta_F \cdot P_n - \gamma_F \cdot W_F \cdot \mathrm{d}t - m_F \cdot \left(\frac{W_F}{N}\right) \cdot \mathrm{d}N \qquad [6.5]$$

$$\mathrm{d}W_R = \eta_R \cdot P_n - \gamma_R \cdot W_R \cdot \mathrm{d}t - m_R \cdot \left(\frac{W_R}{N}\right) \cdot \mathrm{d}N \qquad [6.6]$$

$$\mathrm{d}W_S = \eta_S \cdot P_n - m_S \cdot \left(\frac{W_S}{N}\right) \cdot \mathrm{d}N, \qquad [6.7]$$

where P_n is Net Primary Production (NPP) [t ha^{-1} d^{-1}],
η_i is the fraction of NPP allocated to the i^{th} pool,
γ_F is the litterfall rate [d^{-1}],
γ_R is the root turnover rate [d^{-1}],
N is the stand stocking [trees ha^{-1}],
m_i is the fraction of the biomass per tree (Wi/N) in the ith pool that is lost when a tree dies. Tree mortality is considered in Section 6.5.1.2.5.

The NPP is derived from intercepted radiation, as determined by *L* and radiation incident above the canopy, through

$$P_n = 0.552 \cdot \alpha_C \cdot Y \left(1 - e^{\frac{kL}{\zeta}}\right) \cdot \zeta \cdot \overline{Q} \cdot \mathrm{d}t \qquad [6.8]$$

where $\overline{Q}$ is the mean daily solar radiation above the canopy over the time period d*t* [MJ m^{-2} d^{-1}],
ζ is the fractional ground cover by the canopy,
α_C is the canopy quantum efficiency modified by multipliers that take account of environmental effects as described in Section 6.5.1.2.5 [mol mol^{-1}],

k is the light extinction coefficient and,
Y Y is the (constant) ratio of NPP to GPP.

The factor 0.552 was introduced to combine the conversion of total radiation into photosynthetic active radiation PAR (2.3 mol MJ^{-1}), of mol C into wood (24 g_{DM} mol^{-1}), and g m^{-2} to t ha^{-1} (10^{-2}). Stand Leaf Area Index (LAI) is described as follows

$$LAI = 0.1 \cdot \sigma \cdot W_F \qquad [6.9]$$

where σ (m^2 kg^{-1}) is the age-dependent specific leaf are (*SLA*) and the factor 0.1 converts t ha^{-1} to kg m^{-2}.

6.5.1.2.3 Growth Modifiers

Since environmental effects on biomass production need to be considered, dimensionless modifiers f_i ($0 \le f_i \le 1$) multiplicatively applied to the canopy quantum efficiency are introduced. Those effects are expressed as effects of mean air temperature (through f_T), frost days per month (through f_F), atmospheric vapor pressure deficit (VPD through f_D), available soil water (through f_θ), site nutrition (through f_N), and stand age (through f_{age}). Then canopy quantum efficiency coefficient (mol C (photon)$^{-1}$) is computed as

$$\alpha_C = \alpha_{Cx} \cdot \varphi \; f_T f_F f_N \qquad [6.10]$$

$$\varphi = f_{age} \cdot \min\{f_D, f_\theta\} \qquad [6.11]$$

where φ (known as physical modifiers) also affects canopy conductance. In summary growth modifiers are calculated through

$$f_T(t_\alpha) = \left(\frac{t_\alpha - t_{\min}}{t_{opt} - t_{\min}}\right) \cdot \left(\frac{t_{\max} - t_\alpha}{t_{\max} - t_{opt}}\right)^{\frac{t_{\max} - t_{opt}}{t_{opt} - t_{\min}}} \qquad [6.12]$$

$$f_F(d_f) = 1 - k_F \cdot \left(\frac{d_f}{30}\right) \qquad [6.13]$$

$$f_N(FR) = 1 - (1 - f_{N0}) \cdot (1 - FR)^{n_{fN}} \qquad [6.14]$$

$$f_D(D) = e^{-k_D D} \qquad [6.15]$$

$$f_\theta(\theta_S) = \frac{1}{1 + [(1 - \theta_S / \theta_{Sx}) / c_\theta]^{n_\theta}} \qquad [6.16]$$

$$f_{age}(t) = \frac{1}{1 + [(t / t_x) / r_{age}]^{n_{age}}} \qquad [6.17]$$

where

$t_{a,\min,opt}$	are various temperature modifiers,
k_F	is the number of days production lost for each frost day,
d_f	is mean number of days production,
FR	is the fertility rating,
n_{f_N}	is power of (1-FR) in f_N,
m_0	is value of m when $FR = 0$,
f_{N0}	is value of f_N when $FR = 0$,
k_F	defines stomatal response to VPD,
θ_S, θ_{Sx}	is available soil water and minimum available soil water,

c_θ, n_θ	is moisture ratio deficit which gives f_θ = 0.5 and power of moisture ratio deficit in f_θ,
n^{age}	is power of relative age in f_{age},,
t, t_x	are stand age and maximum stand age used to compute relative age.

Hence, the temperature modifiers need to be estimated or assigned values, and these modifiers are multiplicative.

6.5.1.2.4 Biomass Allocation

The biomass allocation ratios η_i are calculated using

$$\eta_R = \frac{\eta_{Rx} \cdot \eta_{Rn}}{\eta_{Rn} + (\eta_{Rx} - \eta_{Rn}) \cdot m \cdot \varphi} \qquad [6.18]$$

$$\eta_S = \frac{1 - \eta_R}{1 + p_{FS}} \qquad [6.19]$$

$$\eta_F = p_{FS} \cdot \eta_S \qquad [6.20]$$

where η_{Rn}, η_{Rx} are the minimum and maximum root allocation ratios,
p_{FS} is the ratio of foliage and stem allocation,
m determines the effects of site fertility on allocation through

$$m = m_0 + (1 - m_0) \cdot FR \qquad [6.21]$$

where m_0 is a parameter and FR ($0 \le FR \le 1$) is the site fertility rating.

The ratio p_{FS} (foliage/stem allocation) is derived by an allometric relationship of mean stem diameter *B,* e.g. quadratic mean diameter at breast height (cm). Latter is given from an allometric relationship between *B* and mean stem mass w_S (kg) expressed as sum of stem, branch and bark. Those relationships are represented by equations

$$p_{FS} = a_p \cdot B^{n_p} \qquad [6.22]$$

$$w_S = a_S \cdot B^{n_S} \qquad [6.23]$$

where the *a*'s and *n*'s are parameters. SANDS & LANDSBERG (2002) showed how a_p and n_p are expressed in terms of the values p_2 and p_{20} of p_{FS} at B = 2 and 20 cm, and then used p_2 and p_{20} as parameters. After the initialization of Equation 6.23 the mean stem diameter is related to stand stem biomass and stocking through

$$B = \left(\frac{1000 \cdot W_s}{a_S \cdot N} \right)^{\frac{1}{n_S}} \qquad [6.24]$$

where w_S is 1 000W_S/N, and the factor 1 000 converts tonnes to kilograms.

6.5.1.2.5 Stem Mortality

While random or stress-induced tree mortality is density-independent, self-thinning processes are considered to be density-dependent. A fraction m_i of the mean biomass w_i in the i^{th} biomass pool is removed, when a tree dies or is harvested. In most cases is $m_i \leq 1$, since dead trees tend to be suppressed. The values of m_i for density-dependent and density-independent mortality are assumed to be the same. Density-independent mortality is computed by

$$\mathrm{d}N = -\gamma_N \cdot N \cdot \mathrm{d}t \qquad [6.25]$$

where γ_N (d^{-1}) is the mortality rate. Currently, γ_N is age-related, but a later version of 3-PG will implement stress related effects on γ_N as well.

Density-dependent mortality is computed by applying the self-thinning rule as discussed by LANDSBERG & WARING (1997). Thus, it is ensured that the mean single-tree stem biomass w_S does not exceed the maximum permissible single-tree stem biomass w_{Sx} (kg tree^{-1}). The self-thinning rule calculates w_{Sx} as a function of the actual stocking rate as follows

$$w_{Sx} = w_{Sx1000} \cdot \left(\frac{1000}{N}\right)^{n_N}, \qquad [6.26]$$

where n_N is the exponent (usually 3/2) and w_{Sx1000} (kg tree^{-1}) is the value of w_{Sx} when the stem number is 1 000 trees ha^{-1}. (If the stem number is 1 000 trees ha^{-1}, then the total stand-level stem biomass where self-thinning starts is about w_{Sx1000} t ha^{-1}). The need for self-thinning is checked at the end of each time step, and if $w_S > w_{Sx}$, the self-thinning process is initiated as follows. If W_S^+ and N^+ are stem biomass and stocking rate after self-thinning, then

$$W_S^{\ +} = W_S - m_S \cdot (N - N^+) \cdot \frac{W_S}{N} \qquad [6.27]$$

and after self-thinning the stand must satisfy the self-thinning law, i.e.

$$\frac{W_S^{\ +}}{N^+} \leq w_{Sx1000} \cdot \left(\frac{1000}{N}\right)^{n_N} \cdot 10^{-3} \qquad [6.28]$$

Equations 6.27 and 6.28 are explicit equations for N^+ and W^+. They are applied iteratively to ensure the self-thinning law is satisfied for the new state.

6.5.1.2.6 Evapotranspiration and Soil Water Balance

The soil water balance model in 3-PG is determined by a balance between evapotranspiration E_T, rainfall R_P and irrigation R_I, and allows canopy interception. All components are expressed in mm per month. The water balance equation considered in 3-PG is

$$\Delta\theta_S = (1 - i_R) \cdot R_p + R_I - E_T \qquad [6.29]$$

where i_R is the fraction of rainfall intercepted, and subsequently evaporated from the canopy. Interception increases with canopy LAI up to maximum i_{Rx} and thereby i_R can be determined by

$$i_R = i_{Rx} \min\left\{1, \frac{LAI}{LAI_{ix}}\right\} \qquad [6.30]$$

where LAI_{ix} is the LAI with maximum interception.

According to SANDS (2004), available soil water θ_S is bound below by a minimum allowed available soil water θ_{SX} (mm), since any excess of θ_S over θ_{SX} is lost as run-off or deep soil drainage. This is usually zero but can be non-zero to represent access to a water table or to simulate an irrigation strategy based on application of water when available soil water falls below a certain value.

Evapotranspiration is calculated using the PENMAN-MONTEITH formula, and therefore is controlled by the parameters solar radiation, mean day time (*VPD*) and canopy conductance g_C (m s^{-1}). Canopy conductance is affected by stand age, VPD and soil water through the physiological modifier φ. It increases with increasing LAI up to a maximum g_{Cx} (m s^{-1}):

$$g_C = g_{Cx} \cdot \varphi \min\left\{1, \frac{LAI}{LAI_{Cx}}\right\} \qquad [6.31]$$

where LAI_{Cx} is the LAI value corresponding to maximum conductance. The PENMAN-MONTEITH formula requires various parameters that are physical in nature and have standard values, e.g. density of air and latent heat of vaporization of water. Since it considers the fact that transpiration occurs only during daylight hours, the day length h (s d^{-1}) is computed for the time of year depending on latitude.

6.5.1.2.7 Age-dependent Variables

As discussed by LANDSBERG & WARING (1997) there are a variety of parameters used in 3-PG that are strongly related to stand age and therefore provided by empirical relationships. These species-specific parameters are the leaf litterfall rate γ_F, stress-free density-independent mortality rate γ_N the specific leaf area σ, the fraction of stem biomass in bark and branches p_{BB}, and basic density ρ (t m^{-3}). Litterfall rate is given by

$$\gamma_F(t) = \frac{\gamma_{F1} \cdot \gamma_{F0}}{\gamma_{F0} + (\gamma_{F1} - \gamma_{F0}) \cdot e^{-(\frac{t}{t_{\gamma F}}) \cdot \ln(1 + \frac{\gamma_{F1}}{\gamma_{F0}})}} \qquad [6.32]$$

where γ_{F0} and γ_{F1} (d^{-1}) are litterfall rates at the age of zero and for mature stands, and $t_{\gamma F}$ is the age where the litterfall rate is ½$(\gamma_{F0} + \gamma_{F1})$.

The other age-dependent variables are computed by common functional equations where only the parameters differ. Define the function f_e by

$$f_e(t, f_0, f_1, t_f, n) = f_1 + (f_0 - f_1) \cdot e^{-(\ln 2) \cdot \left(\frac{t}{t_f}\right)^n} \quad [6.33]$$

where f_0 and f_1 are the values of f_e when at age 0 and for mature stands, respectively, t_f is the age at which $f_e = ½(f_0+f_1)$, and n is a constant (usually 1 or 2). Then

$$\gamma_N(t) = f(t, \gamma_{N0}, \gamma_{N1}, t_{\gamma N}, n_{\gamma N}) \quad [6.34]$$

$$\sigma(t) = f(t, \sigma_0, \sigma_1, t_\sigma, 2) \quad [6.35]$$

$$p_{BB}(t) = f(t, p_{BB0}, p_{BB1}, t_{BB}, 1) \quad [6.36]$$

$$\rho(t) = f(t, \rho_0, \rho_1, t_\rho, 1) \quad [6.37]$$

and the meaning of the parameters is implied by the dependent variable and the definition of the function f_e (Equation 6.33).

6.5.1.2.8 Stand-level Variables

Stand-level variables such as stem diameter B (cm), basal area A (m² ha⁻¹), height H (m), and stem volume V_S (m³ ha⁻¹) are derived from predicted stem mass and stocking using simple empirical relationships. When mean stem diameter B is provided from Equation 6.24, basal area is computed by

$$A = \pi \cdot \left(\frac{B}{200}\right)^2 \cdot N \quad [6.38]$$

Basal area estimated by Equation 6.38 is unbiased when Equation 6.23 is parameterized using observed quadratic mean diameter as B. Mean height H is estimated from the allometric relationship

$$H = a_H \cdot B^{n_{HB}} \cdot N^{n_{HN}} \quad [6.39]$$

where a_H is a constant and B^{nHB} and N^{nHN} are parameters related to DBH and stocking rate.

Stem volume V_S (e.g. utilizable volume, total volume over or under bark, etc.) can also be computed by an allometric relationship

$$V_S = a_v \cdot B^{n_{VB}} \cdot N^{n_{VN}}, \quad [6.40]$$

where a_V is a constant and B^{nHB} and N^{nHN} are parameters related to DBH and stocking rate. Alternatively, stand volume can be determined from total stem mass, basic density and the branch and bark fraction using

$$V_S = \frac{(1 - p_{BB}) \cdot W_S}{\rho} \quad [6.41]$$

where p_{BB} and ρ are given by Equation 6.36 and 6.37. Because of uncertainties due to unaccounted age- and site-related effects on the prediction of p_{BB} and ρ, it is recommended to use Equation 6.40.

6.5.1.3 Model Approach

The aim of the plant growth modeling with 3-PG is to provide plant-biophysical parameters which can be used for the parameterization of the hydrological model. Analyzing the forest data base, it was found that the majority, i.e. almost 95 % of the NECF estates were planted with *Pinus patula, Pinus radiata* and several Eucalyptus species. Consequently, plant growth modeling efforts have been focused on these species. For the same reason, these three species were intensively investigated in the field (see Section 6.2). As a result, numerous empirical data were available and could be used for model parameterization and moreover to evaluate forest growth with respect to landscape dynamics.

The methodological approach for the modeling of forest dynamics is illustrated in Figure 6.13 and discussed in more detail in the following sections.

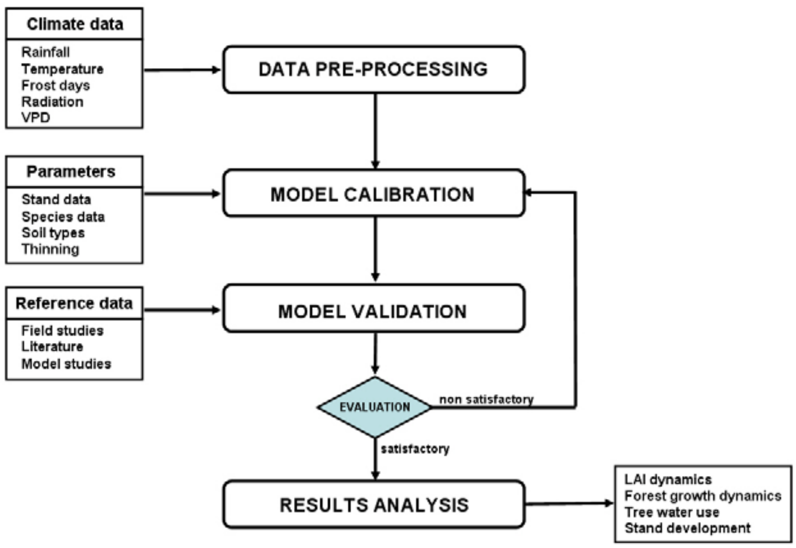


Figure 6.13: Schematic illustration of the methodological approach applied to model plant growth of pine and eucalyptus stands with 3-PG.

6.5.1.3.1 Data Pre-Processing

As a first step, the user needs to define the number of years for the modeling. For this study, different periods were chosen to satisfy species-related differences in rotation cycles. A 15 year period (1983-1998) was chosen to simulate *Eucalyptus nitens* stands and 20 years were considered for *Pinus patula* (1976-1998) and *Pinus radiata* (1975-1998) stands.

In general, required monthly averages of daily total solar radiation, and daytime atmospheric vapor pressure deficit (VPD), monthly rainfall, frost days per month, and mean air temperature (SANDS, 2004) can be either actual monthly weather data or long-term monthly averages. All climate data were extracted from data records from the Maclear climate station. Daily rainfall and temperature were averaged to monthly values for the considered periods. Days of frost were calculated from daily temperature data. Daily solar radiation was computed using an empirical equation provided by CLEMENCE (1992) which requires daily minimum and maximum temperatures. Vapor Pressure Deficit (VPD) was determined from an empirical relationship found by DYE (2000, pers. comm.).

Stand data have been extracted from the forest data base. These data included information on age, stocking, DBH and management (thinning and rotation practice). Given the assumption of good growth conditions, 12 stands have been chosen for each species to provide representative averages of each necessary parameter.

6.5.1.3.2 3-PG - Parameterization, Calibration and Validation

Parameters required for parameterization and calibration in 3-PG can be divided into climate input data, stand-related and species-related parameters. Depending on their nature, these parameters are provided from either empirical observations, inventories or the literature. In this context, SANDS (2004) published a guideline which can be efficiently used to assign species-related parameters.

Initially, averaged climate data (rainfall, solar radiation, atmospheric VPD, frost days per month and temperature) were manually typed in a spreadsheet mask for each month of each year after defining the period of interest. Hereby, the averaged values provided from the pre-processing were used. In a second step, the stand-related and species-related parameters were set. These parameters can be divided into age-related variables, parameters defining soil water conditions, tree canopy, transpiration and growth parameters, and management-related parameters.

Age-related variables such as tree age for rate of physiological decline and tree age at the start of the simulation run were assigned with respect to data from the forest data base and earlier model experiences (DYE, 2000, pers. comm.). Although the 3-PG simulations can be started at any age, usually stand growth is simulated beginning at year 2. Soil water parameters have been set with respect to field observations. Therefore, soil-physical data defining soil water constant, soil type coefficients and available soil water (e.g. vegetation rooting depth) were determined in the selected reference stands or were taken from the forest soil survey. Methods used to provide soil parameters are described in Sections 6.2. and 6.3 resp.

Tree canopy and transpiration related parameters were estimated either on the basis of earlier vegetation studies or from literature values. Specific leaf area values were obtained from DYE (2000, pers. comm.) for pine stands and from LANDSBERG *et al.* (2003) for eucalyptus stands. Since litterfall is assumed to be at a constant rate through the year, observed annual averages were converted to monthly totals. As discussed by LANDSBERG & WARING (1997) transpiration is very sensitive to maximum canopy and stomatal conductance values. Consequently, these values were calibrated by testing several literature values (DYE *et al.*, 2004; MORRIS, 1992, 1995; SANDS, 2004; WATSON, 1999) for each species.

With the exception of geographic location values (latitude, longitude) which were calculated as the centre coordinates of all stands, tree growth parameters have been initially set using default values. Since the defaults for initial biomasses of foliage, root and stem and cardinal temperatures seemed to provide insufficient model results, the given values were iteratively calibrated to optimize tree growth performance with regard to studies carried out by DYE *et al.* (2004), MORRIS (1992, 1995) and HELMSCHROT (1999) and interviews to foresters. Because of the non-linearity of equations used to calculate stand parameters, small variations in the parameter values of constant (a) and power coefficients (n) can cause significant differences in the values of DBH, stand volume and basal area (LANDSBERG *et al.*, 2003). Thus, these parameters were set to fixed values for each model run which have been taken from DYE (2000, pers. comm.) and DYE *et al.* (2004). Since no information was available on wood density values at the start and end of rotation, defaults were adopted for this study.

Management parameters are considered to include thinning treatments for pine stands. The needed parameters for thinning treatments were assigned on the basis of interviews with four foresters during field campaign in 1998.

Since some parameters are estimates, the calibration procedure was done iteratively by testing results provided by an individual parameter set against observed data continuously. Parameter values were then adjusted to enhance the model performance. As shown by LANDSBERG *et al.* (2003) successive adjustments lead, in most cases, to good fits between observed and simulated variable values. Although a number of parameters can be varied to alter the model output remarkably, LANDSBERG *et al.* (2003) recommend using standard defaults or best available empirical values for as many parameters as possible, since too much flexibility makes it difficult to identify the factors controlling and determining growth and yield differences accurately. Thus, only these parameters measured in the stands, e.g. LAI, stocking, DBH and mean litterfall have been varied with respect to observed minima, maxima and averages to test the reliability of the model. Such efforts were primarily applied to pine species addressing the dominance of pine stands in the afforested areas.

Data not being used in calibration were applied for validation of the model. Thus, observed LAI, stocking, DBH and mean litterfall values from different sites were plotted against modeled values. Moreover, these parameters have been evaluated with respect to data published from other forest studies in South Africa. To provide realistic estimates of NPP, results were discussed with forest experts and compared to studies carried out in similar forests in South Africa (DYE *et al.*, 2004). In addition, estimates of monthly evaporation and transpiration from pine and eucalyptus stands were evaluated by comparing simulated values with results published by VAN LILL *et al.* (1980), SCOTT & SMITH (1997) and SCOTT & LESCH (1997)

6.5.1.3.3 Results Analysis

The primary 3-PG outputs include species- and site-related stem, root and foliage biomass, available soil water and stand evapotranspiration, specific leaf area and canopy LAI, and net primary production (SANDS, 2004). The model also provides stand parameters such as stem volume, mean annual volume increment, and mean DBH which are of importance for forest management. Model outputs can be either monthly or annual values (LANDSBERG & WARING, 1997).

Since this study is mainly focused on plant-biophysical parameters which can be used to characterize and quantify forest dynamics in the study area, only those parameters have been investigated. In this context, the following analyses have been carried out:

- analysis of simulated LAI time courses and comparison of model results with observed (averaged) and literature values to regionalize age-dependent stand cover density,
- comparison of simulated and observed stocking, DBH, biomass and basal area for pine and eucalyptus stands,
- analysis to estimate age-dependent annual stand water use for each species which will be used to calibrate interception, evapotranspiration and soil moisture accounting processes in PRMS.

The achieved results and their implication for the presented research are discussed in detail in Chapter 7.

6.5.2 Hydrological Modeling Using MMS/PRMS

The MMS/PRMS model developed by the USGS is a modular, physical-based, distributed parameter model system simulating water fluxes and storages on catchment scale. While the **M**odular **M**odeling **S**ystem provides a framework and a toolset of algorithms to develop, support, and apply models (LEAVESLEY *et al.*, 1996), the **P**recipitation-**R**unoff **M**odeling **S**ystem is the basic hydrological model (LEAVESLEY *et al.*, 1983).

In recent years the PRMS model has been successfully applied in different basins and environments, and thereby showed its potential to simulate hydrological systems on several scales and environments (*inter alia* BONGARTZ, 2001; FLÜGEL, 1995; JETON & SMITH, 1993; LÜLLWITZ, 1993; MICHL, 1999; STAUDENRAUSCH, 1996). The model has been compared to other catchment models such as NASIM (MÜLDERS, 1992) and HSPF (DAAMEN, 1996). Considerable progress was achieved to enhance the model performance by implementing an improved HRU concept (FLÜGEL, 1996), an improved snow module (HERPERTZ, 2001), and topological HRU routing (STAUDENRAUSCH, 2001). Actual trends give attention to the combination of PRMS with the MODFLOW model coupling surface processes described in PRMS and groundwater processes represented in MODFLOW (MARKSTROM, 2005, pers. note). A variety of studies evaluating the applicability of PRMS and its potential for hydrological modeling purposes are summarized in BONGARTZ (2001) and MICHL (1999).

This section provides an overview on the basic concept of the model, the process implementation as well as the requirements for model calibration, parameterization and validation. In this context, a more detailed description of the model and its physical-based background is given by LEAVESLEY *et al.* (1983).

6.5.2.1 Modular Design and Model Concepts of MMS/PRMS

The core of the PRMS model is the system library that contains a standard set of process modules representing dominant hydrological processes. The process modules are considered as adaptable subroutines and can thereby be used to build the catchment model. The built model is considered to be physically-based, since physical laws and empirical relationships that have physical interpretation based on measurable basin characteristics are implemented in the process modules. As a consequence of the modular structure, new modules can be developed and implemented in PRMS to suit the modeler's specific needs. The basic modular configuration and associated processes and parameters are graphically summarized in Figure 6.14.

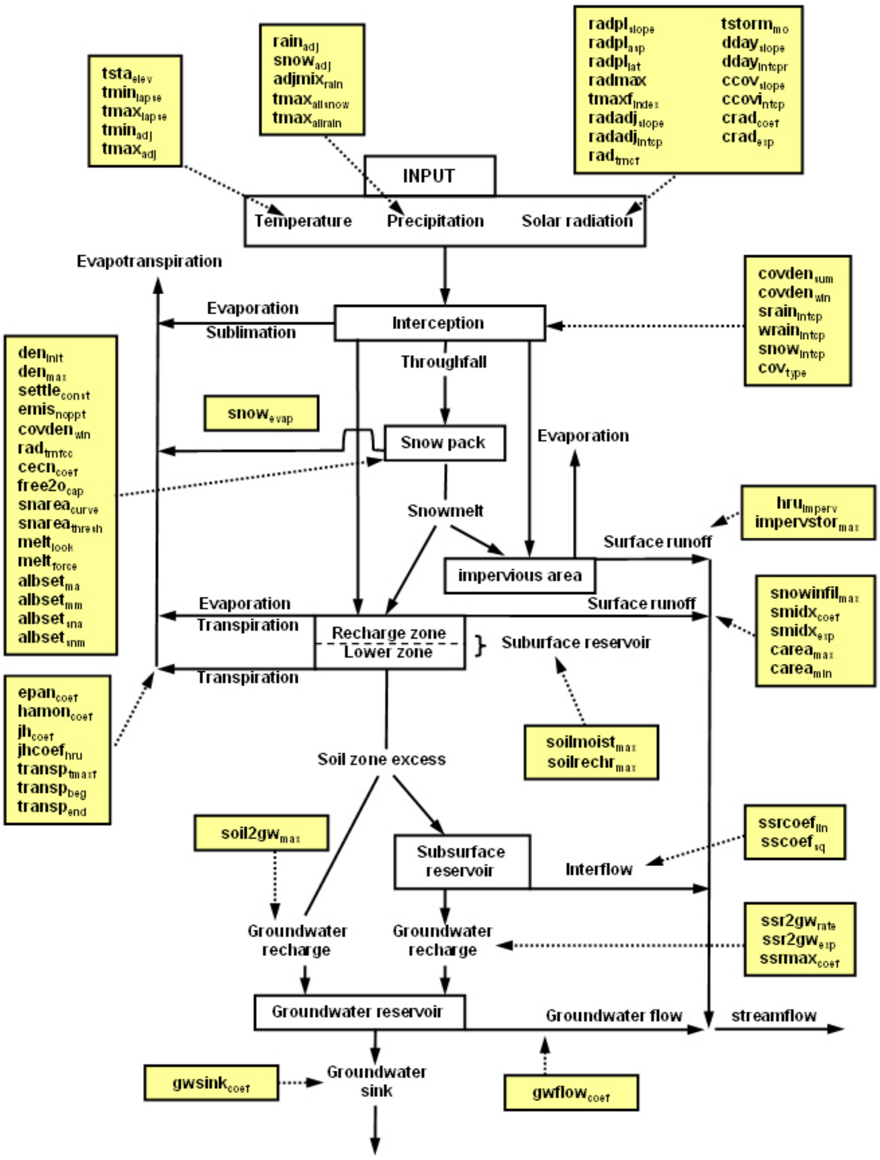


Figure 6.14: Modular structure representing processes and parameters considered in MMS/PRMS (mod. after LEAVESLEY*, 1983).*

The PRMS model can simulate basin hydrology on a daily or storm time scale. Minimum climate data requirements are hydro-meteorological time series of daily total precipitation and daily temperatures (min, max). If not available, sun radiation will be calculated by the model itself. The parameterization requires a variety of empirical data for process modules and HRU-related data provided by GIS and remote sensing analysis, additional model simulations and field-based system analysis. Model results are major hydrological system components, which are predicted separately for each HRU and routed to obtain the total runoff for the watershed. Flow components are simulated as mean daily flows for each HRU and as a basin total, when daily precipitation, minimum and maximum temperature and solar radiation are used as basic input data.

In addition, the storm mode can be used to simulate selected hydrologic components like infiltration, surface runoff, sediment yields, etc. at shorter intervals.

6.5.2.2 Meteorological Input Data Adjustment

Hydro-meteorological input data are usually measured at one or several climate stations within or near the basin, and thereby need to be extrapolated to each HRU. Therefore, adjustment factors which are computed as functions of the differences in elevation, slope and aspect between climate station and its associated HRU are used to estimate daily maximum and minimum temperature, precipitation and solar radiation data for each HRU.

Daily maximum and minimum air ***temperature*** ($t_{\max}$, $t_{\min}$) need to be adjusted to represent effects caused by differences in elevation and slope-aspect between the measuring station and each HRU. All temperature data and related parameters are expressed in either Celsius [°C] or Fahrenheit [°F], but need to be consistent throughout a simulation. The HRU-specific, corrected maximum and minimum temperatures are calculated by

$$t_{\max corr} = t_{\max} \cdot t_{\max lapse} \cdot \left(hru_{elev} - \frac{tsta_{elev}}{1000} \right) - t_{\max adj} \qquad [6.44]$$

$$t_{\min corr} = t_{\min} \cdot t_{\min lapse} \cdot \left(hru_{elev} - \frac{tsta_{elev}}{1000} \right) - t_{\min adj} \qquad [6.45]$$

where $t_{\max corr}, t_{\min corr}$ are corrected maximum and minimum daily temperatures [°C or °F],

$t_{\max lapse}, t_{\min lapse}$ are maximum and minimum temperature lapse rates [°C or °F per 1 000 ft],

$t_{\max}, t_{\min}$ are maximum and minimum daily temperatures [°C or °F],

hru_{elrv} is mean elevation of HRU [ft],

$tsta_{elrv}$ is the mean elevation of an HRU minus the elevation of the associated climate station [ft],

$t_{\max adj}, t_{\min adj}$ are maximum and minimum correction factors.

The correction factors are expressed as an average difference in temperature between horizontal surface and the slope-aspect of an HRU. In addition, those factors can also be used to correct measurement errors.

Precipitation (*precip*) represents the system input and is considered as either rainfall or snow in inches. Depending on the form of precipitation it can be adjusted using monthly correction factors ($rain_{adj}$, $snow_{adj}$). The total daily precipitation depth (hru_{ppt}) received on an HRU is than computed by

$$hru_{ppt} = precip \cdot rain_{adj} \qquad [6.46]$$

$$hru_{ppt} = precip \cdot snow_{adj} \qquad [6.47]$$

where hru_{ppt} is the total daily precipitation on a HRU [in],
$precip$ is the daily precipitation measured at the associated station [in],
$rain_{adj}, snow_{adj}$ are type-dependent correction factors for the HRU.

The form of precipitation (rain, snow, or mixture of both) on each HRU is either considered as additional input from the station data or estimated by the model using HRU maximum and minimum daily temperatures, a user-defined threshold temperature, and a monthly correction factor. The latter can be calculated by

$$prmx = \frac{t_{\max} - t_{\max allsnow}}{t_{\max} - t_{\min}} \cdot adjmix_{rain} \qquad [6.48]$$

where $prmx$ is the part of the total precipitation occurring as rain [in],
$t_{\max allsnow}$ is a base temperature that defines a threshold to separate snow and rain [°C or °F],
$adjmix_{rain}$ is a monthly mixture adjustment coefficient.

The ***solar radiation*** characterizes thermal conditions of the air temperature, and thereby it is used to simulate evapotranspiration and snow melt dynamics. It is considered as either measured input or an internal estimated variable. In areas with seasonal rainfall pattern, i.e. relatively clear sky areas, solar radiation is computed using the relationship of actual and potential solar radiation. Thus, a modified degree-day method introduced by LEAF & BRINK (1973) is combined with the daily potential solar radiation for a horizontal surface and a sky cover correction factor for rain days. Solar radiation is than computed as

$$solrad = solf \cdot horad \cdot ppt_{adj} \qquad [6.49]$$

where $solrad$ is the daily solar radiation [ly day^{-1}],
$solf$ is the ratio of actual-to-potential radiation for a horizontal surface,
$horad$ is the daily potential for a horizontal surface [ly day^{-1}],
ppt_{adj} is a sky cover correction factor for rain days.

A method based on the relationships between solar radiation and sky cover (THOMPSON, 1976) as well as daily range in air temperature and sky cover (TANGBORN, 1979) is used to estimate solar data for regions that are characterized by extensive periods of cloudiness with and without rainfall. Sky cover and solar radiation are then expressed as

$$ccov = ccov_{slope} \cdot (t_{\max} - t_{\min}) - ccov_{intcp} \quad [6.50]$$

$$solrad = \left(crad_{coef} + (1 - crad_{coeff}) \cdot (1 - ccov)^{crad_{ex}}\right) \cdot horad \quad [6.51]$$

where $ccov$ is daily sky cover,
$ccov_{slope}$ is the slope of the sky cover-daily air temperature range relationship for month,
$ccov_{\text{int}cp}$ is the intercept of the sky cover-daily air temperature range relationship for month,
$crad_{coef}$, $crad_{ex}$ are empiric coefficients.

The observed daily short wave radiation, measured on a horizontal surface, is adjusted to reduce HRU-specific topographical effects (slope-aspect combinations), and therefore can be computed using

$$swrad = solrad \cdot \frac{pot_{sw} \cdot horad}{\cos slope_{HRU}} \quad [6.52]$$

where $swrad$ is daily short wave radiation received on the slope-aspect combination of each HRU,
pot_{sw} is the daily potential radiation for the slope and aspect of an HRU [ly],
$\cos slope_{HRU}$ is the cosine of the average slope for an HRU.

6.5.2.3 Processes Implementation in PRMS

6.5.2.3.1 Interception

Interception of precipitation is a function of cover density and storage capacity of the dominant vegetation. The precipitation of a non-vegetated HRU is computed as the sum of rain and snow of each HRU (Equation 6.53). The total precipitation of an HRU is estimated by Equation 6.54, since the intercepted rainfall either falls through the vegetation (Equation 6.55) or is evaporated (Equation 6.56). The seasonality is considered by defining winter or summer vegetation density (*covden*). The maximum interception storage depth on vegetation is defined by precipitation form and season.

$$hru_{ppt} = hru_{rain} + hru_{snow} \qquad [6.53]$$

$$nethru_{rain} = hru_{rain} \cdot (1 - covden) + (thrufall \cdot covden) \qquad [6.54]$$

with

$$thrufall = hru_{rain}\left(rain_{intcp} - intcp_{stor}\right) \quad \text{if} \quad hru_{ppt} > (rain_{intcp} - intcp_{stor}) \qquad [6.55]$$

$$thrufall = 0 \quad \text{if} \quad hru_{ppt} \leq (rain_{intcp} - intcp_{stor}) \qquad [6.56]$$

where hru_{ppt} is the net precipitation [in],
hru_{rain}, hru_{snow} are net precipitation separated by form (rain, snow) [in],
$nethru_{rain}$ is the total precipitation received on an HRU (rain) [in],
$covden$ is the seasonal cover density,
$thrufall$ is the precipitation falling through the canopy [in].
$rain_{intcp}$ is the maximum interception storage depth on vegetation [in],
$intcp_{stor}$ is the current interception storage depth [in].

The intercepted rain is evaporated assuming a free water surface. The evaporation rate is either used from measured evaporation rates or computed as a relation of potential evapotranspiration and a monthly evaporation-pan coefficient (Equation 6.57). Stemflow is not considered in the model.

$$evcan = \frac{pet}{epan_{coef}} \qquad [6.57]$$

where $evcan$ is the intercepted rain that is assumed to evaporate at a free-water surface rate [in],
pet is the daily potential evapotranspiration [in],
$epan_{coef}$ is the monthly evaporation-pan coefficient.

Sublimation of intercepted snow is expressed as a percentage of potential evapotranspiration. As a consequence daily interception loss occurs either as the total volume of the interception storage if less than *evcan*, or as actual daily evaporation if *evcan* is less than the actual interception storage. In addition to sublimation, intercepted snow can be removed from the canopy by melting and thereby is transferred to soil water storage or snowpack at the surface as net precipitation. This process is controlled by an energy balance that is considered in Equation 6.60 and 6.62.

6.5.2.3.2 Snow Dynamics

As discussed in Chapter 4, the snow component is not considered to be important factor in the water budget of the simulated basins, and therefore only the main processes are summarized in this section. More details are given in LEAVESLEY *et al.* (1983).

The snow routines simulate the initiation, accumulation, and depletion of a snowpack on each HRU based on an energy balance model. The water equivalent as measure for the stored water in the snowpack is the driving parameter to simulate the snowpack-water balance on a daily basis. The energy balance is computed on a 12-hour basis to represent both day and night conditions. The snowpack is modeled as a 2-layer system where the upper layer of about 3 to 5 centimeters is linked to atmospheric processes and the lower layer is the remaining snowpack. Heat exchange between both layers occurs by conduction when the surface layer temperature is less than 0°C. This relation is

$$qcond = 2 \cdot pk_{den} \cdot cs \cdot \sqrt{\frac{k_{eff}}{pk_{den} \cdot cs} \cdot \frac{dt}{\pi}} \cdot \left(ts - pk_{temp}\right) \qquad [6.58]$$

where $qcond$ is the conduction of heat between the snow surface and the lower layer of the snowpack,
pk_{den} is the snow pack density [g cm^{-3}],
pk_{temp} is the temperature of the lower layer of the snowpack [°C or °F],
ts is the temperature of the upper layer of the snowpack [°C or °F],
cs is the specific heat of ice [cal s^{-1} °C^{-1}],
k_{eff} is the effective thermal conductivity of the snowpack [cal s^{-1} cm-1 °C^{-1}].

When the temperature of the upper layer exceeds the lower layer temperature as a consequence of Equation 6.51 or additional rainfall, the temperature for the lower layer is computed by

$$pk_{temp} = \frac{-pk_{def}}{\left(pkwater_{equiv} \cdot 1.27\right)} \qquad [6.59]$$

where pk_{def} is the energy that is required to bring the lower layer to an isothermal state at 0°C [cal],
$pkwater_{equiv}$ is the snowpack water equivalent [in].

The constant 1.27 is the product of the specific heat of ice (0.5 cal g^{-1} °C^{-1}) and the conversion factor for inches to centimeters (2.54).

When the surface layer temperature is 0°C the heat transfer occurs as conduction when the net energy balance at the air-snow interface is negative and as mass transfer by surface melting when the energy balance is positive. The energy balance is computed as the sum of net shortwave and longwave radiation and an estimate of latent and sensible heat. These variables are expressed as

$$swn = swrad \cdot (1 - albedo) \cdot rad_{trncf} \qquad [6.60]$$

$$lwn = ((1 - covden_{win}) \cdot [(emis \cdot air) - sno] + [covden_{win} \cdot (air - sno)]) \qquad [6.61]$$

$$cecsub = cecn_{coef} \cdot temp \qquad [6.62]$$

where

swn	is daily shortwave radiation [ly],
lwn	is the daily longwave net radiation [ly],
$cecsub$	is an estimate of latent and sensible heat,
$swrad$	is the computed shortwave solar radiation received [ly],
$albedo$	is the albedo of the snowpack surface,
rad_{trncf}	is the transmission coefficient for the vegetation canopy over the snowpack,
$covden_{win}$	is the winter cover density of the predominant vegetation above the snowpack,
$emis$	is the emissivity of the air,
air	is the long wave energy emitted from a perfect black body at the average air temperature for the 12-hour period [cal],
sno	is the long wave energy emitted from the snowpack surface at the surface temperature for the 12-hour period [cal],
$cecn_{coef}$	is a monthly correction factor,
$temp$	is the mean air temperature for a 12-hour period [°C].

In addition, precipitation on the snowpack is assumed to influence the temperature of the surface layer, while heat exchange at the snowpack-soil interface is negligible. The energy balance at the snow-atmosphere interface occurs depending on the form of precipitation (snow, rain) as negative or positive energy balance. If the precipitation occurs as snow, it is added to the snowpack and its heat content is used to re-compute the snowpack temperature and cold content. Then, free available water is frozen using the cold content of the snow. If the precipitation falls as rain, the heat content of the rain changes the temperature and water content of the snowpack. Depending on the temperature of the snowpack, the rain either warms the snowpack or all rain is frozen and releases energy to warm the snowpack. If the snowpack reaches 0°C, then any remaining liquid water is used to satisfy the free-water-holding capacity of the snowpack. Liquid water that exceeds the free-water-holding capacity leaves the snowpack as snowmelt and either is infiltrating to the soil storage or contributing to surface runoff. If the precipitation falls as a mixture of snow and rain, the rain is assumed to occur first.

Sublimation and evaporation from the snow surface are expected to occur only when there is no transpiration from vegetation. In vegetated areas the loss from the snow surface is calculated as the daily percentage of the computed potential evapotranspiration, and therefore computed as

$$snow_{evap} = (pot_{sublim} \cdot potet) - (intcp_{evap} \cdot cov) \qquad [6.63]$$

where	$snow_{evap}$	is the loss due to evaporation and sublimation from the snow surface [in],
	pot_{sublim}	is a loss coefficient,
	$potet$	is the potential evapotranspiration [in],
	$intcp_{evap}$	is the evaporation and sublimation loss from interception [in],
	cov	is the vegetation cover density for the date of computation.

The loss from the snow surface is also computed as a function of the snow-covered area of an HRU. Consequently, $snow_{evap}$ is multiplied with the snow-covered area using a user-defined areal depletion curve that is a plot of the areal extent of snow cover versus the ratio of snowpack water equivalent to a daily computed index value.

6.5.2.3.3 Evapotranspiration

Actual evapotranspiration (aET) is a function of the potential ET, i.e the rate of water loss which reflects the availability of water to satisfy the potential ET. When available water is not limited, actual ET equals potential ET in non-open water bodies, potential ET is first considered as part of the interception storage, retention storage on impervious areas and evaporation/sublimation from snow surfaces. The remaining demand on water is covered by the soil water storage. The water loss is computed for both soil-zones (recharge zone, lower zone) separately using the ratio of currently available soil water and available water holding capacity. When taken from the soil zone actual ET is first computed for the recharge zone to satisfy potential ET and any remaining demand is provided by computed actual ET from the lower zone. Since HRU soils are designed as being predominantly sand, loam, or clay, three functions of the soil-water ratio are considered to describe the actual ET-potential ET relation for these soil types. Transpiration can be estimated from both soil layers using a pre-defined vegetation period for each HRU, while evaporation is limited to the recharge zone.

PRMS provides different algorithms to compute potential ET by default. The Class-A-Pan method is assumed to be used when no temperature data are available, while approaches developed by JENSEN & HAISE (1963) and HAMON (1961) need daily temperature input. As shown by STAUDENRAUSCH (1996), the JENSEN & HAISE (1963) model seemed to be the most appropriate of the given models to compute ET in semi-arid Southern Africa.

Potential evaporation is then computed by

$$pET = jh_{month\_coef} \cdot \left(t_{mean} - jh_{coef}\right) \cdot solrad_{in} \qquad [6.64]$$

where jh_{month_coef} is a coefficient for the month,
t_{mean} is the daily mean air temperature [in °C],
jh_{coef} is a coefficient,
$solrad_{in}$ is the daily solar radiation expressed in inches of evaporation potential.

Since coefficients used in formula 6.64 tend to be variable in different environments, they can be estimated using the approach discussed by LEAVESLEY *et al.* (1983).

6.5.2.3.4 Soil Moisture Accounting

The soil moisture accounting is considered as the algebraic summation of all moisture additions to, and depletions from, the active soil profile. The soil water storage is filled by rainfall and/or snowmelt infiltration and emptied by evapotranspiration, interflow and recharge to the groundwater reservoir. Basically, those processes are controlled by the type of soil (sand, loam, and clay) and the available soil water. Evapotranspiration losses are expressed as a rate that is a function of soil-moisture storage. As shown in Figure 6.14 the active soil profile that is extrapolated to an HRU is divided into two layers. The upper part is defined as the recharge zone losing water due to evaporation and transpiration, while water of the lower layer defined as lower zone is only released by evaporation. The depth of the active soil profile is determined by the average rooting depth of the predominant vegetation on an HRU. The maximum water-holding capacity ($soilmoist_{max}$) is expressed as the difference between field capacity and wilting point of the profile. The recharge zone is user-definable as to depth and maximum available water-holding capacity ($soilrechr_{max}$), whereas the maximum available water-holding capacity of the lower profile is determined by the difference between $soilmoist_{max}$ and $soilrechr_{max}$. If available water exceeds the maximum water-holding capacity of the recharge zone ($soilrechr_{max}$), water is transferred to the lower zone. When this storage is filled, excess water is released to the subsurface and groundwater reservoirs by interflow and groundwater flow respectively. As a consequence, soil moisture is a key parameter to control basinwide evapotranspiration and discharge.

6.5.2.3.5 Runoff Processes

The total daily ***basin streamflow*** is computed as the sum of daily surface runoff, subsurface and groundwater flow from pre-defined groundwater aquifers. Surface runoff is either simulated using the contributing-area concept (DICKENSON & WHITELY, 1970; HEWLETT & NUTTER, 1970) in a daily mode or computed as saturated '*Hortonian'* overland flow (event-based mode). Interflow is characterized as that portion of rainfall that infiltrates into the soil and moves rapidly and laterally through the upper soil horizons until intercepted by a stream channel or until it returns to the surface at some point downslope from its point of infiltration. Conceptually, the groundwater system is considered as being a linear reservoir and is assumed to be the source of all generated baseflow. Different subsurface and groundwater reservoirs can be defined which are conceptually linked to the soil water system and processes directly. Spatially the HRUs are related to one or more specific subsurface and groundwater reservoirs. The mathematical descriptions of runoff processes used in PRMS are given below.

The daily ***surface runoff*** from rainfall is strongly controlled by the surface properties and the infiltration capacity of an HRU. On a daily basis, PRMS uses the contributing-area concept on snow-free and pervious HRUs. Therefore, the percentage of an HRU contributing to surface runoff is related to that area of an HRU which is assumed to be saturated. As a consequence, the surface runoff contributing-area can either be computed as a linear (Equation 6.65) or a non-linear (Equations 6.66 and 6.67) function of antecedent soil moisture and rainfall amount.

$$ca_{perc} = carea_{min} + \left(\left(carea_{max} - carea_{min} \right) \cdot \frac{soil_{rechr}}{soil_{rechrmax}} \right) \quad [6.65]$$

$$ca_{perc} = smidx_{coef} \cdot 10^{smidx_{exp} \cdot smidx} \quad [6.66]$$

$$smidx = \frac{soil_{rechr} + soil_{moist}}{2} + \frac{nethru_{ppt}}{2} \quad [6.67]$$

where ca_{perc} is the percentage of an HRU contributing to surface runoff,
$carea_{min}, carea_{max}$ are minimum and maximum possible area contributing to surface runoff,
$smidx$ is the soil moisture index,
$soil_{rechr}$ is the moisture content for the upper soil zone for each HRU,
$soil_{rechrmax}$ is the maximum value for available water in the upper soil zone for each HRU,
$smidx_{coef}, smidx_{exp}$ is an empiric coefficient and exponent respectively for computing runoff in non-linear contributing area algorithms
$soil_{moist}$ is the soil moisture content for each HRU [in],
$nethru_{ppt}$ is the rain on an HRU minus interception [in].

The surface runoff of an HRU is then computed as the product of daily net precipitation and the contributing area:

$$sroff = ca_{perc} \cdot nethru_{ppt} \quad [6.68]$$

where $sroff$ is the runoff for the pervious area from each HRU [$ft^3\ s^{-1}$],
ca_{perc} is the percentage of an HRU contributing to surface runoff,
$nethru_{ppt}$ is the rain on an HRU minus interception [in].

Surface runoff from snowmelt is limited to simulations on a daily basis. Snowmelt runoff occurs on pervious areas when the soil zone of an HRU reaches field capacity. Once field capacity is reached, a daily maximum infiltration rate is assumed and any snowmelt exceeding infiltration becomes surface runoff. For impervious areas, snowmelt first fills available retention storage, and the remaining snowmelt becomes surface runoff.

For event-based ***surface runoff*** simulations, the kinematic wave approximation to overland flow is utilized in PRMS. The concept is based on the assumption that overland flow occurs when net rainfall exceeds the field capacity of a soil. Consequently, the overland flow is controlled by the infiltration capacity which is defined for a specific HRU and can be computed using a modified *Green & Ampt* equation (GREEN & AMPT, 1911; DAWDY *et al.*, 1972):

$$fr = ksat \cdot \left(1 + \frac{ps}{sms}\right) \quad [6.69]$$

where *fr* is the soil infiltration capacity at one point,
ksat is the hydraulic conductivity of the transmission zone [in h^{-1}],
ps is an effective value of the product of capillary drive and moisture deficit [in],
sms is the current value of accumulated infiltration [in].

The effective value of the product of capillary drive and moisture deficit (*ps*) is varied linearly as a function of the ratio of the soil moisture storage of the recharge zone to its maximum moisture storage over a range from the value of the product of capillary drive and moisture deficit at field capacity (*psp*) to a maximum value. It is expressed as

$$ps = psp \cdot \left(rgf \cdot (rgf - 1) \cdot \frac{soil_{rechr}}{soil_{rechrmax}} \right) \quad [6.70]$$

where *psp* is the value of the product of capillary drive and moisture deficit at field capacity,
rgf is the ratio of actual *psp* and *psp* at wilting point.

The net infiltration is computed assuming that infiltration capacity varies linearly from zero to its maximum. Thus, infiltration is then calculated using net precipitation and maximum infiltration capacity (CRAWFORD & LINSLEY, 1966) as follows

$$infil = nethru_{ppt} - \frac{nethru_{ppt}^2}{2 \cdot fr} \quad \text{if} \quad \inf il < nethru_{ppt} \quad [6.71]$$

$$\text{or} \quad infil = \frac{fr}{2} \quad [6.72]$$

where	$infil$	is the infiltration,
	$nethru_{ppt}$	is the rain on an HRU minus interception [in],
	fr	is maximum infiltration capacity.

The rainfall excess which is assumed to contribute to surface runoff is simply expressed as

$$hru_{pptexc} = nethru_{ppt} - infil \qquad [6.73]$$

The ***subsurface flow (Interflow)*** is characterized as the relatively rapid movement of water from the unsaturated zone to a stream channel and occurs during, and for a period of time after, rainfall or snowmelt. Subsurface flow is simulated as flow into and from a subsurface reservoir which is associated to an HRU. A subsurface reservoir can receive inflow from one or several HRUs. The number of subsurface reservoirs in a basin varies between one to the number of HRUs delineated. Inflow to the subsurface reservoir is computed when the maximum available water-holding capacity of the soil-zone of an HRU exceeds the recharge rate to the groundwater reservoir. The dynamic of the subsurface reservoir per unit of time is then computed as the difference between inflow and outflow using the continuity of the mass equation for the subsurface flow system as follows

$$ssres_{flow} = ssres_{in} - \frac{\mathrm{d}\left(ssres_{stor}\right)}{\mathrm{d}t} \qquad [6.74]$$

where	$ssres_{stor}$	is the storage in each subsurface reservoir,
	$ssres_{in}$	is the total inflow to each subsurface reservoir,
	$ssres_{flow}$	is the contribution to streamflow from each subsurface reservoir.

The rate of outflow from the subsurface reservoir is calculated by an empirical relationship introducing two routing coefficients, and which can be defined either as linear ($sscoef_{sq}$ = 0) or non-linear relationship as follows

$$ssres_{flow} = \left(ssres_{stor} \cdot ssrescoef_{lin}\right) + \left(ssres_{stor}^{2} \cdot ssrcoeff_{sq}\right) \qquad [6.75]$$

where	$sssrescoeff_{lin}$	is the linear subsurface routing coefficient routing subsurface storage to streamflow,
	$ssrcoef_{sq}$	is the non-linear subsurface routing coefficient to route subsurface storage to streamflow.

Initial storage volumes and routing coefficients are defined by the user for each subsurface reservoir, whereas the initial estimate of storage normally starts at zero. The routing coefficients are usually fitted using historic streamflow data.

In addition to the rate of subsurface flow, the subsurface reservoir provides recharge to the groundwater reservoir by a vertical water movement which will be discussed in detail in the following groundwater section.

The ***groundwater flow (base flow)*** is defined as the flow from one or several groundwater reservoirs. The replenishment of the groundwater reservoir is expressed as the sum of recharge provided by the soil water excess from the soilzone (available water exceeds the maximum water-holding capacity of the lower soil zone, $soil2gw_{max}$) and the recharge from the subsurface reservoir to the groundwater reservoir (*ssr2gw*). The latter can be computed by

$$ssr2gw = ssr2gw_{rate} \cdot \left(\frac{ssres_{stor}}{ssr2gw_{max}} \right)^{ssr2gw_{exp}} \qquad [6.76]$$

where *ssr2gw* is the recharge from subsurface to the groundwater reservoir,
$ssr2gw_{max}$ is the maximum value for water routed from subsurface to groundwater,
$ssr2gw_{rate}, ssr2gw_{exp}$ are coefficients to route water from subsurface to groundwater.

The empirical routing coefficients can be used to describe a linear relationship between storage in the subsurface reservoir and water movement when they are set to 1.

The base flow dynamics are strongly influenced by the relative proportion of groundwater recharge from the soil zone and the subsurface reservoir. Recharge from the soil zone only occurs on days when maximum soil water-holding capacity is exceeded by infiltration, while recharge from the subsurface reservoir occurs as long as water is available in the reservoir. As a consequence, the increase of the recharge from the subsurface reservoir will increase the base flow contribution to the simulated hydrograph and decrease the subsurface flow portion. The base flow from each groundwater reservoir is linearly expressed as

$$gwres_{flow} = gwflow_{coef} \cdot gwres_{stor} \qquad [6.77]$$

where $gwres_{flow}$ is the baseflow,
$gwflow_{coef}$ is the reservoir routing coefficient,
$gwres_{stor}$ is the groundwater reservoir storage.

Since the user is able to define one or more groundwater reservoirs for one basin, sufficient data are required to estimate initial storage volumes and routing coefficients. In small catchments only one groundwater reservoir is usually specified.

When groundwater is transferred to areas beyond the watershed, groundwater loss is computed by the multiplication of the groundwater reservoir ($gwres_{stor}$) and a user-defined loss coefficient ($gwsink_{coef}$).

6.5.2.3.6 Basin Runoff

The net basin runoff for daily timesteps ($basin_{cfs}$) is finally computed as the sum of all flow components and can therefore be expressed as

$$ba\sin_{cfs} = ba\sin_{sroff} + ba\sin_{ssflow} + ba\sin_{gwflow} \qquad [6.78]$$

where $basin_{sroff}$ is the basin surface runoff [ft^3 s^{-1}],
$basin_{ssflow}$ is the basin subsurface runoff [acre],
$basin_{gwflow}$ is the basin groundwater flow [ft^3 s^{-1}].

The flow rate at the outlet of the watershed is computed as the areal averaged discharges of all HRUs and is computed as

$$Q = \sum_{i=1}^{n} \frac{A_{HRU_i} \cdot Q_{HRU_i}}{\mathrm{d}t} \qquad [6.79]$$

where Q is the discharge at point of reference [ft^3 s^{-1}],
A_{HRU} is the area of a specific HRU [acre],
Q_{HRU} is the discharge of a specific HRU [ft^3 s^{-1}].

6.5.2.3.7 Routing

The ***channel-flow routing*** of daily streamflow is limited to cases when surface reservoirs are designated. The channel-flow routing for storm events is considered by characterizing the drainage network of channel, reservoir, and junction segments that describe the drainage pattern. A detailed description of channel-flow routing for single rainfall events and sediment transport is given in LEAVESLEY *et al.* (1983).

Principally, the ***reservoir routing*** in PRMS is based on a general form of the continuity equation, and thereby can be expressed as

$$outflow = inflow - \frac{\mathrm{d}(stor)}{\mathrm{d}t} \qquad [6.80]$$

where *outflow* is the reservoir outflow,
inflow is the reservoir inflow,
stor is the reservoir storage,
t is the time.

The reservoir inflow is the sum of the streamflow contribution from all HRUs and the part of subsurface and groundwater reservoirs above the channel reservoir. The reservoir is treated as an individual stream segment in the channel-routing stream. It also can include the outflow of up to three channel, reservoir, and junction segments.

Reservoir routing in PRMS can be done either based on a linear storage routing through the routing parameter (*rcs*) or by a modified-Puls routing (US SOIL CONSERVATION SERVICE, 1971). The linear routing is expressed as

$$outflow = \left(1 - \frac{1 - e^{-(rcs \cdot \mathrm{d}t)}}{rcs \cdot \mathrm{d}t}\right) \cdot inflow \cdot \mathrm{d}t + \left(1 - e^{-(rcs \cdot \mathrm{d}t)}\right) \cdot stor \qquad [6.81]$$

where *rcs* is routing parameter,
inflow is the reservoir inflow,
stor is the reservoir storage at the start of d*t*,
d*t* is the time interval.

The modified-Puls routing uses mean values for inflow and outflow terms at the beginning and the end of time interval d*t*. To specify start and end values the subscripts 1 and 2 can be used to rearrange equation 6.80 as follows

$$\frac{2 \cdot stor_2}{\mathrm{d}t} + outflow_2 = \left(inflow_2 - inflow_1\right) + \frac{2 \cdot stor_1}{\mathrm{d}t} - outflow_1 \qquad [6.82]$$

While the terms on the right-hand side of the equation are known at the beginning of the routing period, $outflow_2$ is solved by using an interpolation method introduced by DAWDY *et al.* (1978). Reservoir evaporation, leakage, bank storage, and inflow by direct precipitation are not considered in the routing model.

6.5.2.4 Model Application

In this study, the PRMS model was applied to analyze the impacts of afforestation on hydrological dynamics at different scales. At the catchment scale, PRMS has been used to quantify the water budget prior to and after afforestation for the Weatherley and Mooi catchments. In addition, the impact of afforestation on wetland water budget and process dynamics has been investigated considering each wetland type as a specific HRU.

The model procedure applied for each catchment and each land use scenario can be divided into five steps. Initially, the hydro-meteorological and spatial input data were processed addressing the requirements of PRMS. In a second step, a model was built using the Modular Modeling System framework (LEAVESLEY & STANNARD, 1995) considering the specific needs of each process scale. The created model was then parameterized using parameters obtained from field observation, GIS analysis and other empiric studies. Based on a defined period, model calibration has been performed to estimate realistic model parameter and coefficient values for each scenario in order to simulate the hydrological basin dynamics as accurately as possible. To evaluate model performance, all parameter sets have been verified using an independent data set. Finally, model results have been analyzed to identify changes of the hydrological process dynamics at catchment and wetland scale comparing and evaluating model outputs statistically. The model procedure applied in this study is illustrated in Figure 6.15.

6.5.2.4.1 Pre-Processing of Input Data

PRMS requires pre-formatted input data files including time series of daily runoff, climate parameters and form data by default. Corrected daily runoff data are given for the lower weir of the Weatherley catchment from 1998 until 2005 and the Mooi weir in

Maclear for the period from 1970 to 2005. Since the PRMS model uses the US system, runoff data have been converted to time series representing daily mean volumes in cubic feet per second.

Climate data requirements for the PRMS model are daily precipitation, minimum and maximum temperature and solar radiation. Corrected time series of these data were available for both the experimental Weatherley catchment (1998-2005) and the Mooi catchment (1970-2005). Addressing the requirements of PRMS, all precipitation time series have been converted to daily depths in inches. Since solar radiation data were considered for the modeling of the Weatherley catchment, data have been converted to daily means in langleys (ly). Form data is a user-defined value which can be used to consider the type of precipitation falling at a specific day as snow or rain independently from temperature. In this study, it has been excluded for all model exercises, because all precipitation was assumed to be rain.

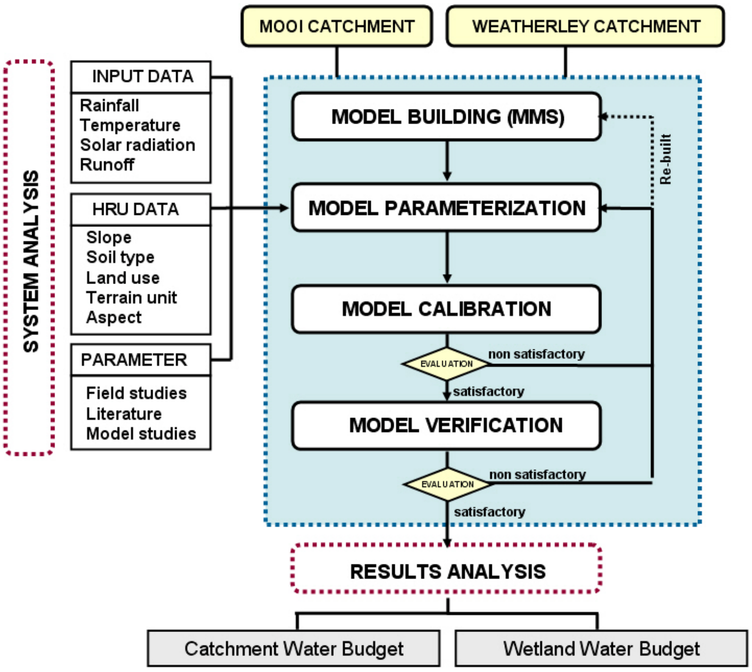


Figure 6.15: Schematic illustration of the methodological approach applied to model water budget and hydrological dynamics on catchment and wetland scale using PRMS.

All parameters which are relevant to characterize the basins (size in km²) and the HRUs of each scenario (size in km², mean elevation in m, mean slope in %) were calculated using ARCGIS 9.0. Finally, metric values (km², m) have been converted to the US system (acre, feet).

6.5.2.4.2 Model Building and Improvement

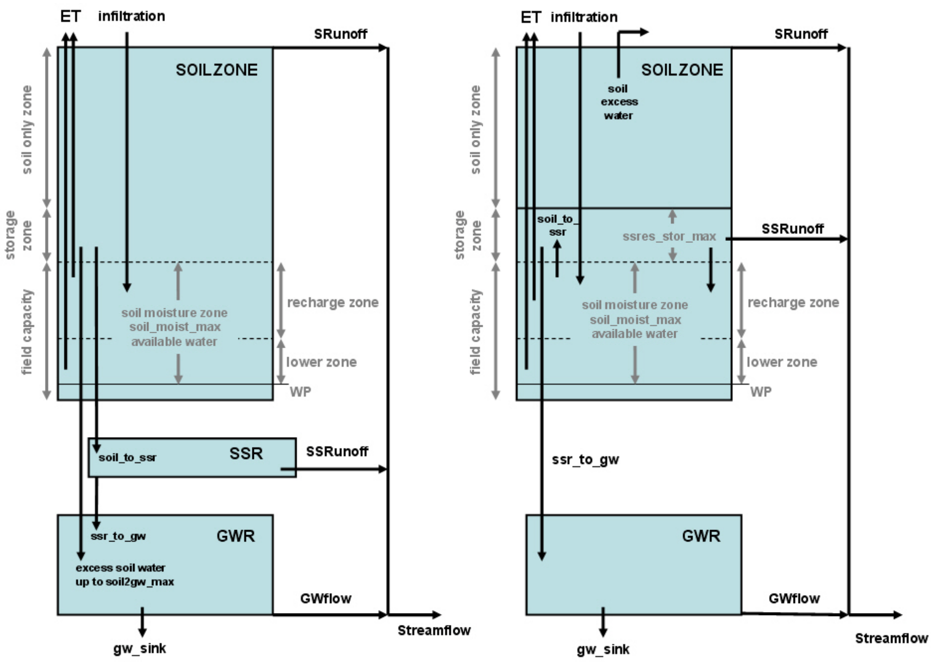
The used PRMS and its modules is the integral part of the previous version of the Modular Modeling System (MMS). Based on a thorough library of compatible program modules for simulating a variety of hydrologic and ecosystem processes, MMS provides the research and operational framework to create a watershed model (LEAVESLEY & STANNARD, 1995). Such a model is built by selectively coupling the most appropriate process modules from the library to create an "optimal" model for the addressed research or management model application. Therefore, the *model builder* provides a graphical user interface which enables the user to select and link the modules from the library interactively. Since the modules are written in FORTRAN or C programming language, process modules might be recoded or improved to address specific model requirements. Moreover, MMS allows implementing additional modules to the PRMS model to meet the modeler's specific needs.

In this study, a basic version of MMS including a standard set of process modules was used. Using the *model builder*, two models have been built. Initially, the standard model was calibrated for the Weatherley catchment. First model results indicated that the standard model seemed not appropriate to simulate soil water dynamics within wetlands for two reasons:

i) The wetland storage at the beginning of the rainy season was considerably underestimated which resulted in erroneous saturation conditions and thus surface runoff values when none were observed.

ii) Permanent and temporarily saturated wetlands had only limited surface water holding capacity, since standing water was instantaneously removed through surface runoff.

Hence, a new module, namely *soilzone.prms.f* (LEAVESLEY & REGAN, 2004, pers. comm.) was implemented to remedy these shortfalls. As shown in Figure 6.16, the new module merges the soil zone and the subsurface reservoir into one single physical unit. The storage capacity of the subsurface reservoir was defined as the available storage between field capacity and saturation. When storage in the subsurface reservoir exceeds this capacity, the excess water is routed to surface runoff.



ET … Evapotranspiration; WP … Wilting point; SSR … Subsurface reservoir; GWR … Groundwater reservoir; SRunoff … Surface runoff; SSRunoff … Subsurface runoff; GWflow … Groundwater flow

Figure 6.16: Schematic representation of the original and the modified modules to simulate soil water dynamics (mod. after LEAVESLEY *&* REGAN*, 2004, pers. comm.).*

In addition, a supplementary routing module *cascade* (LEAVESLEY & REGAN, 2004, pers. comm.) was implemented which allows routing of a percentage of flow from a specific HRU to a number of down slope HRUs using a 1-n relationship. The user defines the percentage of flow; the index numbers of the affected down slope HRUs and the channel segment index that cascade area.

6.5.2.4.3 Model Parameterization

Once the user-specific model is built, it needs to be parameterized. The structure of PRMS allows the user to save model input parameters in data files (Section 6.5.3.1) and parameter files. Both types can be replaced by another data set to evaluate model performance or system changes. In this study, parameter sets have been developed for both catchments representing conditions prior and after afforestation. Initial parameter sets were provided for the standard PRMS model automatically using the GIS WEASEL (VIGER, 2004, pers. comm.). After modifying the model structure, parameters sets were performed manually using the spreadsheet editor of PRMS. Basically, model parameters and coefficients can be categorized into three basic types: *i) dimension size related parameters, ii) distributed* and *iii) non-distributed parameters*.

- *Dimension size parameters*

Initially, dimension size parameters were set to define the number of HRUs (*nhru*), rain (*nrain*), temperature (*ntemp*) and solar (*nsol*) stations, weirs (*nobs*), groundwater and subsurface reservoirs (*ngw*, *nssr*), radiation planes (*radpl*) and routing-related dimensions such as number of channel segments (*nchan*), cascading units (*ncascade*) and channel storage reservoirs (*nsfres*).

- *Distributed parameters*

Distributed parameters primarily describe the physical characteristics of individual HRUs and represent measurable characteristics such as land cover type (*covtype*), seasonal cover density (*covden*), surface runoff contributing area (*carea*), aspect (*radpl*), soil type (*soiltype*), HRU area (*hruarea*), and mean HRU altitude (*elev*) and slope (*slope*). With the exception of *covden* and *carea*, these parameters result either from the HRU delineation directly or have been derived from GIS analysis using standard tools of ARCGIS 9.0.

Seasonal cover density (*covden*) was set based on field studies in the several environments and validated with estimates given by DYE (2004, pers. comm.), HELMSCHROT (1999) and SCHULZE (1997). Since little empirical information was available, the surface runoff contributing area for each HRU (*carea*) was estimated using the GIS WEASEL initially (VIGER, 2004, pers. comm.). The exponent used in non-linear contributing area algorithm (*smidx_exp*) was estimated based on STAUDENRAUSCH (1996). Both values were reviewed concerning their plausibility and adjusted utilizing the PRMS-internal optimization procedure (LEAVESLEY *et al.*, 1983).

Moreover, a number of distributed parameters need to be set to satisfy the process modules. Seasonal interception storage capacity (*srain, wrain*) is the sum of crown canopy interception storage and litter interception storage. The canopy interception capacity is primarily a function of leaf area, leaf area index, storm intensity, and surface tension forces resulting from leaf surface configuration, liquid viscosity, and mechanical activity. It is expressed as depth of water per unit area of the representative plant community. Although numerous physically-based models exist to describe interception dynamics in several canopy structures (GASH *et al.*, 1995; VALENTE *et al.*, 1997), storage capacities are often estimated on the base of LAI due to the lack of empiric parameters to fulfill such models. Many authors (*inter alia* ASTON, 1979; FLEISCHBEIN *et al.*, 2005) found that storage capacity of any canopy is strongly related to LAI. Thus, storage capacities for grassland-dominated HRU and forest structure were estimated based on LAI data derived from remote sensing analysis, field measurements (HELMSCHROT, 1999) and plant growth modeling using the equation published by SCHULZE (1995). With respect to the work presented by PUTUHENA & CORDERY (1996), litter interception capacity in forest stands was considered as being 20 % (without grassy understory) and 50 % (with grassy understory) of the value computed for crown interception storage capacity. The estimates of interception storage capacities have been compared to literature values presented by VALVENTE *et al.* (1997). Maximum impervious storage area retention (*imperv_stor_max*) and percentage of impervious area per HRU (*percent_imperv*) were set to zero, since it was found from land use analysis and field survey that impervious areas are not relevant to the hydrological dynamics within the landscape of the Eastern Cape.

A variety of distributed parameters also affect components and processes of the hydrological cycle on or within an HRU directly. Parameters controlling climate input variables are index numbers of the stations used to compute rain and snow (*psta*) and temperature (*tsta*) for each HRU. Regarding the size of the catchment, only one station was chosen for the Weatherley model runs. For the Mooi basin, *psta* and *tsta* have been defined with respect to the station which is closest to the center coordinate of each HRU. In cases where rough terrain affected the rainfall or temperature dynamics significantly, the analysis of spatial rainfall and temperature pattern was considered in defining the most appropriate station. Rainfall adjustment (*rain_adj*) was determined by analyzing rainfall patterns. Based on rainfall distribution of an 18-year rainfall record, average rainfall was computed for each HRU and compared to the station data. Using analysis of differences, mean deviations per HRU were calculated and used to define *rain_adj*. The same procedure was applied to receive minimum and maximum temperature adjustment factors (*tmin_adj, tmax_adj*). The air temperature coefficient (jh_{coef}) used in evapotranspiration computation for each HRU was provided using the procedure described by LEAVESLEY *et al.* (1983) and compared to studies in similar environments (LEAVESLEY, 2004, pers. comm.).

PRMS allows defining the beginning and the end of the transpiration period (*transp_beg, transp_end*) for evapotranspiration accounting. According to southern hemisphere conditions, this period was set from October to April for agriculture and grassland dominated HRUs, while a 12-months period was chosen for evergreen vegetation (forest plantations and indigenous forests).

Parameters affecting soil and groundwater condition in each HRU are based on field observation and laboratory analysis of soil profiles. The soil moisture capacity (*soil_moist_max*) and initial value of available water (*soil_moist_init*) of the soil profiles were set by determining averaged values for each HRU. Parameters routing subsurface (*soil2gw_max, ssr2gw_rate, ssrcoef_lin, sstor-init* and *ssrcoeff_sq*) and groundwater (*gwflow_coeff,* *gwsink_coef* and *gwstor_init)* flows have been estimated initially with respect to the soil profile for each HRU and its underlying geology. By the comparison of model results of different parameter sets, it was found that these parameters significantly control basin runoff dynamics. Using sensitive analysis and ROSENBROCK (1960) optimization tools implemented in PRMS and runoff curve analysis, these parameters were iteratively adjusted during the calibration procedure.

Routing parameters required by the cascade module (*hru_area_pct, hru_cascade_id, hru-down_id,* and *strm_cascade_id*) were estimated by comparing the relation of mean HRU altitude and the length of shared boundary with the neighboring HRUs. Moreover, relief characteristics of the flow generating HRU like exposition and slope curvature were analyzed to identify the flow directions. By weighing each of the variables, a factor was introduced to describe the percentage of flow which is transferred from one HRU to a number of downslope HRUs.

Since snow is assumed to be a minor influence on the basin hydrology in this environment, parameters controlling snow dynamics such as snow interception storage capacity (*snow_intcp*), maximum threshold water equivalent (*snarea_thresh*), and maximum daily snow infiltration (*snowinfil_max*) were defined with respect to recommendations given by LEAVESLEY (2004, pers. comm.) and consequently little attention has been given regarding their assessment.

- *Non-distributed parameters*

Non-distributed parameters are characteristics which apply over the entire catchment. They usually represent monthly values and coefficients used to adjust temporal dynamics of hydrological components and processes. Monthly values to adjust rainfall dynamics (*adjmix_rain, tmax_allrain*), temperature (*tmax_lapse, tmin-lapse*) and solar radiation (*ddintcp, dday_slope, ppt_rad_adj,* and *tmax_index*) were set based on the work carried out by STAUDENRAUSCH (1996). Using the equation published by LEAVESLEY *et al.* (1983), monthly air temperature coefficient (jh_{month_coef}) was calculated to correct monthly variations in the JENSEN & HAISE (1963) evapotranspiration estimates.

Parameters used for each model scenario have been continuously evaluated regarding their importance for model performance. These efforts were complemented by incorporating model experiences of LEAVESLEY (2004, pers. comm.).

6.5.2.4.4 Model Calibration, Optimization and Verification

Model calibration and verification are fundamental and critical steps in any environmental model application. Model calibration is defined as the iterative process evaluating and refining the model to achieve a desired degree of correspondence between the model output and actual observations of the environmental system that the model is intended to represent. The purpose of model verification is to assure that the calibrated model properly assesses all the variables and conditions which can affect model results, and demonstrate the ability to predict field observations for periods separate from the calibration effort.

In this study, the purpose of model calibration was to estimate realistic model parameters and coefficient values so that PRMS closely simulates the hydrological process dynamics of the two basins and their wetlands prior and after afforestation. Initially, a calibration period reflecting prior and after afforestation conditions was chosen for each model run (Table 6.4). Since the monthly air temperature coefficient (*jh_{month_coef}*) and rainfall adjustment (*rain_adj*) are two of the most important controls on the water amount entering and leaving an HRU and the watershed, the first step of model calibration focused on these parameters that control the computation of evapotranspiration and rainfall dynamics. Both parameters have been adjusted until the simulated total runoff volume was within the range of 5% of the measured runoff. Model parameters and coefficients identified by the subsequent sensitivity analysis of each model run were manually adjusted to adequately fit the shape of the hydrograph and baseflow recession curves on a trial-and-error base. Herein, the timing and magnitude of measured hydrograph peaks were used to adjust parameters controlling expansion of contributing areas for surface runoff and parameters describing soil moisture dynamics. The shape of baseflow recession was used to adjust parameters related to subsurface and groundwater flows.

The manual calibration process was facilitated by the use of an interactive interface supported by the model. Measured and simulated runoff hydrographs were visually evaluated and compared after each change of parameters. In addition, statistical analysis of total flow volume, distribution of errors and the coefficient of efficiency (NASH & SUTCLIFFE, 1970) have been examined to evaluate model performance of each scenario. The internal optimization tool based on the two-dimensional ROSENBROCK (1960) was applied to determine whether further parameter optimizations could be achieved. The optimization tools were only used for parameters which were not measured, related to any measured parameter or available from other studies. Thus, the optimization was restricted to a small number of coefficients, mainly related to evapotranspiration computation using the JENSEN & HAISE (1993) formula.

While the model was calibrated to achieve the best fit to the calibration period, the verification results represent an independent assessment of the model capabilities. The verification of the model was carried out to the periods listed in Table 6.4 using the optimized parameter sets for each model scenario. Lastly, simulated and measured hydrographs of the verification periods were visually evaluated and compared. Moreover, the same statistical parameters as described above have been computed and were used to revise model performance in terms of accuracy and plausibility.

Table 6.4: Periods used for calibration and verification for each model scenario.

	Calibration	Verification	Entire period
Weatherley (pre-aff)	01.10.1998-30.09.1999	01.10.1999-30.09.2001	01.10.1998-30.09.2001
Weatherley (aff)	------	01.10.1998-30.09.2001	01.10.1998-30.09.2001
Mooi (pre-aff)	01.10.1988-30.09.1990	01.10.1990-30.09.1993	01.10.1980-30.09.1993
Mooi (aff)	01.10.1995-30.09.1997	01.10.1997-30.09.2002	01.10.1995-30.09.2002

6.5.2.4.5 Model Results Analysis

The PRMS model output tools provide daily, monthly or annual averages and totals for the model interval, which are available as both tabular summaries and graphs. Moreover, basic statistical summaries such as mean, min, max, standard deviation and skewness of each variable can be plotted. The user-defined output variables are computed separately as basin totals and for each individual HRU.

Addressing the objectives of this study, the hydrological modeling aims to evaluate hydrological changes resulting from afforestation activities at catchment (Weatherley, Mooi) and ecosystem (wetland) and its implication for landscape and water resources management. Thus, the analysis of model results was mainly focused on the volumes of basin runoff and the proportion of runoff components of for each watershed. With respect to this, the following analysis has been carried out at catchment scale:

- visual comparison of simulated and measured runoff in order to characterize and evaluate annual and seasonal flow dynamics,
- additional statistical analysis of model results was performed by computing and comparing supplementary statistical measures such as empirical coefficient of correlation, relative error in percent, and coefficient of efficiency (NASH & SUTCLIFFE, 1970) of the simulated and measured basin runoff,
- analysis of volumes and timing of the individual flow components and their proportion of the basin-wide runoff, and
- plausibility analysis and evaluation of individual water balance elements comparing model outputs with results from other studies.

In addition, the hydrological dynamics and its changes due to afforestation have been investigated at the ecosystem level, while individual HRUs characterizing grassland and forest areas and different types of wetland areas were analyzed in more detail. The analysis was primary focused on the following aspects:

- changes of evapotranspiration and runoff dynamics in areas which have been transformed from grassland to forest plantations, and
- the impact of afforestation on wetland dynamics by relating changes of water flow components of each wetland type to conditions prior and after planting.

Chapter 7

Results and Discussion

This chapter focuses on major results of the presented study. Addressing the scientific and methodological aims of this study, the chapter is organized in three main sections. Section 7.1 concerns with results obtained from the analysis of field measurements and existing data. Aggregating and integrating information received from the empirical observations and data analysis, Section 7.2 presents the integrated system analysis approach in order to provide a theoretical framework on hydrological system dynamics at different spatial and temporal scales, their relationships and regionalization. The empirical studies and the integrated system analysis formed the base for the parameterization and application of the models used for plant growth modeling in forest stands and the hydrological modeling of afforestation impacts on catchment scale. The results of the model applications are presented and discussed in Section 7.3, whereas specific attention has been given to the evaluation of the impact of afforestation at wetland and catchment scale.

7.1 Observation and Data Mining

The observation and data mining section focuses on the results from the field survey and the exploitation of existing data records. The results presented herein provide the base information and empiric data used for integrated system analyses at the specified scales (Section 7.2) and model applications (Section 7.3).

7.1.1 Hydro-meteorological Data

Hydro-meteorological data records are fundamental base data for environmental system analysis and modeling. Based on the processing of existing time series from several stations in the region and data records from monitoring efforts in the experimental catchment Weatherley, time series of regional climatological data and runoff as well as a variety of hydrometric data sets were provided for further analysis.

7.1.1.1 Regional Hydro-meteorological Data (Mooi Catchment)

Based on an intensive pre-processing, rain data from 66 stations distributed over the entire Umzimvubu catchment were selected to gather information about rainfall dynamics at different scales. For this study, a consistent data record representing daily rainfall was assembled for the period from 1970 to 1988 from all 66 stations. These data were used to identify and evaluate regional rainfall trends and spatio-temporal patterns (see Section 7.2.1).

Moreover, accurate records of daily precipitation are available for the period from 1970 to 2005 for the station Maclear (1 259 m asl.) which is the main station within the Mooi catchment and its neighboring stations Bele (1 036 m asl.) and Bloemgohoef (1 515 m asl.). As shown in Figure 7.1, the data records illustrate the variability of temporal rainfall dynamics, whereas a significant change of rainfall volumes is observed between summer (rain season) and winter (dry season). The data were used to identify rainfall dynamics in the Mooi catchment (Section 7.2.1) and to provide input data for hydrological modeling purposes (Section 7.3).

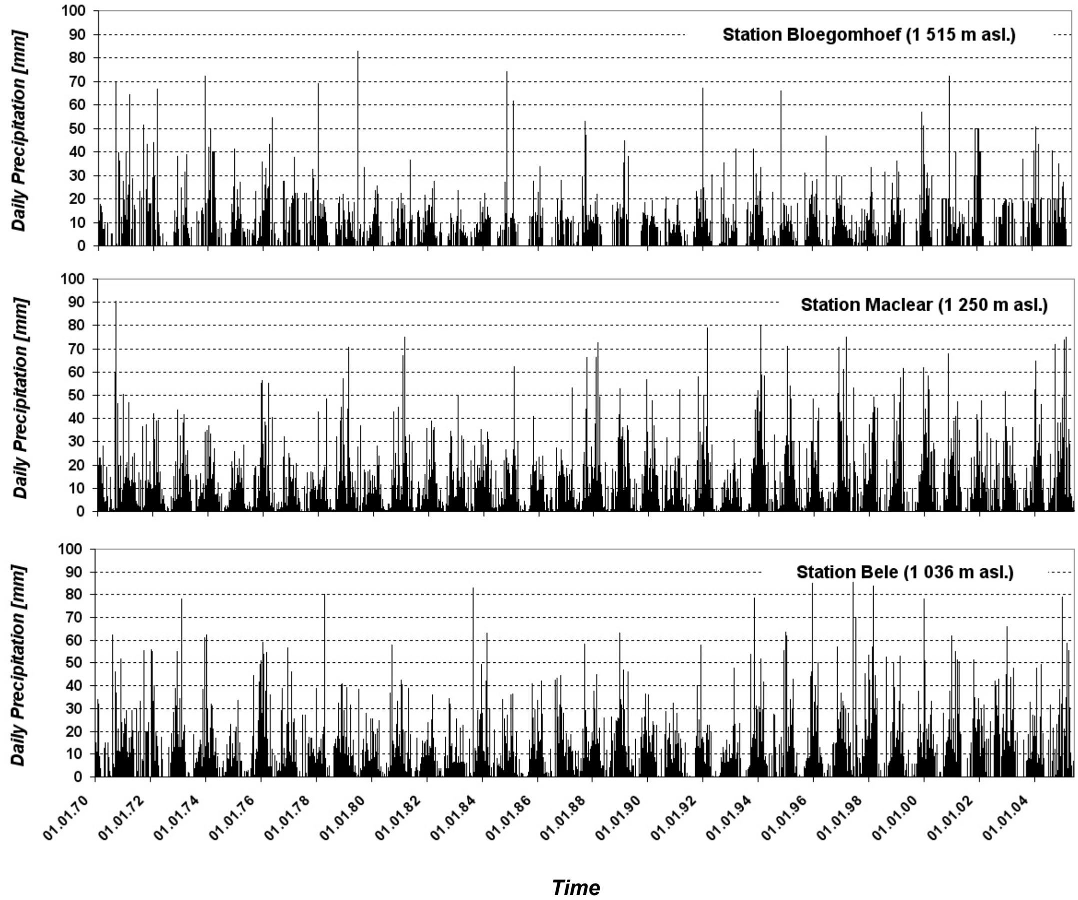


Figure 7.1: Rainfall records from 1970 to 2005 for the stations Bele, Maclear and Bloemgohoef.

Consistent records of daily minimum and maximum temperature starting in 1970 are available for climate stations in Umtata, Matatiele and Cape Hermes. For the climate station in Maclear, only a record ranging from 1980 to 2002 was available after preprocessing confirming intra-annual variation of temperatures (Figure 7.2). Moreover, time series of daily sunshine hours, relative humidity and wind speed were taken from the station Umtata which is closest to the Mooi catchment for the period from 1980 – 2006. Figure 7.2 illustrates the variability of humidity recorded at the climate station in Umtata.

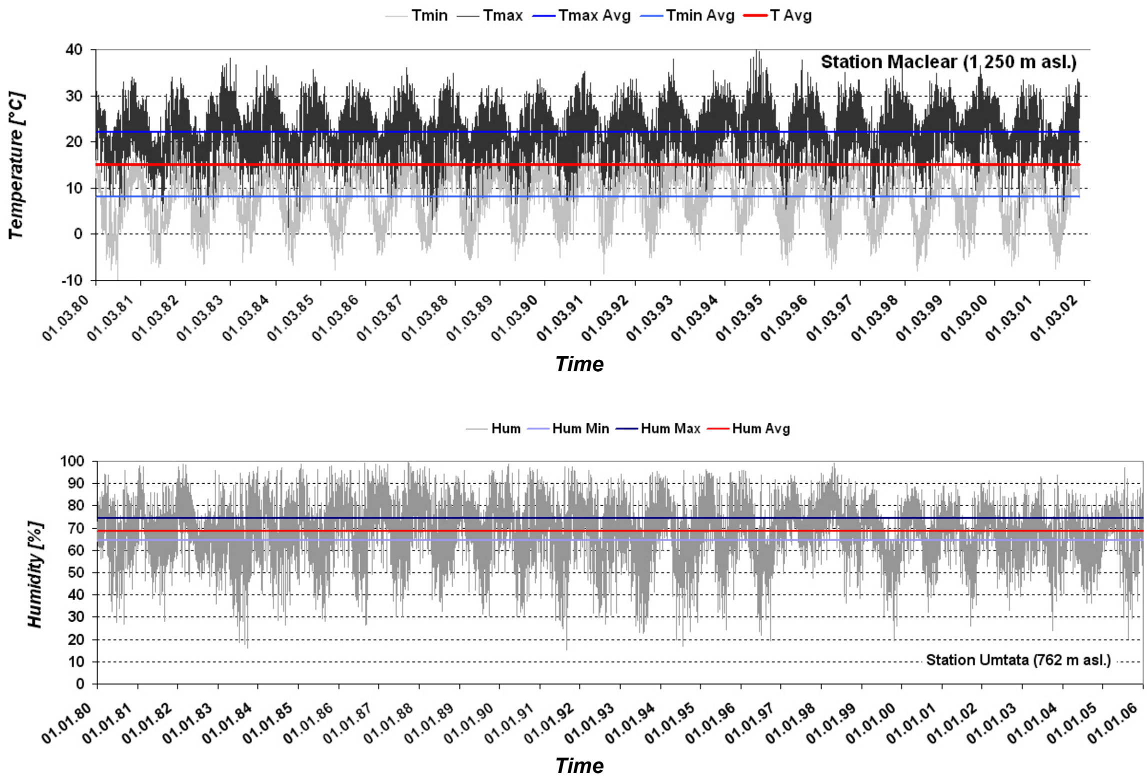


Figure 7.2: Minimum (grey) and maximum (black) temperature (above) curve for the station Maclear from 1980-2002 and relative humidity recorded in Umtata (below).

Observed runoff data of the river Mooi were available at a daily base for further analysis and modeling. Figure 7.3 shows the graph of daily averages of runoff measured at the weir in Maclear from 1970-2005. It is indicated, that the timing and volume of runoff is strongly controlled by the rainfall variability.

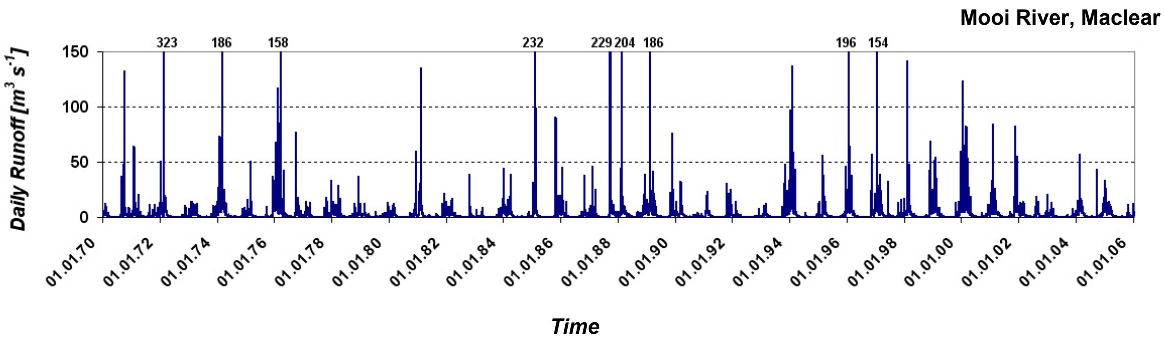


Figure 7.3: Long-term runoff record recorded at the Mooi river weir in Maclear from 1970 to 2005.

Comparing monthly averages of meteorological data sets with data published by SCHULZE (1997), WRC (1994) and HERBERT (1997), it was found that all climate data are in the range of annual and monthly averages given for the Eastern Cape Province. In addition, monthly and annual rainfall has been compared to averages from several stations published by WRC (1994), while runoff was compared to long-term averaged data computed for the Mooi catchment (WRC, 1994). Since these tests showed good correspondences with correlation coefficients varying from 0.63 – 0.87 for rainfall and

0.51 – 0.82 for runoff, data records were considered as being valid for further analysis and modeling.

7.1.1.2 Hydrometric Monitoring in Weatherley

A variety of hydrometric parameters were measured in the experimental test catchment Weatherley. Rainfall, temperature, radiation and runoff were used to describe the hydrological system behavior as well as for model calibration and verification. Soil moisture and groundwater fluctuation readings were related to rainfall events and associated runoff in order to identify and characterize runoff generation mechanisms on slopes.

A corrected, averaged daily rainfall record from 1998 - 2005 was created by the analysis of data from three gauges installed in Weatherley. Moreover, daily runoff volumes for the same time span were received by the analysis of runoff records from the lower weir which were validated with data from the upper weir. Figure 7.4 shows the intra-annual variations of corrected daily rainfall and runoff records received from measurements in Weatherley (1998 – 2005) confirming trends identified in the Mooi catchment.

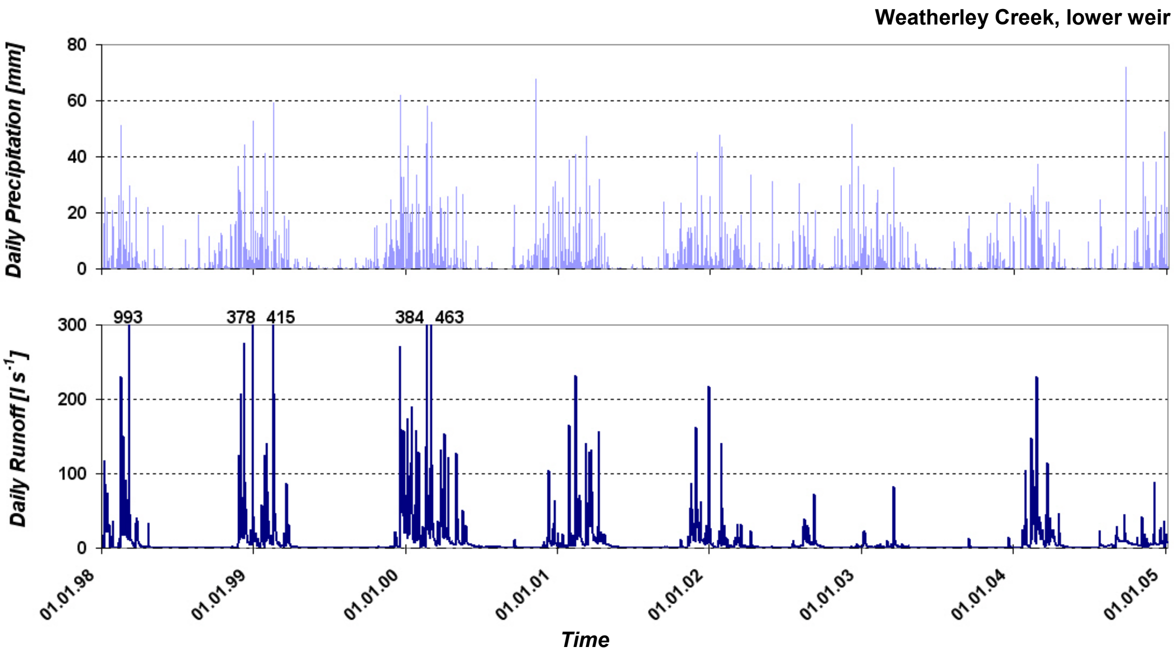


Figure 7.4: Daily rainfall (above) and daily runoff (below) observed in Weatherley from 1998-2004.

To obtain input parameters for the evapotranspiration model used in PRMS, daily radiation was calculated from temperature differences using an equation according to BRISTOW & CAMPBELL (1984). After verification of model results with station data from Umtata, a combined measured and estimated solar radiation records for the Weatherley catchment (1995 – 2002) was computed. Figure 7.5 shows the temporal dynamics of temperature and solar radiation records available for the test site Weatherley.

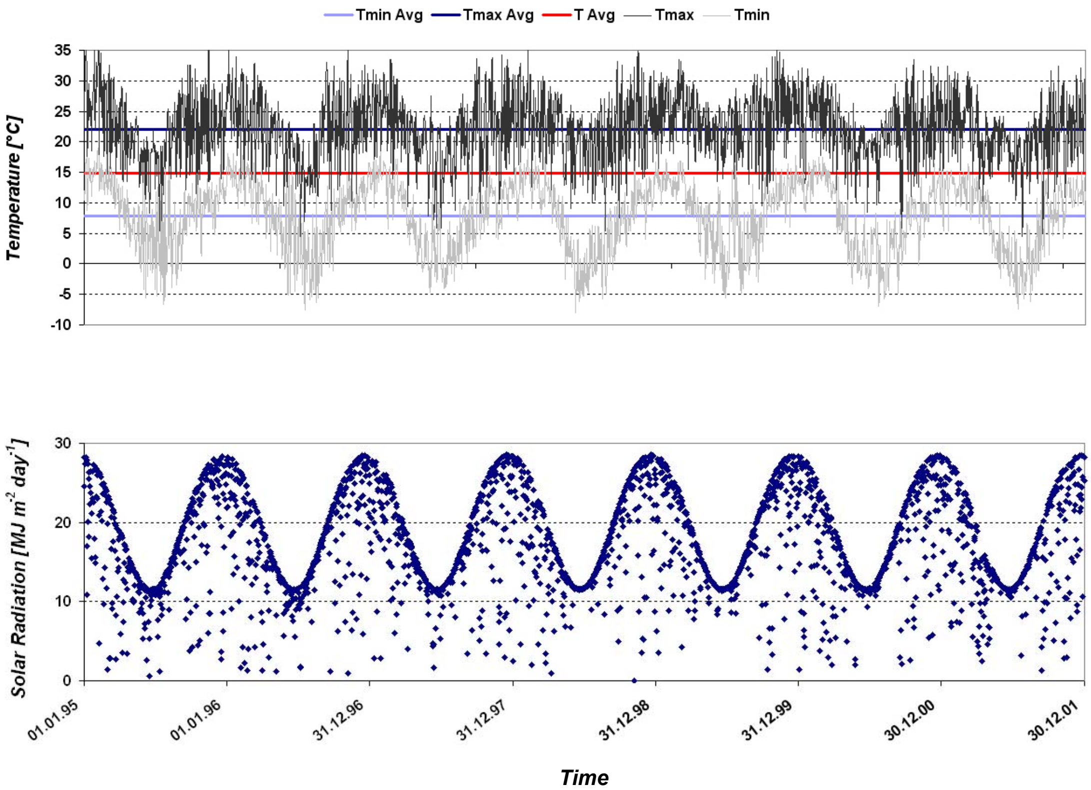


Figure 7.5: Minimum, maximum and mean temperature and estimated solar radiation for Weatherley for the period from 1995 to 2002 (after BRISTOW *&* CAMPBELL*, 1984)*

Since subsurface flow in unsaturated conditions is assumed to control wetland water inflow, soil moisture status was monitored along several transects in order to characterize mechanisms of soil water fluxes on hillslopes. Based on the data provided by LORENTZ *et al.* (2004), tensiometer and groundwater records were analyzed during and after individual rainfall events. Figure 7.6 shows an example of tensiometer response representing hourly readings of the capillary pressure head at three depths (35, 70, and 130 cm) at nest 8 in the lower catchment from February to March 2001 together with associated rainfall. Information received from those analyses allowed the development of a model characterizing hillslope dynamics.

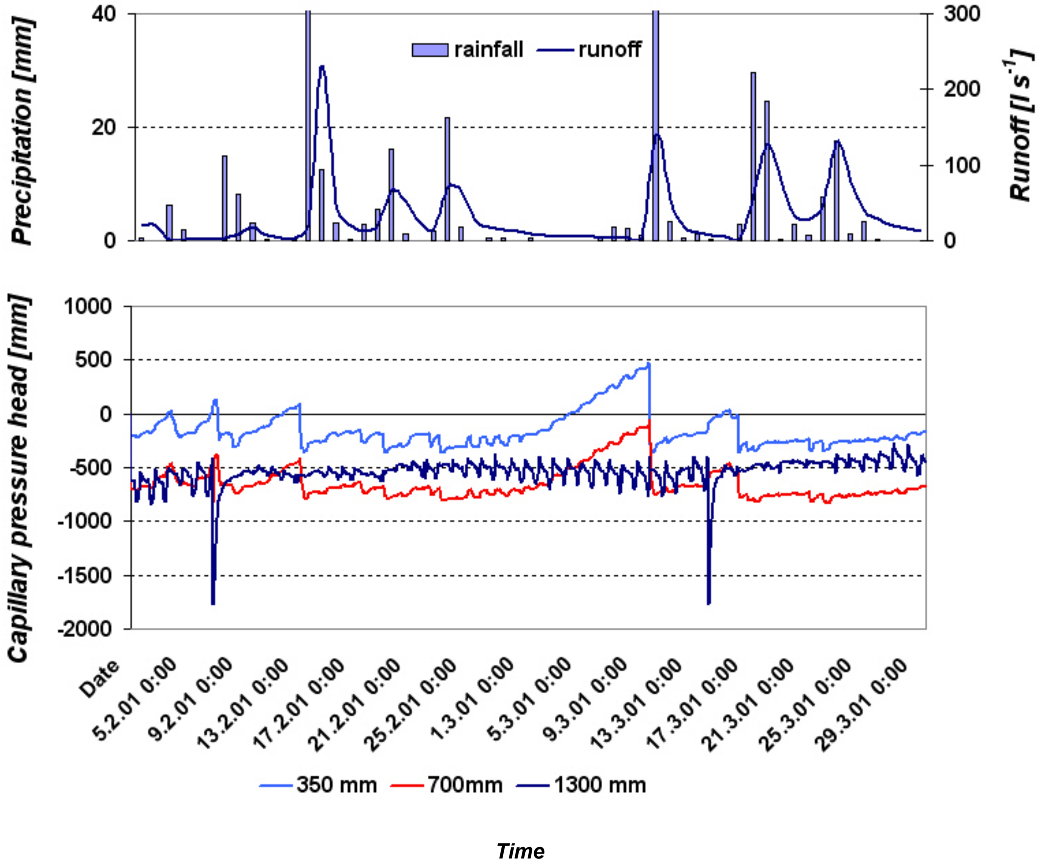


Figure 7.6: Tensiometer response at nest 8 which is located in a wetland in the lower catchment and associated rainfall-runoff graph for February and March 2001(Values lower than 0 indicate the level of the water table).

7.1.2 Soil Survey

A detailed soil survey was carried out incorporating existing data, field survey and laboratory analysis in order to identify and characterize dominant soil types, their distribution and in order to provide a variety of soil physical parameters which are of particular importance to calibrate the hydrological model. With respect to the objective of this study, specific attention has been given to wetland soils in selected wetland sites.

As a result of the soil survey, soil describing parameters were provided for 20 profiles in Weatherley and for 18 profiles of wetland soils from the Gatberg Vlei and Ku'Ntombininzinzi Vlei. Since soil physical properties are important parameters for soil water accounting simulations, soils were analyzed to obtain standard soil parameters for major soil types. This included field-based description of the profiles including soil type, color, depth of horizon, effective rooting depths and texture, and laboratory analysis to receive parameters such as particle size distribution, TOC, pH, hydraulic conductivity and cations exchange capacity (CEC) for all dominant soils. Table 7.1 gives a list of the locations of the investigated soil profiles and the respective soil types including a variety of characteristic parameters for each site, while Table 7.2 summarizes the main soil types of the sites and soil physical properties of a reference profile of each of these main soil types.

Table 7.1: Location of soils, selected stand characteristics and soil parameters, surveyed during field campaigns from 1997-2003.

Site	No.	Long	Lat	Altitude [m asl.]	Type	Soil Type	Slope [%]	Aspect	Depth [cm]	EffRoot Depth [cm]
Weatherley	1	28 19 34	31 06 32	1 301	SC	Cambisol	7	N	123	111
	2	28 19 45	31 06 01	1 263	SC	Luvisol	6	N	118	94
	3	28 19 40	31 06 00	1 309	SC	Regosol	11	NW	76	37
	4	28 19 39	31 06 01	1 306	SP	Stagnic Cambisol	5	N	117	117
	5	28 19 30	31 06 25	1 305	SC	Regosol	9	NE	45	45
	6	28 19 32	31 06 26	1 297	SP	Stagnic Luvisol	3	E	131	87
	7	28 19 31	31 06 31	1 305	SC	Regosol	6	NE	62	45
	8	28 19 34	31 06 26	1 323	SP	Cambisol	7	NE	180	143
	9	28 19 41	31 06 25	1 293	SP	Luvisol	6	NE	158	85
	10	28 19 47	31 06 24	1 292	SP	Stagnic Cambisol	4	NW	146	67
	11	28 19 46	31 06 23	1 284	SP	Gleysol	4	NW	152	152
	12	28 19 49	31 06 23	1 290	SC	Stagnic Cambisol	6	NW	167	78
	14	28 19 54	31 06 23	1 301	SP	Arensol	8	W	160	130
	15	28 20 04	31 06 01	1 258	SC	Cambisol	3	NW	180	92
	16	28 19 55	31 06 13	1 267	SC	Gleysol	1	NW	109	37
	17	28 19 42	31 06 27	1 294	SC	Gleysol	P	P	144	94
	18	28 19 42	31 06 30	1 310	SC	Stagnic Cambisol	6	NE	137	78
	19	28 19 34	31 06 32	1 272	SP	Stagnic Luvisol	4	E	240	116
	20	28 19 54	31 06 13	1 276	SC	Gleysol	2	NE	176	135
Gatberg Vlei	GV1	28 05 56	31 14 33	1 363	SP	Gleysol	1	N	240	195
	GV2	28 06 29	31 14 51	1 363	SC	Gleysol	P	P	175	175
	GV3	28 06 23	31 14 46	1 366	SC	Gleysol	P	P	270	184
	GV4	28 06 20	31 14 46	1 366	SC	Gleysol	1	NW	265	172
	GV5	28 05 58	31 14 34	1 363	SP	Gleysol	P	P	374	204
	GV8	28 06 29	31 14 46	1 363	SC	Gleysol	P	P	175	175
	GV11	28 06 30	31 14 46	1 363	SC	Gleysol	P	P	270	217
	GV12	28 06 00	31 14 49	1 363	SC	Gleysol	P	P	125	75
	GV13	28 06 01	31 14 46	1 364	SC	Gleysol	P	P	76	76
	GV14	28 05 59	31 14 42	1 367	SC	Gleysol	1	NW	100	63
	GV16	28 05 51	31 14 42	1 364	SC	Gleysol	P	P	143	143
Ku'Ntombininzinzi Vlei	CH1	28 16 27	31 07 52	1 290	SC	Gleysol	P	P	165	165
	CH2	28 16 24	31 07 53	1 289	SC	Gleysol	P	P	205	180
	CH3	28 16 33	31 07 53	1 289	SC	Gleysol	P	P	195	195
	CH4	28 17 51	31 08 42	1 290	SC	Gleysol	P	P	178	125
	CH7	28 13 42	31 07 29	1 325	SC	Gleysol	P	P	195	165
	CH8	28 13 43	31 07 29	1 326	SC	Gleysol	P	P	140	140
	CH9	28 13 42	31 07 28	1 325	SC	Gleysol	P	P	145	145

SC … soil core; SP … soil pit; P …plane

Addressing the purpose of this research, wetland soils were studied more intensely. Herein, soils were described by detailed field work and by analyzing disturbed and undisturbed soil samples at the laboratory. To illustrate a typical wetland soil, Figure 7.7 shows the entire profile of a soil from a valley bottom wetland (Gatberg Vlei), while Figure 7.8 gives an example of the soil physical and chemical parameters derived from a typical wetland soil from the Ku'Ntombininzinzi Vlei.

Table 7.2: Typical soil types and selected parameters from a reference profile shown for each soil type found in the Weatherley and Mooi catchments.

Soil Type (No. of Profiles)	H	Depth [cm]	Gravel [%]	Sand [%]	Silt [%]	Clay [%]	Corg [%]	pH [H_2O]	pH [KCL]	HCond [µS cm-1]	CEC [meq 100g-1]	Color
Cambisol	A	0-53	0.0	69.3	21.3	9.4	0.84	5.83	4.62	41	3.41	10YR3/5
	B	54-111	0.0	55.5	27.1	17.4	0.14	5.72	4.27	20	3.57	5YR4/6
	C	112-167	0.1	72.5	15.3	12.1	0.02	5.40	4.34	22	2.93	2.5YR3/5
Luvisol	A	0-48	0.0	52.0	30.1	17.9	1.41	5.47	4.22	29	3.82	5YR3/2
	B	49-94	0.1	46.2	28.3	25.4	0.32	5.78	4.16	24	2.40	2.5YR3/4
	C	95-185	0.0	43.0	20.9	36.1	0.16	5.70	4.19	23	6.63	5YR4/4
Regosol	A	0-45	0.1	58.3	28.6	13.0	1.21	4.63	3.79	25	3.16	5YR3/2
	C	46-70	1.4	49.6	27.0	22.0	0.11	4.01	3.69	21	2.84	5YR3/4
	C	71-104	0.7	60.2	22.9	16.2	0.10	4.50	3.90	19	2.54	5YR3/4
Stagnic Cambisol	A	0-41	0.0	70.4	19.1	10.5	1.36	5.48	4.21	34	3.03	5YR3/2
	E	42-84	0.4	62.1	22.7	14.8	0.31	5.59	4.17	31	1.84	2.5YR4/4
	B	85-117	0.6	62.7	19.3	17.4	0.11	5.71	4.04	19	2.31	5YR3/4
	C	111-185	0.0	52.5	16.4	31.4	0.18	5.69	3.98	11	4.02	2.5YR3/3
Stagnic Luvisol	A	0-31	0.0	41.6	41.3	17.1	1.63	4.50	4.18	40	3.93	10YR4/2
	E	32-54	1.3	42.36	38.1	18.3	0.77	4.25	4.10	16	4.42	5YR5/4
	B	55-116	0.3	41.0	32.1	26.6	0.12	4.58	4.35	13	4.12	7.5YR5/4
	C	117-185	0.2	30.4	32.6	37.0	0.04	4.71	4.07	13	6.21	10YR6/3
Gleysol	A	0-35	0.1	33.3	40.3	26.4	1.82	5.94	4.12	35	7.69	2.5YR4/2
	G	36-160	2.1	35.0	31.1	31.8	0.39	6.50	4.26	17	8.80	10YR4/3
	C	161-240	1.2	37.4	38.5	22.9	0.13	6.67	4.71	24	9.37	7.5YR4/2

H … horizon; Corg … organic matter content; HCond. … Conductivity; CEC … cations exchange capacity;

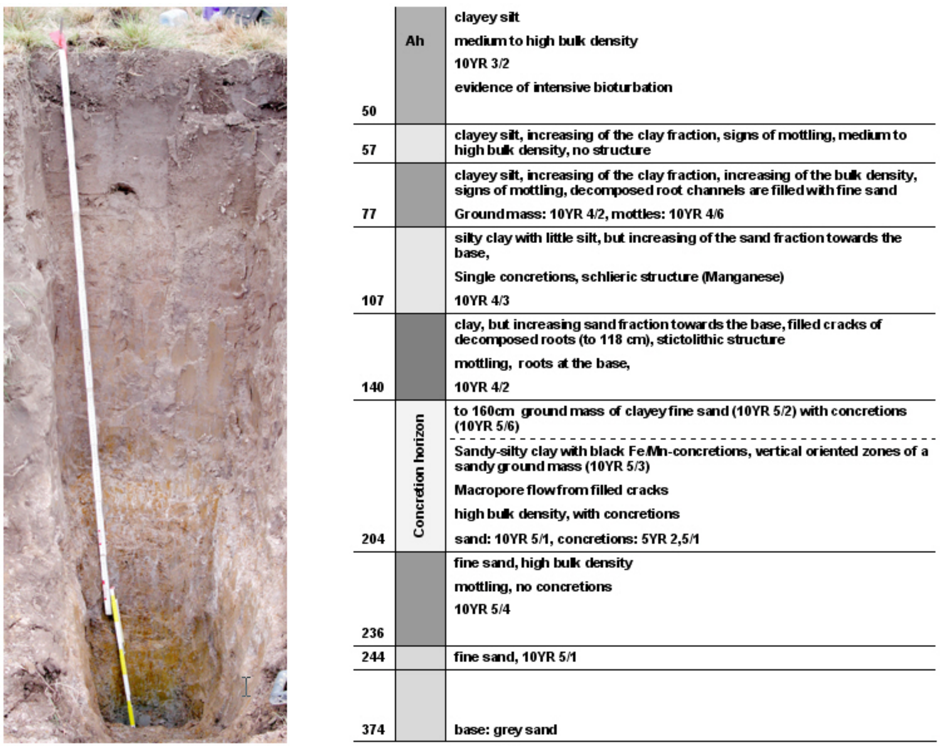


Figure 7.7: Characteristic profile of a wetland soil of a valley bottom wetland (GV 5, Gatberg Vlei).

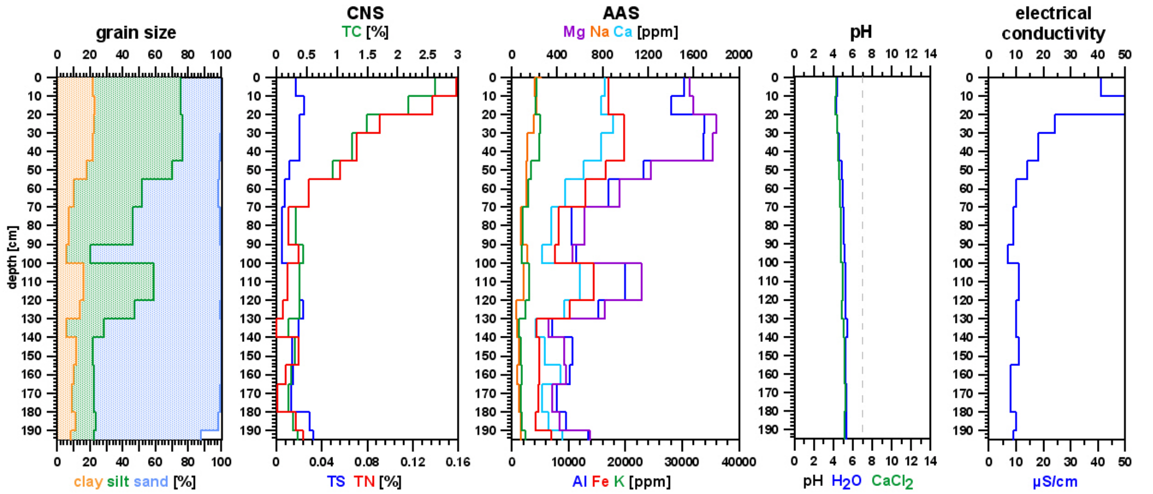


Figure 7.8: A selection of physical and chemical soil properties received from a typical wetland soil. The profile was taken in the northern central part of the Ku'Ntombininzinzi Vlei (CH3).

To determine soil moisture retention characteristics, undisturbed soil samples were taken from selected wetland soil profiles. Based on laboratory analysis using the ceramic plates technique, pF-curves and hydraulic conductivity were measured. Figure 7.9 shows three pF-curves received from representative wetland soils in Weatherley and the Gatberg Vlei.

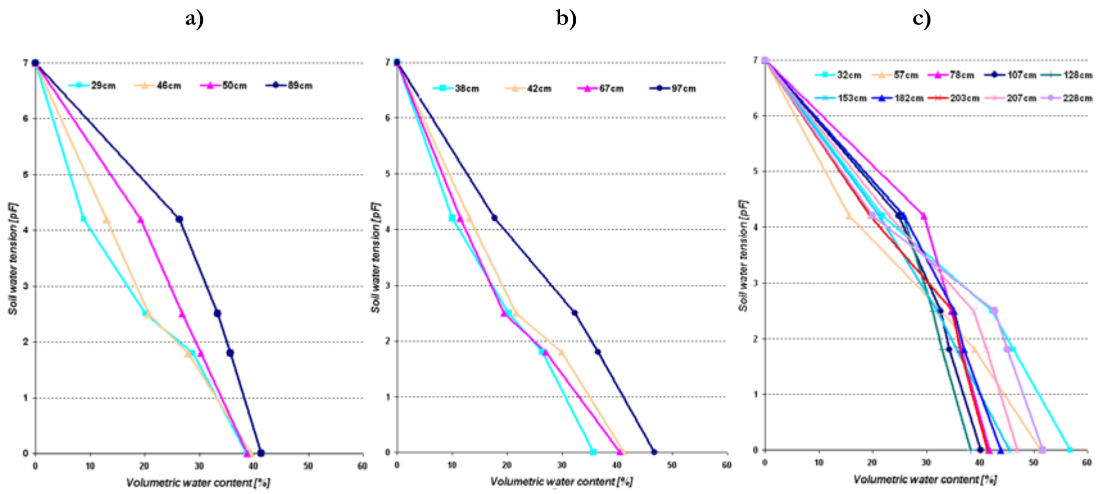


Figure 7.9: Examples of pF-curves for three wetland soils measured using ceramic plates (Eijkelkamp). Examples a) and b) are derived from shallow slope wetland soils in Weatherley, while example c) represents a wetland soil of the Gatberg Vlei.

The analysis results were compared to soils identified by various authors (ESPREY, 1997; HERBERT, 1997; LORENTZ *et al.*, 2001; LORENTZ *et al.*, 2004; ROBERTS *et al.*, 1996). From this effort it was found, that once the soils were converted from the South African Soil Taxonomy (SOIL CLASSIFICATION WORKING GROUP, 1991) to the FAO taxonomy (FAO, 1998), major soil types correspond very well regarding their distribution and soil physical properties and therefore confirm the appropriateness of these surveyed soils. Thus, soil data from these authors can be used for system analysis and modeling.

7.1.3 Geophysical and Sedimentological Survey

Geophysical and sedimentological studies were conducted in order to provide data which can be used to develop a landscape model incorporating wetland formation. Therefore, wetland sediments were studied to obtain information on their structure, thickness and the sediment layering. These studies were completed by the dating of organic materials and palynological studies aiming to associate sediment dynamics to palaeoclimatic conditions and historic land use.

7.1.3.1 Refraction Seismic Measurements

As discussed by BURGER (1992) and PULLAN & HUNTER (1999), refraction seismic surveys can be utilized to identify depth of bedrock, thickness and subsurface structures of unconsolidated sediments and underlying bedrock surface, and type of sediments or bedrock. In this study, refraction seismic measurements were carried out along seven representative cross and longitudinal profiles in several wetlands in Weatherley and in the Ku'Ntombininzinzi Vlei and Gatberg Vlei. In addition, measurements were used to verify and regionalize soil information obtained from existing data and point measurements in the field (Section 5.3.1; Section 6.2).

In general, the analyses of wave velocities indicate that relatively homogenous sediments with a varying thickness of 2 – 4 m overlay the triassic sandstone in all wetlands. As shown in several studies (BURGER, 1992; PULLAN & HUNTER, 1999), unconsolidated sediments usually provide low values of wave velocities. Thus, measured velocities of 300 - 500 m s^{-1} are assumed to represent the overburden, i.e. the wetland sediment. Since the variation of wave velocities is very small, the variation of the physical properties of the sediments seems to be very small too. As a consequence it is assumed that the sediments are very homogenous generally.

The interface to the underlying sandstone and thereby the sediment thickness was detected by a sharp increase of wave velocities. Its variation between 2 200 and 4 800 m s^{-1} is associated to jointing and unsteady weathering of the sandstone which could be surveyed at several outcrops. Significant inhomogeneities of traveltimes indicate weathered and fractured or non-weathered zones. Those zones were not measured in detail, since it was not of interest to this study and refraction seismic techniques are limited in reliably modeling such structures.

Figure 7.10 shows the raw data of a cross profile measured in Weatherley. By combining five single sequences, the total length of the profile was 102 m. Geophones were set in 2 m intervals, offset was 22 m. Measured travel times for the overburden ranged from 290 to 680 m s^{-1} and for the sandstone from 3 100 to 4 600 m s^{-1}. In this example, a 12-channel system was used.

Soil drilling comparisons indicated that all measured sequences provided good results. Thus, the derived profiles could be used to reconstruct wetlands subsurface structures and thereby to regionalize wetland characteristics. Moreover, information on thickness and subsurface structures of the unconsolidated sediments were used in the calibration of wetland HRUs.

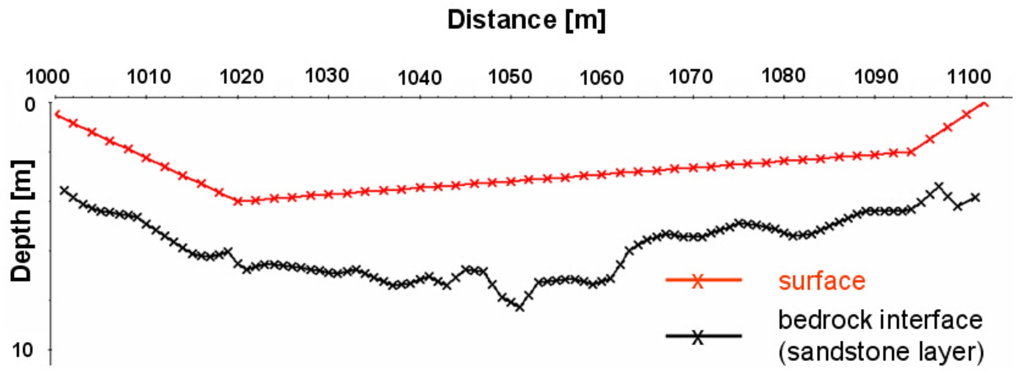


Figure 7.10: Example of a cross profile received from the seismic survey in Weatherley.

7.1.3.2 ^{14}C Dating

Since it was hypothesized that wetland formation was influenced by human beings, some efforts were undertaken to derive information on landscape evolution in general. For that reason, ^{14}C dating has been utilized to analyze organic samples collected from two wetland sites in the study area.

The samples from the Gatberg Vlei taken at depths between 220 cm and 240 cm were dated at 3 370 ± 51 radiocarbon yrs BP (Erl-1000, $\delta^{13}C$: -15.1‰) and 3 384 ± 58 radiocarbon yrs BP (Erl-1000, $\delta^{13}C$: -14.8‰). Consequently, the derived dates indicate a minimum age of valley floor sediments of about 3 550 calibrated yrs BP. Assuming that the date represents approximately the initial phase of the deposition of fine grained sediments found at the base and relatively steady conditions over the last 2 000 years, it furthermore can be concluded that at least 2 m of sediment have been deposited in a relatively short time span of about 1 500 years (3 500 yrs BP – 2 000 yrs BP).

The samples of the second wetland site (Diepfontain Farm) taken at a depth of 42 cm and 92 cm were dated at 5 487 ± 104 radiocarbon yrs BP (Erl-1000, $\delta^{13}C$: -26.3‰) and at 9 014 ± 107 radiocarbon yrs BP (Erl-1000, $\delta^{13}C$: -24.3‰) respectively. As a consequence it is assumed that the core represents a time span of nearly 10 000 years (1 cm/100 yrs.). It need to be noted that the wetland is identified as a specific wetland type regarding its position and the high organic content over the whole profile. Latter was not found to a comparable extent anywhere else. For that reason and the topography of the surroundings, the bog was supposed to be developed from an ancient lake and therefore different from wetlands occurring at lower altitudes. The lake theory was confirmed by maps from the early 1950s showing a lake and an interview with the farmer of the Diepfontein farm, who reported that earlier the bog site was completely covered by water. Although the dating can only be roughly used to reconstruct wetland evolution, it was shown that archives representing Holocene landscape dynamics exist. When considered for further investigation (e.g. isotope analysis), the cores can be analyzed to support the reconstruction of the Holocene climate and to validate existing climate records.

Presented ages of wetland samples and associated error values indicate the accuracy of the dating inherently and thereby the potential of such methods for landscape analysis.

Once established, depth-age relationships in sediment and peat chronologies can be used to provide estimates of deposition dynamics and age of wetlands. Nevertheless, supplementary data are needed to validate dating results and implications. Such data can be provided by pollen analysis, anthropological studies and other dating techniques.

7.1.3.3 Palynological Studies

In this study, pollen analysis was considered to provide additional information on vegetation dynamics in the past, i.e. during the formation of wetlands. A total of 23 samples were taken for pollen analysis from 12 open soil pits along the Mooi and the Gatberg Rivers. A pre-test has shown that the samples varied in pollen quantity and preservation. For that reason only samples in good condition were chosen for analysis. As summarized in Table 7.3, five samples from three test sites were finally selected for pollen analysis.

Table 7.3: Sample sites and results of pollen analysis.

Location	Coordinates	Sample	Depth [cm]	Pollen [%]
Mooi River (Glen Cullen)	28 13 24.5 E 31 03 39.8 S 1 313 m asl.	Sa02022507	0-5	Poaecea (30), Cyperaceae (16), Asteroidae (7), Artemisia (5), Caryophyllaceae (3), Lamiaceae (5), Dryopteris (3), Pinus (3), undiff. (30)
		Sa02022500	90-95	Salix (3), Poaecea (57), Cyperaceae (25), Asteroidae (2), Cichorioidae (3), Chenopodiaceae (2), Artemisia (2), Apiaceae (1), Phaeoceros (3), Pinus (2)
		Sa02022504	175-180	Poaecea (63), Cyperaceae (15), Asteroidae (3), wild grasses (?) (3), Cichorioidae (2), Chenopodiaceae (1), Scutellaria (1), Geum (1), Chrysosplenium (2), Phaeoceros (3), Dryopteris (2), Pinus (1), undiff. (3)
Gatberg (Albenia Farm)	28 06 03.4 E 31 14 35.5 S 1 374 m asl.	Sa02022702	195-200	Salix (1), Poaecea (49), Cyperaceae (34), Asteroidae (4), wild grasses (?) (3), Chenopodiaceae (1), Papaver (1), Alnus (3), Pinus (1), undiff. (3)
Ku'Ntombini nzinzi Vlei (Castaneda Farm)	28 13 42.4 31 07 28.6 1 325 m asl.	Sa02022801	125-130	Salix (3), Poaecea (22), Cyperaceae (36), Asteroidae (6), wild grasses (?) (3), Lamiaceae (1), Phaeoceros (2), Dryopteris (3), Alnus (2), Cenaura cf. nigra (2), Brassica-Sinapis (1), Phyteuma (1), Lilium (1), Pinus (1), undiff. (16)

Independent from depth, all samples showed abundance of grass species with dominance of *Poaceae* species (sweet grasses). Only one sample was dominated by *Cyperaceae* species (sour grasses). Bigger grains of *Poaceae* could be related to wild grass species like *Bromus*, but they also could be relics of agricultural activities (cerials). In addition evidence is given for open land vegetation like herbaceous perennials (*Asteroideen, Chenopodiacen*) and related species with lower frequency (*Chichoriodieen, Artemisia*). With the exception of willow (*Salix*), groves were not clearly identified in the samples. The existence of pine pollen (*Pinus*) is associated with wind transport and they are assumed to be washed into the soil by evident macro-pore flow and piping. Unexpectedly, reed pollen was not clearly identified in any of the samples.

Summarizing the results, grass pollen in particular has been found throughout the samples, whereas lesser evidence is given for groves and reeds. The dominance of grass pollen in all samples leads to the conclusion that the surroundings were covered by grassland during the entire time when sediments were deposited. In addition, it can be assumed that the landscape was dominated by sweet grass species over a long period, since the majority of grass pollen was addressed to sweet grass species in each sample of the Mooi site and in 2 m depths in the Gatberg Vlei. Moreover, hypothesizing that the sediment deposition started about 3 500 yrs BP before, it is concluded that the profile of the Mooi site represents grassland vegetation over the last 3 500 years. Pollen grains for higher vegetation like bush or tree species were not found. This indicates that either no higher vegetation was present during the sediment accumulation in the floodplains or indigenous vegetation does not provide preservable grains or mechanisms are insufficient to transport grains and spores over long distances. It is hypothesized that the latter assumption is most likely, since indigenous forest is still preserved in the kloofs but no evidence is given for related grains or spores in the analyzed profiles. Nevertheless, this can only be verified by additional ecological investigations.

The Mooi profile also gives some indication that the grassland composition has changed over time, since the sweet grass portion was reduced in the upper part when compared to the lower parts. The evidence of burning and grazing management for over 600 yrs. (FEELY, 1987) evidently contributed to a succession or even degradation of the sweet grass dominated veld towards resistant sour grass veld that is still ongoing (SHORT *et al.*, 2003). Even though this needs to be verified, the grassland is now largely dominated by sour grass species that tend to be more adapted to recent environmental conditions and fire management (EVERSON & TAINTON, 1984; SHORT *et al.*, 2003).

With respect to the data analysis, it should be noted that macropore flow and piping are evident within the profiles, and therefore transport processes might affect grain distribution. Nevertheless the results give some information on vegetation pattern, but certainly more analysis is needed to verify the given hypotheses. For example, the analysis of the grain condition can provide information on the condition during deposition and the transport process. Once the grass or herbaceous pollen grains are addressed to a specific species, they give information on the habitat, and thereby the environmental condition.

Since time and funding was limited, only a few samples were analyzed. Taking the small number of samples and their locations into account, presented results only give a rough indication of vegetation composition and distribution. Hence, the pollen analysis of further samples from the surveyed and additional profiles, including the soil cores taken from the bog site near the Diepfontein farm, would offer the possibility to verify the obtained results. Moreover this would improve the knowledge on species composition and their spatial and temporal dynamics.

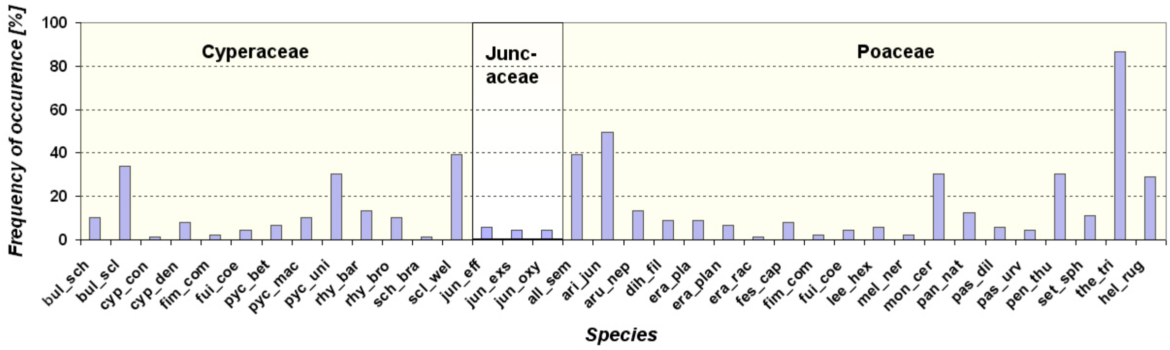
7.1.4 Vegetation Data

In the present study, vegetation observation was mainly focused on areas that are covered by grassy vegetation and commercial forests. The aim of these studies was to characterize vegetation distribution and dynamics and, moreover, to delineate empirical parameters that could be used for the hydrological modeling.

7.1.4.1 Grassland and Wetland Vegetation Monitoring

The vegetation of grassland and wetland areas was intensively investigated during field campaigns in 1997, 1998 and 2001. A comprehensive data pool comprising all major parameters characterizing species, plant physiology and needed site conditions was created. The provided data were used ***i)*** to better understand the distribution and dynamics of grassland and wetland vegetation, ***ii)*** to characterize different wetland types, ***iii)*** as input information for the discretization of HRUs, and ***iv)*** for the parameterization of the PRMS model.

Firstly, species composition and distribution in grassland and wetland areas were determined at 89 randomly selected plots in Weatherley. Utilizing field guides developed for South Africa (GIBBS RUSSEL *et al.*, 1991; HILLIARD, 1996), mainly species of *Cyperaceae, Poaceae* and *Juncaceae* were identified in the field. As illustrated in Figure 7.11 the frequency of occurrence of each species was determined based on dominance and abundance analysis carried out by DAHLKE *et al.* (2003). Indicator plants characterizing environmental conditions were identified. Complementary observations have been done in grassy environments throughout the Mooi and Wildebees catchments and in the Gatberg Vlei in order to verify these results. Summarizing these studies it was found that results from Weatherley can be easily regionalized, since those investigations widely confirmed species composition and their frequency of occurrence in the observed areas.



bul_sch … Bulbostylis schoenoides (Kunth); bul_scl … Bulbostylis scleropus C.B. Clarke; cyp_con … Cyperus congestus Vahl; cyp_den Cyperus denudatus L.f. var. Denudatus; fim_com … Fimbristylis complanata (Retz.); fui_coe … Fuirena coerulescens Steud.; pyc_bet … Pycreus betschuanus (Boeck.) C.B. Clarke; pyc_mac … Pycreus macranthus (Boeck.) C.B. Clarke; pyc_uni … Pycreus uniolides (Boeck.) C.B. Clarke; rhy_bar … Rhynchospora barrosiana Guagl.; rhy_bro … Rhynchospora brownii (Roem. & Schult.); sch_bra … Schoenoplectus brachyceras (A. Rich.) Lye; scl_wel … Scleria welwitschii C.B. Clarke; jun_eff … Juncus effusus; jun_exs … Juncus exsertus Buchen. subsp. exsertus; jun_oxy … Juncus oxycarpus E. Mey. ex Kunth; all_sem … Alloteropsis semialata (R. Br.) Hitchc. subsp. eckloniana (Nees); ari_jun … Aristida junciformis Trin. & Rupr. subsp. Junciformis; aru_nep … Arundinella nepalensis Trin.; dih_fil … Diheteropogon filifolius (Nees) Clayton; era_pla … Eragrostis plana Nees; era_plan … Eragrostis planiculmis Nees; era_rac … Eragrostis racemosa (Thunb.) Steud.; fes_cap … Festuca caprina Nees; fim_com … Fimbristylis complanata (Retz.); fui_coe … Fuirena coerulescens Steud.; lee_hex … Leersia hexandra Swartz; mel_ner … Melinis nerviglumis (Franch.) Zizka; mon_cer … Monocymbium ceresiiforme (Nees) Stapf; pan_nat … Panicum natalense Hochst.; pas_dil … Paspalum dilatatum Poir.; pas_urv … Paspalum urvillei Steud.; pen_thu … Pennisetum thunbergii Kunth.; set_sph … Setaria sphacelata (Schum.) Moss var. Torta (Stapf) Clayton; the_tri … Themeda triandra Forssk.; hel_rug … Tristachya leucothrix Nees

Figure 7.11: Frequency of occurrence for species found at 89 vegetation plots along seven transects in Weatherley.

Reliable plant-biophysical parameters obtained from empiric observations allow a better calibration of processes of physically-based hydrological models than that provided by using defaults or literature values (WATSON, 1999). Thus, parameters that are of importance for the modeling of evapotranspiration and interception processes were measured at the same plots as described above. Combining data from earlier studies (DAHLKE, 2002) with current measurements, the averages of vegetation height, root length, LAI and cover density were found for grassland and the different wetland types. Because LAI was derived from two different methods, results were evaluated. From this effort it was found that reliable LAI values can be derived from its empiric relationship to dry biomass, in particular in grasslands shorter than 30 cm, where directly measured LAI using the plant canopy analyzer showed insufficient results (DAHLKE, 2002).

Based on statistical analysis it was shown that data measured in the field seemed to be consistent and reliable according to their range and standard deviations. On the other hand, estimations of root density did not provide consistent results, i.e. results showed a high inconsistency in each specific group. Consequently, this parameter was excluded from further studies. Table 7.4 summarizes the statistics of all parameters derived from the grassland and wetland analysis that were used for further analysis.

Table 7.4: Summary of statistics derived from the analysis of parameters measured in grassland and wetland areas.

Type	Parameter	Samples	Min	Max	Mean	Median	Std
Grassland	Cover density [%]	158	15	100	55	60	21.7
	Vegetation height [cm]	158	8	64	26	26	10.8
	Root length [cm]	158	4	48	16.6	15	7.7
	LAI	105	1	4.1	2.4	2	0.8
Valley B. Wetland	Cover density [%]	69	50	100	89.3	90	51.9
	Vegetation height [cm]	69	33	79	52	51	9.5
	Root length [cm]	69	19	56	35.2	35	7.3
	LAI	69	1.28	6.1	4	4.1	0.89
Slope Wetland	Cover density [%]	65	45	100	80.8	80	13
	Vegetation height [cm]	65	11	56	33.2	35	10.1
	Root length [cm]	65	14	56	31.1	28	11.6
	LAI	65	1.2	4.8	3.18	3.4	0.92
Plateau Wetland	Cover density [%]	4	55	38	67.5	67.5	11.9
	Vegetation height [cm]	4	33	42	37.5	37.5	3.7
	Root length [cm]	4	30	41	37.5	39.5	5.0
	LAI	4	1.4	3.7	2.4	2.25	0.97

These studies were complemented by measuring slope, aspect and soil moisture and by determining the soil type at each location. Topographic impacts on vegetation composition and distribution could be ascertained, and moreover, the requirements of specific grassland and wetland plant communities regarding soil moisture and type were identified, thus completing earlier studies (DAHLKE *et al.*, 2003).

7.1.4.2 Forest Plantation Monitoring

The distribution of forest communities, ground cover, and climate strongly influence the spatial variability of interception losses (BRYANT *et al.*, 2005). Although canopy storage capacity is a property of individual trees, a linear relationship exists between canopy storage capacity and the number of trees per hectare (TEKLEHAIMANOT & JARVIS, 1991). This indicates that canopy storage capacity and interception losses are a function of canopy cover in forest communities.

As found in earlier studies (HELMSCHROT, 1999), there is a close relationship between stand characteristics and canopy structure. Thus, intensive field surveys were carried out annually from 1997 – 2005 to measure plant-biophysical data such as DBH, crown diameter, tree height, rooting depths, wet and dry biomass, cover density, LAI and stocking in selected pine and eucalyptus stands of different ages. For example, Table 7.5 shows stand parameter for *P. patula* stands sorted by ages. Characterizing stands and canopy structure, these data could be used to calibrate the plant growth model, and thereby to model evapotranspiration, interception and soil water dynamics in forest stands of varying species and ages.

Table 7.5: Summary of statistics derived from the analysis within Pinus patula stands grouped to four different age classes.

Type	Parameter	Stands	Min	Max	Median	Mean	Std
P.pat. 2-5 yrs.	Stocking [stems ha^{-1}]	11	917	1107	1012	1024	71
	DBH [cm]	11	8.4	10.1	9.8	9.72	0.72
	Mean Height [m]	11	2.6	4.3	3.9	3.85	0.82
	Cover density [%]	11	45	55	58	57	7.89
P.pat. 5-10 yrs.	Stocking [stems ha^{-1}]	18	913	1150	1018	1025	66
	DBH [cm]	18	14.8	21	17.9	17.9	1,83
	Mean Height [m]	18	10.9	15.04	13.65	13.36	1.17
	Cover density [%]	18	65	80	70	70	5.3
P.pat. 10-15 yrs.	Stocking [stems ha^{-1}]	22	653	1105	913	910	114
	DBH [cm]	22	18.8	26.3	21.5	21.8	2.07
	Mean Height [m]	22	14.04	21.4	17.03	17.5	1.76
	Cover density [%]	22	65	85	75	74	6.03
P.pat. 15-22 yrs.	Stocking [stems ha^{-1}]	36	390	1322	936	919	231
	DBH [cm]	36	18.6	33.7	24.6	25.4	3.7
	Mean Height [m]	36	14.4	22.7	17.3	17.5	2.1
	Cover density [%]	36	35	85	65	63.8	11.7

Based on the analysis of data measured in 152 forest stands, time series representing species and age dependent parameters were provided for the three species. Exploring the forest data base in order to provide information of the species-related distribution of forest stands it was found that about 96 % of the forest stands are planted with *Eucalyptus nit.*, *Pinus pat.* and *Pinus rad.*

Consequently, *Eucalyptus grandiis* and *Pinus ell.* were excluded from further analysis. Figure 7.12 summarizes selected parameters (stocking, DBH, height, cover density and LAI) as averages for each stand age for *Eucalyptus nit.*, *Pinus pat.* and *Pinus rad.* The graphs show that an age-dependent relation can be derived for each of the parameter. Tree density decreases for all species with increasing age, while DBH and height increase. Cover density and LAI, which are strongly related, show a similar behavior, i.e. increasing values until the canopy is closed. Once the canopy is closed, both parameters tend to decrease. The comparison of these data with findings from other studies (SCHULZE, 1995; SUMMERTON, 1995, WATSON, 1999) proved the plausibility and reliability of the results.

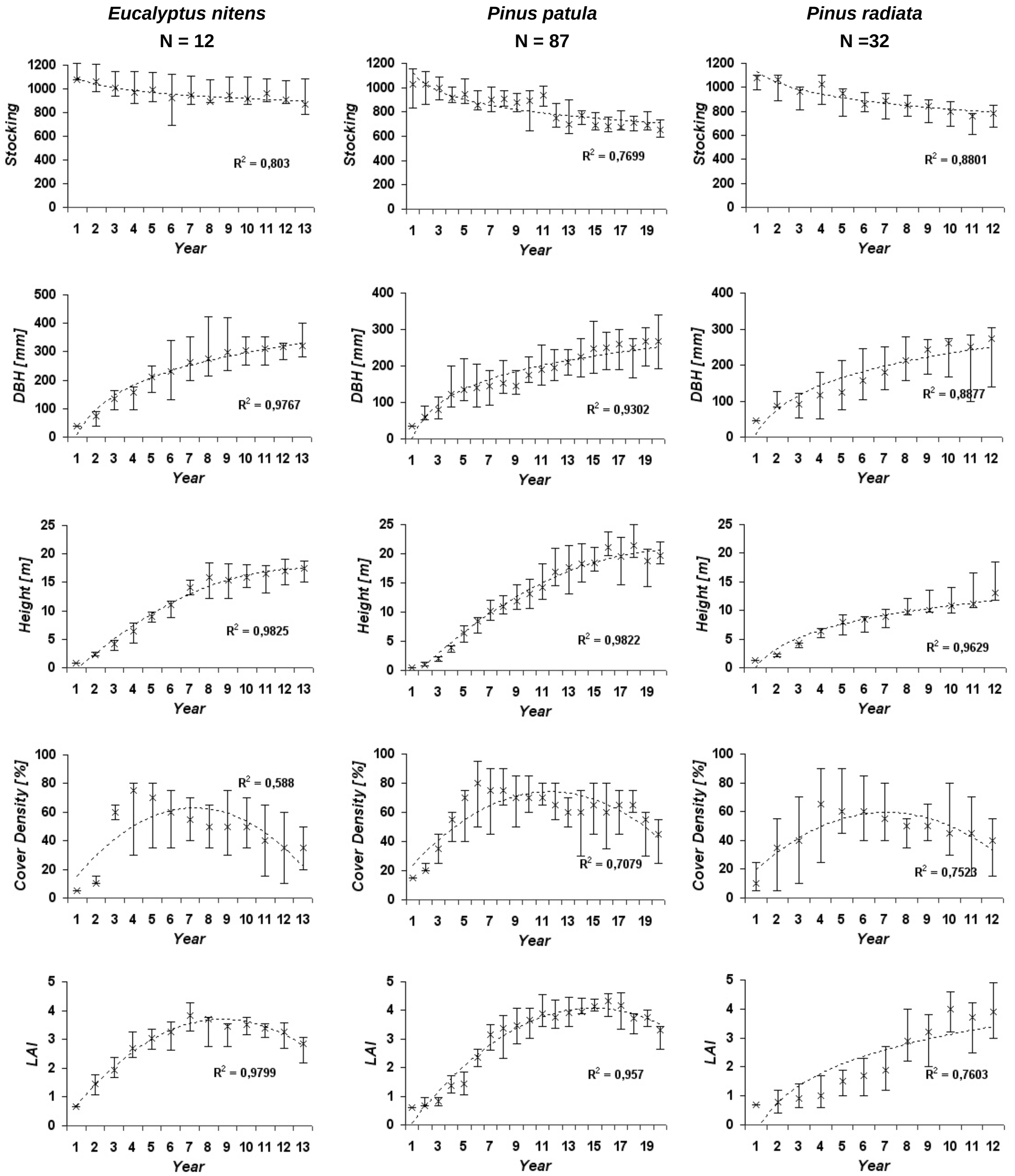


Figure 7.12: Stocking, DBH [mm], Height [m], Cover density [%] and LAI for E. nit., P. pat. and P. rad. defined as averages for each stand age and their skewness. (For 1-2 years old pine trees, diameter was measured 25 cm about surface instead of DBH).

Summarizing field observations, forester's interviews and data analysis, it is assumed that forest structural variations with age are affected by many more factors than the measured parameters. For example, relief-related effects and management practices like pruning and thinning influence forest and canopy structures and growth dynamics. Even though information was available on these parameters, only little attention has been given to the analysis of their impact on forest dynamics, since time and funding was limited. Using these data sets to improve knowledge on forest dynamics in the study area is recommended to be an objective of further studies.

Since litter is considered as important factor with major influence on interception and soil water dynamics (HEWLETT, 1982), the age-dependent litter thickness was additionally measured for *P. pat., P. rad.* and *E. nit.* The litter thickness was measured at 15 sites within 19 eucalyptus stands and 64 pine stands (*P.pat*: 32; *P.rad.*: 32). The taken measurements were averaged and considered as mean litter thickness of each stand at a defined age. As illustrated in Figure 7.13, the litter accumulation is clearly related to the age of the stands ($r_{P.pat}$=0.88, $r_{P.rad}$= 0.92 and $r_{E.nit}$=0.89). It indicates that litter accumulation is increasing with increasing age, but it also reveals that the decomposition of litter starts with the closure of the canopy. Consequently, interception losses are increasing by the accumulated effect of increasing LAI (canopy closure) and litter accumulation. Thus, the developed relations of litter deposition and age need to be considered to provide reliable estimates of interception, water use by trees and infiltration capacities within the forest stands in the model applications.

Summarizing the efforts of forest monitoring it is concluded that an appropriate and valid data pool derived from field studies and empirical relationships respectively has been provided, and thereby can be used in the general characterization of forest dynamics and for model calibration.

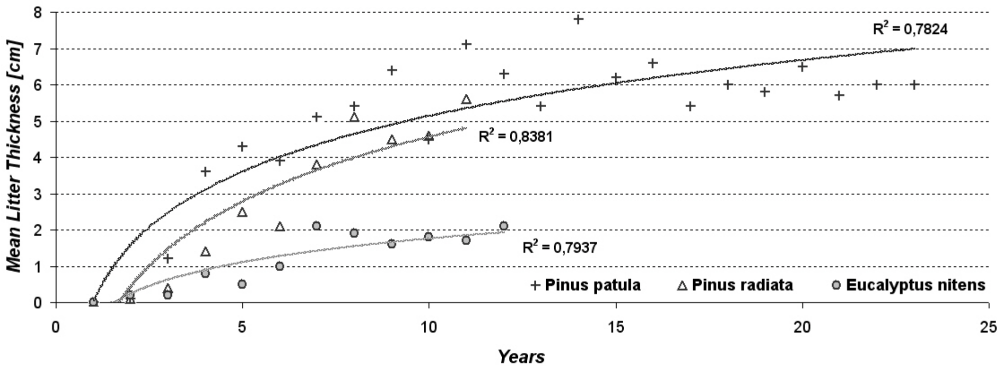


Figure 7.13: Age-related litter accumulation expressed as mean litter thickness (cm) per stand measured for Pinus patula, Pinus radiata and Eucalyptus nitens.

7.1.5 Land Use and Land Cover Data

Land use is a crucial model input parameter which is necessary for reliable modeling of evapotranspiration, interception and soil and groundwater dynamics. Since one of the objectives of this study is the identification and evaluation of the impact of afforestation on hydrological dynamics, multi-temporal land use maps representing prior to and after afforestation conditions at catchment scales were needed. Therefore information derived from satellite-based land use classification, forest data base analysis and terrain-based wetland inventory were merged to receive appropriate data for land use change analysis and HRU delineation.

7.1.5.1 Satellite-based Land Use Classification

Utilizing a procedure developed by HELMSCHROT (1999), Landsat TM/ETM data representing 4 stages since 1989 were classified to provide land use information for the Mooi catchment. Since afforestation activities started in 1989, these maps can be used to accurately analyze and quantify land use changes with specific respect to the transformation of former grassland, agricultural and wetland areas to forest plantations.

After preprocessing, the Landsat data were classified based on the 3-level classification approach described in Section 6.4.4.1 utilizing a hybrid classification approach. The accuracy of the resulting land use maps was continuously evaluated during the several steps of post-processing incorporating ground truth data and existing data from the forest data base. Since spatially variable soil moisture affects the spectral response significantly in non-vegetation or less vegetated areas, weather conditions before the acquisition date were evaluated in order to interpret mis-classifications. This information has been used to improve classification results by reclassifying obviously mis-classified pixels.

Classification accuracies were analyzed using errors of omission and commission derived from confusion matrices for each level. Accuracy assessment of level 3 showed that the overall accuracy using all reference pixels varied in the range from 81 % and 89 %, but was significantly increasing up to 91.4% when weighted by class area. This is caused due to the dominance of dense and moderate grassland areas which cover more than 50 % of the area. Moreover, all types of forests were usually classified with high accuracies. For the 1989 scene, however, overall accuracy was 87.7 % ranging from a minimum of 76.3 % for highly degraded grassland to a maximum of 94.4 % for deciduous woodlands. Basically the land use classes that could be classified with consistently high accuracies (> 90 %) were water bodies, barren lands, dense vegetated areas and agricultural areas. Relatively low accuracies were found for wetland areas (80%) and open grassland (73%) due to the spectral heterogeneity of these classes. A variety of different species of bushes, grass, reeds, additional soil information and to some extent saturated areas with moderate vegetation cover caused a confusing spectral response within the wetlands, while the spectral information of the grassland seemed to be influenced by varying soil moisture distribution, different soil types, aspect effects and disturbed vegetation patterns. An overall accuracy of 87.4 % was achieved for 1995, ranging between 81.6 % for open grassland and up to 98.4 % for Eucalyptus plantations. According to the significant spectral responses it was possible to separate natural woodlands and forest plantations with adequate accuracies. Similar problems as found in the wetland and open grassland areas of the 1989 classification were recognized in the 1995 classification results. Best classification results were performed classifying the 1999 scene. Although eroded grassland again showed the slightest class accuracy (87.1 %), the lower errors of commission led to a better overall accuracy of 91.4 % for the classification of the 1999 scene. Forest plantations and wetlands were classified significantly more accurately (92.1 % and 86.2 % respectively) than in the 1995 scene. This might be caused by a noticeable better spectral response from forested areas of the 1999 data set resulting from fully closed canopies, but also from the better radiometric quality of the data. An overall accuracy of 89.1 % was achieved for the 2001 classification showing the similar difficulties in classifying the open grassland and wetland classes like in the 1989 and 1995 data set, but the accuracies of 76.1 % and 83.3 % respectively indicated little effect on the overall accuracy, because of the areal extent of both classes.

As shown by HELMSCHROT (1999), overall accuracies increase significantly, when classes are aggregated to level 2 and level 1 respectively. This is in particular true, since problem classes like open grassland is either merged to grassland or to bare soil depending on the given spectral signal. Also, the wetland class is more accurately classified at lower classification levels, since in-class confusion can be minimized. In the present study, however, classification results of level 3 were used for land use change analysis (Section 7.2.1.4) and HRU delineation (Section 7.2.4)).

7.1.5.2 Analysis of Forest Data Base

Forest base maps were produced from forest data representing the forest distribution in the NECF area at the dates when Landsat data were acquired for land use classification. Created maps included information on planted species, age of the plantation, stocking and planting and management practices. Since the afforestation is a constant process, planted areas increased continuously from 1989 to 2001. In 1995 first harvestings of older pine stands took place so that deforestation and re-planting found consideration in forest mapping. From this data, it was shown that nearly 95 % of forest area was covered by pine plantations in 2001. Main species planted were *P. patula, P. radiata* and *P. greggii*. Remaining areas were planted with eucalyptus (mainly *E. nitens*), whereas eucalyptus was not planted between 1995 and 2000 for economic reasons. These maps, however, were used to improve the remotely-sensed land use classification and thereby for the spatial and temporal analysis of forest dynamics.

7.1.5.3 Wetland Distribution Mapping and Inventory

Assuming that wetland occurrence in the study area is strongly related to landscape features, a terrain analysis approach was developed in order to delineate wetland types and their distribution utilizing relief and morphometric parameters. These parameters were derived from the analysis of a SRTM-based DEM utilizing GIS tools given by ARCGIS 9.0 (DAHLKE *et al.*, 2003). Based on intensive field survey, three main wetland types (plateau wetland, slope wetland and valley bottom wetland) and associated sub-types were distinguished which differ in terms of surface hydrological characteristics, relief position and morphometric features (Figure 7.14). As discussed in Section 6.4.3, combinations of geomorphometric and geomorphographic parameters were found which could be used to separate each wetland type.

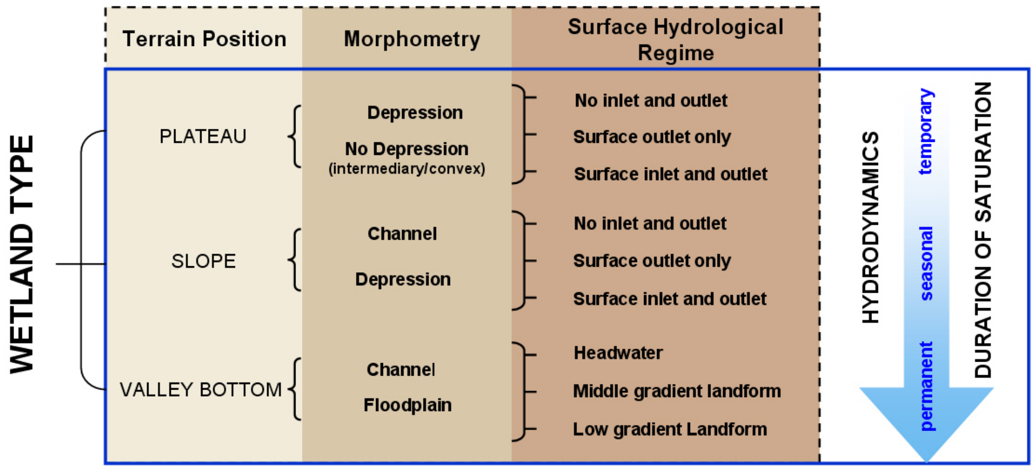


Figure 7.14: Terrain-based wetland classification (mod. after Dahlke, 2003).

From this effort, a wetland distribution map was derived representing the location and sizes of main wetland types in the Mooi, Gatberg and Wildebees catchments covering a total area of about 817 km² (Figure 7.15). Since the given wetland distribution map represents the potential wetland area, it needs to be taken into account that wetlands are highly dynamic elements of the landscape. Their spatial extent controlled by saturation, water table and vegetation is related to climatic conditions, which differ annually and seasonally and thereby affect wetland occurrence considerably. The flexibility of the method, however, allows the consideration of respective changes by an adjustment of parameters, thresholds and combinations within the delineation process.

To evaluate the accuracy of the wetland distribution map, an accuracy assessment was carried out verifying the type, location, extent and topographic parameters of selected wetlands. Therefore, Landsat data, maps obtained from ECDB and field mapping were used. As shown by DAHLKE *et al.* (2005) a good agreement was achieved in particular for the large valley bottom wetlands by overlaying the delineated wetland map with satellite data. Moreover, a good correspondence of 94 % was found when delineated wetlands and wetland distribution received from the ECDB were compared on the basis of confusion matrices. This evaluation was restricted to wetlands in general, since little attention was given to specific wetland types.

To address this deficit, 27 wetland sites were selected in the three basins and mapped for field based verification of the wetland map. These wetlands were accurately surveyed regarding their location and extent (GPS technique), relief position and vegetation and soils. The comparison between both data sets gave an overall accuracy of almost 90 %, which refers to a good consistency of the delineated wetland with real world conditions (Table 7.6).

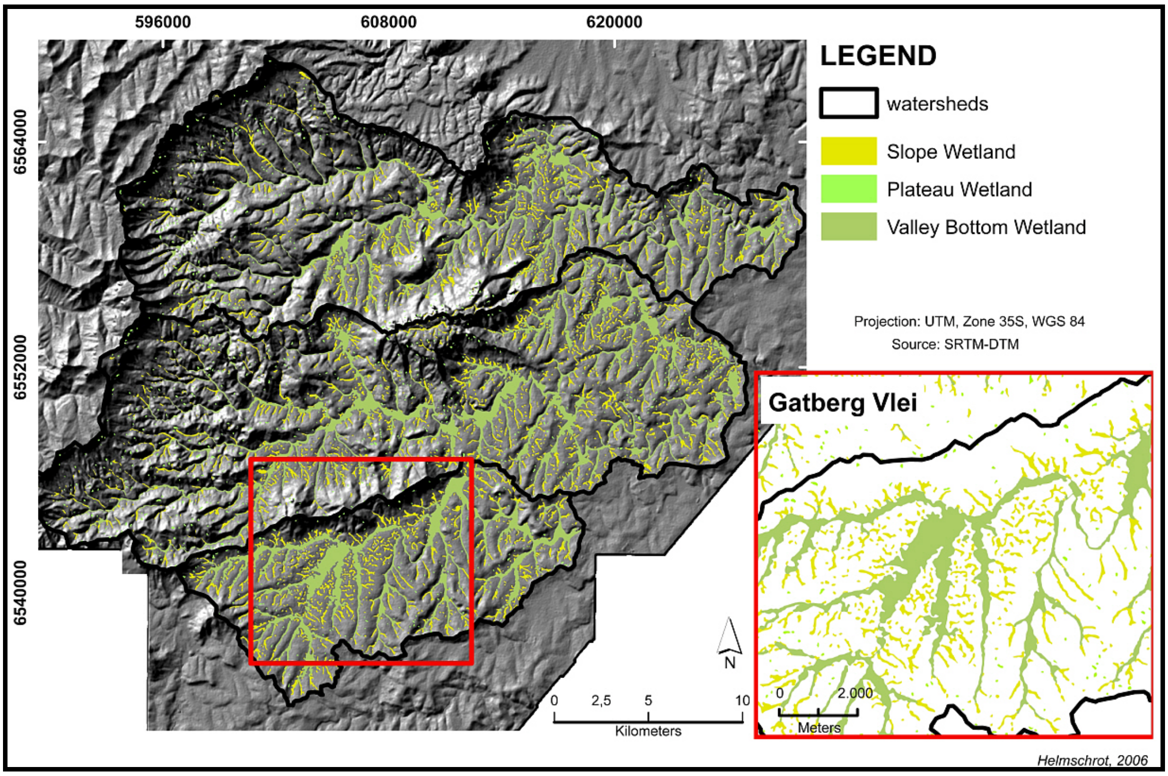


Figure 7.15: Wetland distribution map for the Mooi, Wildebees and Gatberg catchments and a subset showing the Gatberg Vlei (18 km²) to its whole extent (right box).

Table 7.6: Validation of the wetland distribution map by comparing the size of selected wetland areas of each wetland type with the size of wetlands surveyed in the field using GPS.

		Terrain-based delineated wetland areas		Surveyed wetland areas	Difference	Accuracy
		swa [km²]	pwa [%]	swa [km²]	swa [km²]	pwa [%]
TYPE	plateau	0.48	3.43	0,22	0.26	45.8
	slope	4.12	29.47	4.27	0.14	96.6
	valley bottom	9.38	67.10	8.02	1.36	85.5
	total	**13.98**	**100**	**12.51**	**1.47**	**89.5**

swa …total size of wetland area; pwa …percentage of wetland area

Inconsistencies were mainly found for the plateau wetland type which only showed an agreement of about 45.8 %. Since those wetlands are situated in small or flat depressions, the inaccuracies are related to their limited distribution and small sizes causing an aggravating delineation and mapping. About 97 % of slope wetland areas were delineated accurately. Valley bottom wetlands also showed a good correspondence (85.5 %), although their extent has been continuously under-estimated in the field. To explain this it needs to be taken into account that greater parts of those wetlands have been continuously drained and burned in the past, and thereby were intensively used for farming for more than 100 years. This type of management has altered wetland occurrence and dynamics regarding soil development, vegetation patterns and hydrological dynamics considerably, so that those wetlands were difficult to identify and map as wetlands in the field.

The wetland map formed the base for a wetland inventory within the three basins. As shown in Table 7.7 the delineated wetlands cover a total area of about 124 km² which represents 15 % of the study area (817 km²). Valley bottoms wetlands cover an area of 71 km² (57 % of total wetland area), while slope wetlands occupy about 47 km² (37 %). Only 5 % (7 km²) of the study area is characterized by plateau wetlands.

Table 7.7: Size of delineated wetland areas in comparison to size of wetlands excl. planted areas.

		Terrain-based delineated wetland areas			Wetland areas excl. forest area		
		swa [km²]	pwa [%]	psa [%]	swa [km²]	pwa [%]	psa [%]
TYPE	plateau	6.6	5.3	0.8	4.9	4.7	0.6
	slope	46.5	37.5	4.6	35.4	33.6	4.3
	valley bottom	71.1	57.2	8.7	65	61.7	8.0
	total	**124.2**	**100**	**15.2**	**105.3**	**100**	**12.9**

swa …total size of wetland area; pwa …percentage of wetland area; psa … percentage of study area

Furthermore the validation and field survey have shown that forest plantations overlap the terrain-based delineated wetland area especially on slopes and foothills. In those areas the potential land use was delineated as wetland area, while the actual land use is plantation forestry. In most cases it was found, that this phenomenon refers to the planting of trees close to or within temporary wetland areas. Consequently, all wetland areas overlapped by forests were identified and subtracted from the original wetlands layer for the later hydrological modeling using ARCGIS. As a result, a corrected dataset of wetland distribution was provided (see Tab. 7.7).

Summarizing the efforts undertaken for wetland mapping and inventory it is concluded that the applied approach provided reliable information on type-related wetland distribution at regional scale. Thus, data were used for further analysis and modeling applied to the Mooi basin after the basin has been clipped from the regional data set.

7.1.5.4 Land Use and Land Cover Mapping at Catchment Scale

7.1.5.4.1 Mooi Catchment

Finally, classification results were improved by overlaying contemporary plantation maps, land use and wetland distribution in areas where reliable data were available from other studies and field mapping. As a result, four land use maps of the Mooi basin were available representing land use in 1989, 1995, 1999 and 2001 at level 3. The produced maps are illustrated in Figure 7.16. As clearly shown, the extent of forest stands significantly increased from 1989 and 2001. The differences in grassland areas are caused by the varying environmental conditions of the grassland in the year of data acquisition and the timing of the acquisition itself. In 1989 and 2001, good grassland cover was developed resulting from a relatively wet season. Additionally, the acquisition date was still in the rain season. In contrast, data acquired in 1995 were taken two months after the end of the rain season. A relatively dry period was recorded for 1999 causing somewhat open grassland areas. A more detailed discussion of land use change dynamics is given in Section 7.2.1.4.

7.1.5.4.2 Weatherley Catchment

Land use and vegetation maps of Weatherley were provided from field surveys during 1997, 2000 and 2004. Only four classes were identified before afforestation which started in 2002. Three wetland classes could be differentiated addressing the wetland classification approach developed in the present study. Grassland areas are unmanaged and characterized by persistent annual vegetation cover. Detailed information on the extent of forest plantations and planted species was available from the forest data base. To provide highly accurate data, plantation boundaries were verified in the field in 2004 using differential GPS. Finally, the forest plantation layer was overlaid to create a land use map representing after afforestation conditions. Figure 7.17 illustrates land use prior to and after afforestation in Weatherley.

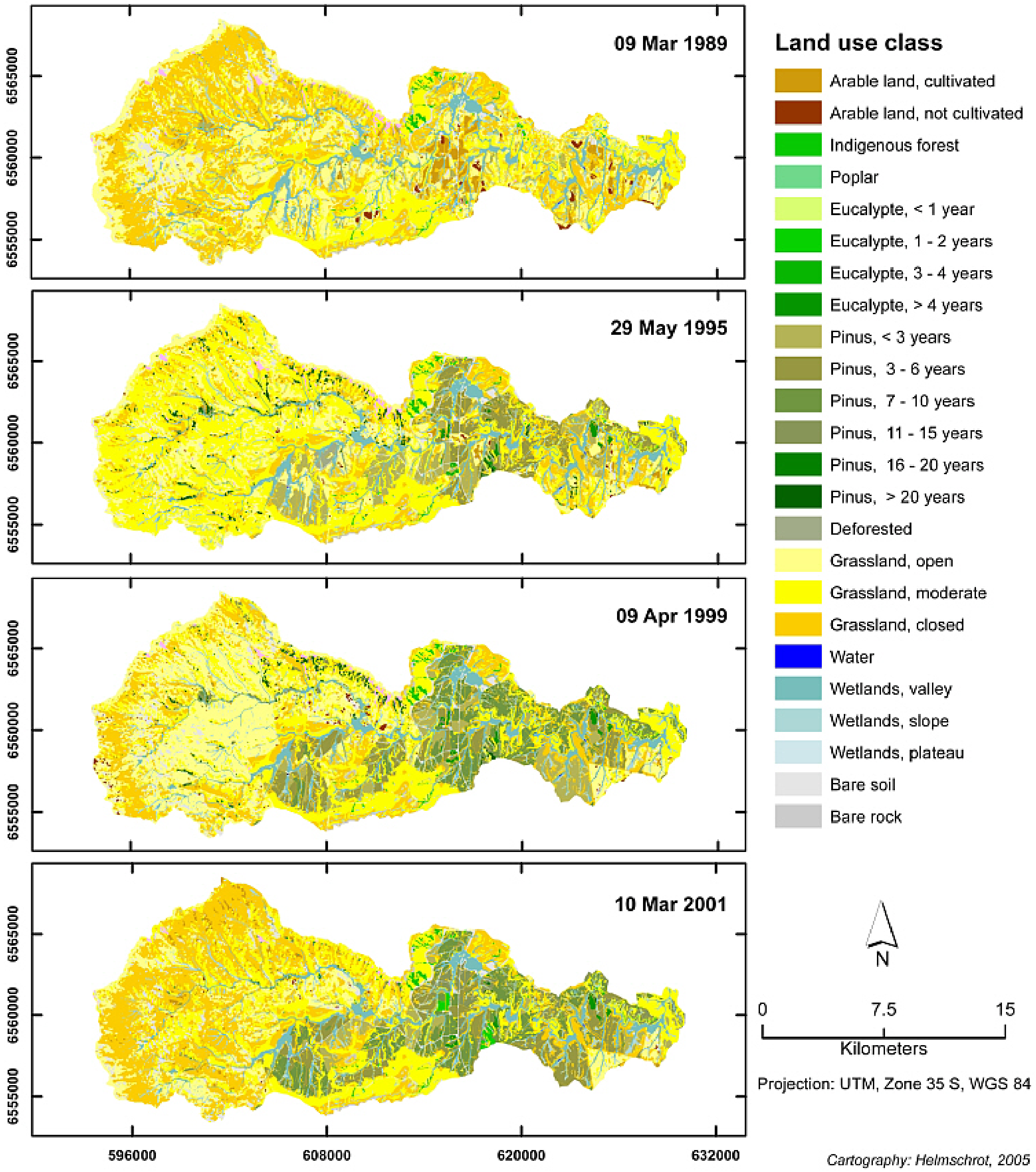


Figure 7.16: Land use maps (Level 3) provided for the Mooi catchment by classifying Landsat TM/ETM data sets from 1989 to 2001 merged with data from the wetland distribution map and forest base maps.

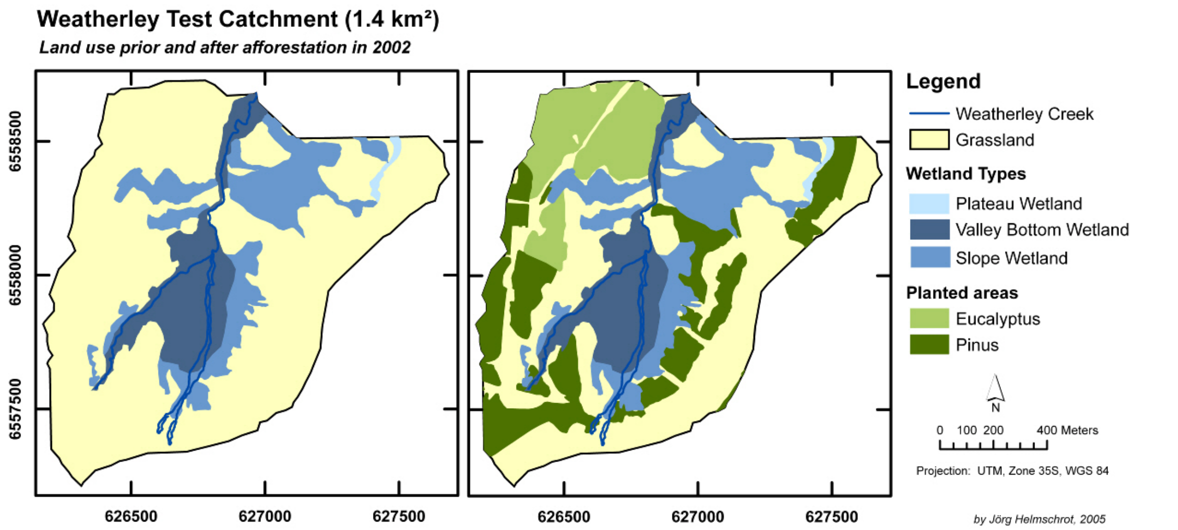


Figure 7.17: Land use maps (Level 3) provided for the Mooi catchment by classifying Landsat TM/ETM data sets from 1989 to 2001.

7.2 Integrated System Analysis

Since processes affecting natural systems are multi-faceted and interrelated, an integrated system-based analysis approach is fundamental to investigate and understand the complex nature of environmental systems (HUANG & CHANG, 2003). This is much more important when environmental systems such as catchments, hillslopes or wetlands need to be represented by physically-based process models. Thus, an integrated system analysis approach was developed to provide reliable information on process dynamics at different scales, and thereby to link multi-dimensional and multi-scale data analysis with environmental system modeling.

In the presented study, the aggregation and integration of the empirical observations built the base for an improved generalized understanding of the interlinked process dynamics at catchment, hillslope and wetland scale. The knowledge derived from theses efforts resulted in a thorough theoretical framework on hydrological system dynamics incorporating process interactivities and regionalization. The processes and system dynamics identified at each scale were considered in the HRU delineation procedure and the development and application of the model applications described in Section 7.3.

7.2.1 System Analysis at Catchment Scale

The analysis of hydrological system components is necessary to develop an understanding of the hydrological process dynamics and their specific relevance at catchment scale. Consequently, such an analysis is a prerequisite for the up- and downscaling of hydrologically relevant processes and parameters. In the presented study, hydrometeorological dynamics, soil and vegetation characteristics, land use dynamics and relief features were analyzed in order to characterize the hydrological system at catchment scale.

7.2.1.1 Hydro-meteorological Data Analysis

With the trend for increasing discretization in hydrological modeling, the need for better information about temporally variable and spatially distributed precipitation data and its implication for runoff responses is growing. Thus, the objectives of the analysis of hydro-meteorological data can be summarized as follows:

- Evaluation of basin characteristics based on general hydrological measures for selected water cycle components;
- Analysis of the temporal rainfall pattern and runoff dynamics and their implications for hydrological modeling; and
- Analysis of the regional distribution of rainfall and its implication for hydrological modeling.

Finally, the information on spatial and temporal rainfall patterns could be used to improve rainfall adjustments in the model application, since a rainfall correction factor was defined for each HRU.

7.2.1.1.1 Mooi Catchment

To address these objectives, long-term, daily rainfall records derived from 66 rainfall stations were corrected and analyzed to provide information on rainfall dynamics and distribution patterns within the entire Umzimvubu basin. For runoff analysis, daily runoff data from the Mooi River measured at the weir in Maclear were available for 1970-2005. Moreover, daily minimum and maximum temperature and radiation were used for the characterization of the hydrological system dynamics.

i) Temporal dynamics

Initially, statistical measures of hydro-meteorological parameters were calculated. It was found that annual rainfall ranges from 1 130 mm (2000) to 609 mm (2003) showing a long-term average of 849 mm. Compared to a regional mean of 754 mm presented by WRC (1994), the mean rainfall of the Mooi watershed is higher which is assumed to be caused by increasing rainfall due to more dominant orographic effects in the valleys close to the escarpment. Highest rainfall is observed in February (141.9 mm) and lowest in June (13.4 mm). More than 80 % of the annual rain falls during the rainy season (October – March). Snowfall is observed only for a few days per year in the study area. With respect to measured temperatures it is indicated that snow usually falls during the nights but melts at the following day immediately. As reported by farmers, snow covers lasting several days are rare. Taken from a 22-year record it was found that mean annual temperature is 14.9 °C, which is below the regional mean of 16.1 °C given for the Eastern Cape Province by SCHULZE (1997). This might be caused by lower temperatures along the escarpment. The warmest month, however, is February (19.5 °C) and coldest is July (9.9 °C). Given from the station in Umtata, mean annual humidity is about 69 % ranging from 76% (March) to 60 % (June). Based on the 35-year record, a runoff coefficient of 10.9 l s^{-1} km^{-2} and a mean daily runoff of 3.31 m^3 s^{-1} (1.67 mm) were computed.

The analysis of monthly mean runoff volumes showed a simple pluvial regime with a runoff maximum in February (291.2 m^3 s^{-1}, i.e. 149 mm) and minimum in July (9 m^3 s-

[1], i.e. 4.5 mm). Moreover, runoff shows a good coincidence with seasonal rainfall dynamics. Thus, it is concluded that runoff is mainly controlled by rainfall intensity and distribution. Table 7.8 summarizes the information on selected parameters computed for the Mooi catchment.

Table 7.8: Statistical measures of selected hydrological parameters of the Mooi catchment calculated from long-term annual averages.

	Period	Min	Max	Mean	Median	Std
Mean Precipitation [mm]	1970 - 2005	609	1 130	849	833	123
Mean Runoff [mm]	1970 - 2005	152	1 342	624	545	310
Minimum Temperature [°C]	1980 - 2002	5.7	10.7	8.2	8.1	1.1
Maximum Temperature [°C]	1980 - 2002	20.6	24.8	22.1	21.8	0.9
Mean Temperature [°C]	1980 - 2002	13.5	17.7	15.1	14.9	0.9
Mean Rel. Humidity [%]	1980 - 2006	64	74	69	69	2.8

Analyzing records to identify long-term trends, rainfall and runoff of the 35-year record received from the Mooi basin were plotted with their percentage deviation from the long-term averages (Figure 7.18).

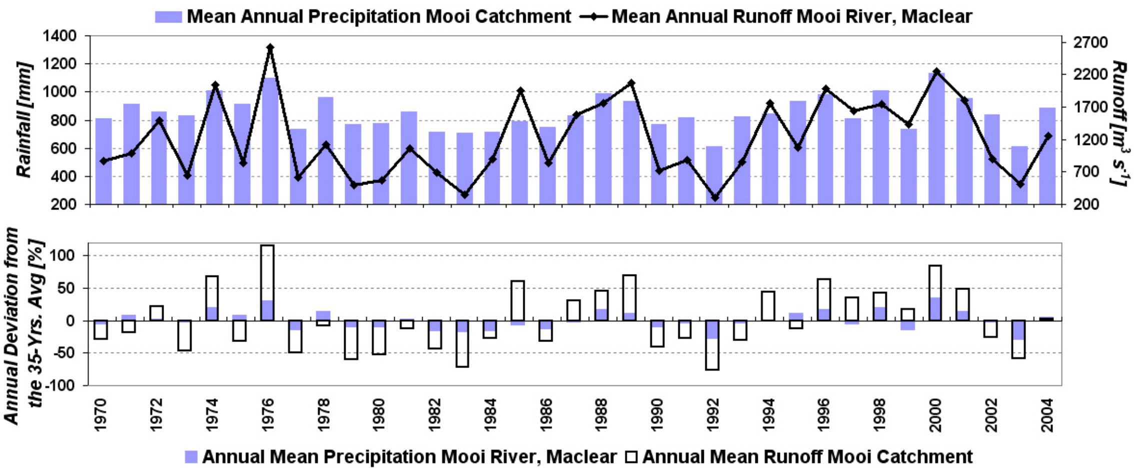


Figure 7.18: Mean annual rainfall and runoff of the Mooi basin received from a 35-years record and the percentage deviation from the long-term average for both components.

Both rainfall and runoff show a high variability compared to their annual means. As shown in Figure 7.18, the parameters widely are highly coincident, i.e. runoff increases when rainfall increases. Moreover, it is concluded that small variations in rainfall dynamics may affect runoff response remarkably with implications for runoff generation processes and wetland functioning in the catchment.

Assuming that the retention capacity of wetlands controls runoff response, and in particular low-flow conditions (SMAKHTIN *et al.*, 1997), it is indicated that in wet years wetlands that are filled lose their retention capacity and support runoff that is generated on the hillslopes as surface runoff and rapid interflow. For example, in 1976 the area received about 20 % more rainfall than the long-term average, but 5 times more runoff was measured at the Mooi weir in Maclear compared to the average. Whereas in dry years when rainfall is reduced, wetlands function as water storage restraining rainfall. For example, rainfall was reduced by 10 % in 1980, but only 50 % of the mean annual runoff was measured. On the other hand, even years with positive rainfall show reduced runoff (1971, 1975, 1981 and 1995), in particular after a relatively dry year with low runoff. In contrast, high runoff volumes were observed in 1985, although rainfall was slightly lower than the long-term average. This might be caused by missed rainfall records (e.g. failure of the rainfall gauges) or rainfall distribution effect, i.e. intense rainfalls were locally restricted and thereby not recorded.

Additionally, attention has been given to the years after 1989 when the afforestation started. Assuming a closed canopy cover since 1996, it seems that the relationship between rainfall and runoff changed since this time. With the exception of the relatively dry 1999, the increase of runoff compared to rainfall is less significant than before the afforestation. For example, the area received its highest rainfall measured during the 35-year record, i.e. 35 % higher than the average, but runoff increased only by 80 %. A similar relationship regarding the increases is found for 1998, but it needs to be noted that the year before was characterized by drier conditions. In 2003 rainfall was reduced by 30 %, but runoff surprisingly only decreased by 55 %. In 1999 runoff was higher than the long-term mean, although rainfall was lower than the average resulting from intense rainfalls and an overall positive balance in 1998.

Summarizing this analysis it is concluded that inter-annual rainfall-runoff relations are very complex. Nevertheless, it is indicated that the main drivers of the hydrological system are the spatio-temporal rainfall dynamics (system input) and the storage behavior of the wetlands.

The importance of wetlands regarding their water storage function in the watershed becomes clearer when individual years are analyzed. Of course, the hydrograph for a certain time only represents an integrated measure of the complexity of runoff mechanisms in a catchment for this specific period. Thus, it is usually difficult to infer catchment process dynamics from the measured data directly, with the exception of some generalizing characteristics such as temporal dynamics or mean times of response (BEVEN, 2001a).

Taking this into account, Figure 7.19 representing the rainfall-runoff graphs for the hydrological year 1976 illustrates that the first significant runoff response occurs about eight weeks after the beginning of the rainy season in October 1975. This indicates that early rainfalls are used to refill wetlands that in turn are emptied during the dry season. To fill a wetland at the beginning of wet season, about 15-20 % of the annual rainfalls are required. Once the wetland storage is filled, the hydrograph respond relatively rapid to rainfall events, usually in the range of 1-3 days depending where the rain falls and in what intensity. Hence, runoff generation during the rain season is dominated by rapid surface flow (high rainfall intensities and volumes in short time) and interflow (moderate rainfall intensities and volumes over hours and days), while baseflow does not notably contribute to the basin runoff in high flow conditions. On the other hand, the low flow conditions in dry seasons are evidently controlled through the release of retaining water from the wetlands. Consequently, a continuous low runoff was observed, even in times of no rainfall. This dynamic has been found in all annual records independent from precipitation patterns (dry *vs.* wet year). These findings were confirmed by tracer measurements, groundwater drillings and hydrograph analysis (UHLENBROCK, 2004, pers. comm.; LORENTZ *et al.,* 2001; HELMSCHROT *et al.*, 2005).

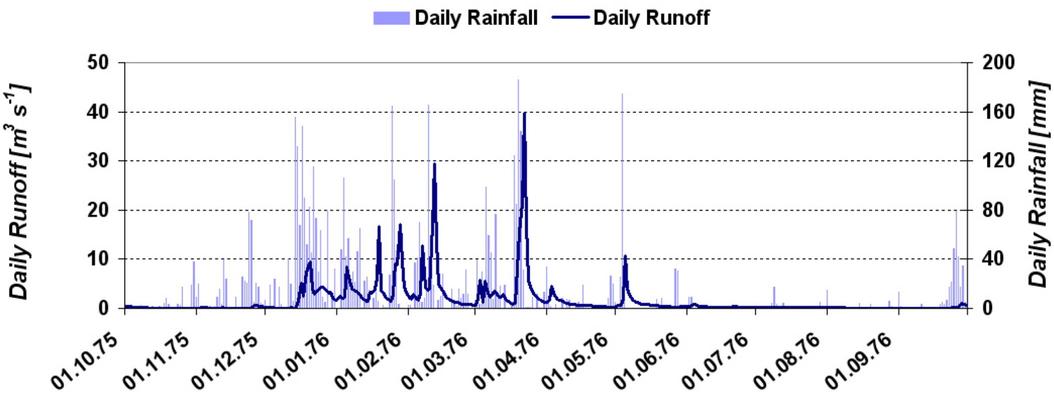


Figure 7.19: Rainfall-runoff graph for the Mooi basin for the hydrological period from October 1975 to September 1976.

To evaluate forest impacts based on measured runoff, cumulated runoff data from the Mooi River were plotted against cumulated data from the Tsitsa River located farther downstream. At the Tsitsa River Bridge the catchment area is about 4.200 km². The upper reaches of the Tsitsa River are also affected by afforestation, but to a smaller proportion related to the catchment size, i.e. about 11 % of the basin was planted since 1989, while in the Mooi catchment about 20 % is covered by forest plantations.

Comparing data given by the double mass curve for the period from 1970 – 2005 (Figure 7.20, left) it is shown that accumulated runoff generally shows a good correlation when compared to the 45° line, but also reveals a significant change starting in 1996. Since the two rivers are connected and thereby dependent to each other, both cumulated runoff series were plotted against independent, cumulated rainfall recorded at the station Maclear (Figure 7.20, right) showing no significant change for these relations.

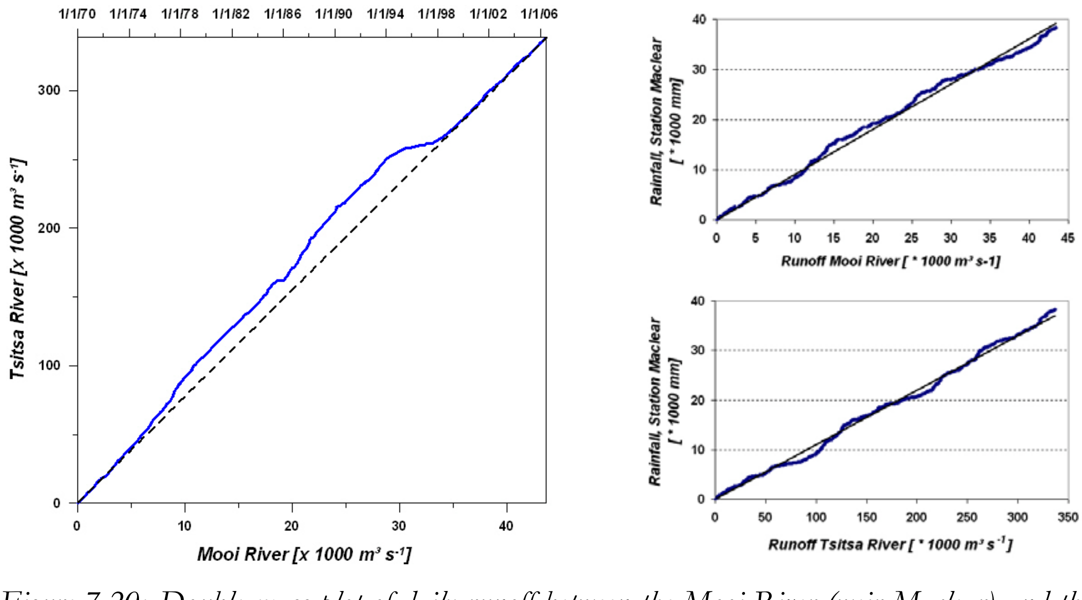


Figure 7.20: Double mass plot of daily runoff between the Mooi River (weir Maclear) and the Tsitsa River (weir Tsitsa River Bridge) from 1970 – 2005 (left). Double mass plot of rainfall recorded at the station Maclear against runoff of the rivers Mooi (upper right) and Tsitsa (lower right) fort eh period 1970-2005.

In addition, the dynamic of inter-annual variability (Figure 7.21) for the two rivers also shows a good agreement with the exception of 1996, 1997 and 1998, whether the Tsitsa curve shows a generally higher variability than the Mooi. Taking this into account, a system change is indicated resulting in a significant runoff reduction of the Tsitsa River between 1996 and 1998, even though 1996 and 1998 showed a positive water balance (i.e. higher rainfall values than the long-term average). Consequently, it is assumed that the Tsitsa tends to be more sensitive to system changes compared to the Mooi.

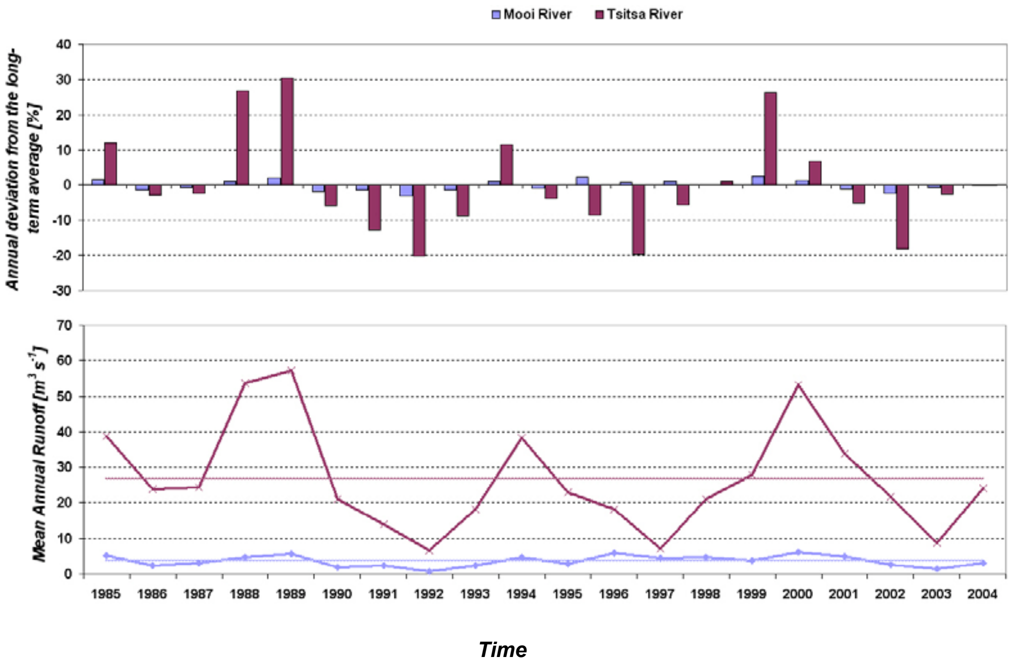


Figure 7.21: Comparison of inter-annual runoff dynamics between the Mooi (blue) and the Tsitsa (red) Rivers from 1985 – 2004. Above: Annual deviation from their long-term averages in percent. Below: Mean annual runoff plotted against its long-term average (25.7 m^3 s^{-1} and 3.31 m^3 s^{-1}).

For more detailed analysis, the slope of the double mass plot in Figure 7.20 (left) was examined in order to identify the extent and duration of these changes in runoff dynamic. It was found that the slope of the plot increases consistently from January 1970 to December 1995 and from February 1998 to 2005. From December 1995 to January 1998, the slope was significantly lower indicating lower runoff values of the Tsitsa River in comparison with runoff observed for the Mooi River. As show in table 7.9, averaged daily runoff values computed for the respective periods have shown that the mean daily runoff for the Mooi was higher during 1995 and 1998 (4.94 m^3 s^{-1}) when compared to the other periods and the long-term average (3.31 m^3 s^{-1}). In contrast, the mean daily runoff of the Tsitsa was significantly lower between 1995 and 1998 (12.9 m^3 s^{-1}) when compared to the other periods or the long-term average (25.76 m^3 s^{-1}).

Table 7.9: Comparison of daily runoff volumes of different periods for the Mooi and Tsitsa basins.

	Mean [35 years]	**1970-1995**	**1996-1998**	**1999-2005**
Daily Runoff Mooi [$m^3 s^{-1}$]	3.31	3.06	4.94	3.70
Daily Runoff Tsitsa [$m^3 s^{-1}$]	25.76	26.52	12.90	26.76

In 1998, the Tsitsa system is again stabilized when related to the Mooi basin. There are two possible reasons explaining this phenomenon. The decrease in runoff is caused by missing or wrong values in the Tsitsa runoff record. A review of runoff data has shown that measured runoff values are relatively low, but seem to be reliable compared to rainfall intensities and volumes during this period. Additionally, the runoff data were compared to an upstream catchment of the Tina River (weir Kinira), also a tributary to the Umzimvubu River. It was found that the upper Tina showed comparable low run-off volumes when compared to rainfall dynamics. On the other hand, this change is related to the time when the majority of forest stands built closed canopies in the head-waters of the Tsitsa and Mooi Rivers. Since this effect is evidently more crucial to the runoff of the Tsitsa, rainfall dynamics were analyzed in detail. Exploring data from 11 stations it was found that the areal mean of rainfall of the Tsitsa basin (783 mm) is considerably lower than in the Mooi catchment (849 mm) and shows a higher spatial variability. Consequently it is indicated that proportional less water is available to main-tain the wetland systems in the upper Tsitsa watershed, and thereby, the basin is more vulnerable to system changes when compared to the Mooi basin. While the Tsitsa shows a similar trend in runoff dynamics under grassland conditions like the Mooi ba-sin, the combined effect of wetlands water retention and increasing forest water use can not be compensated for rainfall, in particularly in areas of lower rainfall intensities and volumes. Considering that afforestation also took place in the Mooi, even to a higher extent when related to the catchment size, it is assumed that this effect is more significant to the Tsitsa basin.

Summarizing these analyses it is concluded that annual rainfall variability influences the magnitude of annual runoff significantly, whereas the wetlands and their storage capac-ity are assumed to be the most important hydrological drivers that control intra- and inter-annual runoff dynamics. Runoff generation is dominated by surface runoff and interflow in the rain seasons, whereas rapid flows are attenuated by the wetlands, in particular at the beginning of the rain season. Base flow (i.e. water released by the wet-lands) controls the hydrograph in dry seasons showing very low values. In addition, afforestation seems to be affective in terms of changing the relation between rainfall and runoff variations. On the other hand, the impact of afforestation is more evident in areas of lower rainfall where the water retention of wetlands is more influential than in wetter areas like in the Mooi basin. These findings also indicate that afforestation influences the system behavior considerably, but it also reveals that these influences are different for different spatial and temporal scales. Nevertheless, more detail studies are needed to verify this scale-related impact of afforestation.

ii) Spatial dynamics

Besides the temporal dynamics, the spatial distribution of rainfall is important informa-tion that needs to be included in distributed hydrological modeling approaches. In the present study, the number of station was highest between 1970 and 1988; this period has been evaluated regarding spatial rainfall dynamics. There are many innovative methods available to generate continuous surfaces from point data (BEVEN, 2001a). In this study, available data were interpolated using two techniques, i.e. Inverse Distance Weighting (IDW) and Kriging. Maps illustrating the distribution of long-term rainfall averages, the distribution in the driest and wettest years and seasonal differences were created with each method. As an example, Figure 7.22 shows the rainfall distribution for the wettest year (1976) computed with universal kriging. According to BURROUGH & MCDONNELL (1998), both methods were evaluated regarding their quality based on the analysis of root mean square error (RMSE) and mean absolute relative error (MARE) and difference maps created in ARCGIS 9.0,. For example, the 19-years average computed with both methods showed similar error measures for IDW (MARE: 16.1, RMSE: 141.2) and for kriging (MARE: 17.6, RMSE: 146.6). From this analysis it is concluded that no significant better results could be achieved by one of the other method.

In addition, the surfaces generated were visually evaluated in comparison to maps provided by FORSYTH *et al.* (1997), SCHULZE (1997) and WRC (1994). Summarizing the quality assessment it is concluded that the general rainfall pattern has been simulated successfully, even though some areas were underpredicted, particularly in dry seasons. A more detailed analysis has shown that these underpredictions are limited to a smaller area in the western part of the Umzimvubu basin. This is primarily caused by the sparsity of rainfall data in this area. Using data from FORSYTH *et al.* (1997) and WRC (1994) this area has been analyzed separately. That information has been incorporated to improve rainfall distribution by adjusting existing maps with an overlay of maps representing averages of the computed maps and the validation data.

Finally, the generated distribution map has been evaluated regarding spatial variations of rainfall in the Mooi catchment. A 20 km, north-south oriented belt of higher rainfall than the average computed for Mooi basin (849 mm) has been identified about 15 km in the west of Maclear. Towards the escarpment, rainfall decreases again to a level of the annual mean.

The influence of elevation, landscape positioning and geographic position on precipitation pattern is of course widespread, being cited, for example by BEVEN (2001a) and BÖSCHL (1996), but little knowledge is available for the study area. Since it was shown that rainfall is characterized by a high spatial variability, attention was given to test data against a number of physiographic factors including, topography, aspect and distance from the coast aiming to determine if these are correlated with precipitation amounts. Following conclusions can be drawn from this effort:

- Rainfall is highest along the coastal belt and in valleys along the escarpment which support the development of convective thunderstorms.
- Different than expected, rainfall intensities and distribution is less driven by the altitude, but rather influenced by local relief phenomena.
- In contrast to findings by HERBERT (1997), no correlation has been found regarding the relation between rainfall intensities and aspects. Although it is indicated that

rainfall is slightly higher on south-eastern slopes, data are too sparse for verified statements.

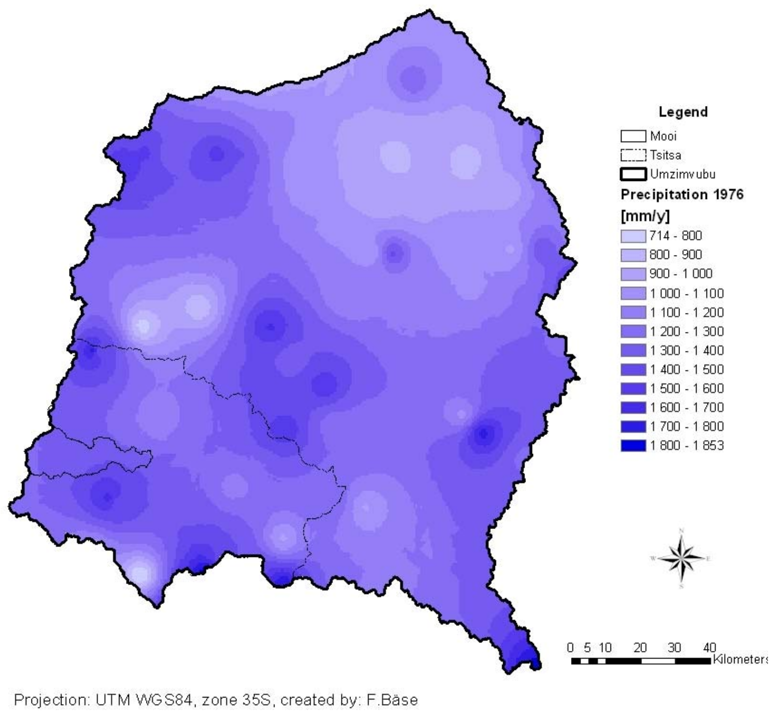


Figure 7.22: Rainfall distribution within the Umzimvubu basin for 1976 (wettest year of a 35-year record) based on universal Kriging (Cartography: Bäse, 2004)

iii) Long-term dynamics

Despite the high temporal and spatial variability, the variation of rainfall over South Africa is considered as being distinctive over long times (TYSON, 1986). Summarizing rainfall analysis of several studies, TYSON (1986) discussed the existence of weak oscillations of a quasi-periodic nature are discerned underlying a large measure of random year-to-year variability. The most prominent of these oscillations has a period of about 18 years, whereas it rarely accounts for more than 30 % of the variance. However, comparing the rainfall record with an average rainfall series provided by TYSON (1986), similarities were found indicating a slightly wetter period from 1970 - 1979 followed by a relatively drier period from 1979-1988, which in turn is again followed by a wetter period (see Figure 7.18). Consequently, the data provided reflect the assumptions made by TYSON (1986).

7.2.1.1.2 Weatherley Catchment

Statistical measures of hydro-meteorological parameters were calculated from records measured in Weatherley to characterize the watershed over a 6-year period. Although the time series was shorter, the data widely confirm findings from the Mooi basin. The highest rainfall was recorded in 2003 (1 304 mm), the lowest in 2000 (724 mm). In contrast to the Mooi basin, most rain falls in January (204 mm), while the least rain (7 mm) is observed in June. February (19.6 °C) is the warmest and June (9.7 °C) the coldest month of the year. Compared to data from the Mooi basin for the same period (1995-2004), it is shown that the Weatherley catchment is slightly wetter and cooler than the Mooi catchment. The runoff coefficient is 7 l s^{-1} km^{-2}. Table 7.10 gives summary information on selected parameters computed for the Weatherley catchment.

Table 7.10: Statistical measures of selected hydrological parameters of the Weatherley catchment calculated from annual averages.

	Period	Min	Max	Mean	Median	Std
Mean Precipitation [mm]	1998 – 2004	724	1 304	1 032	1 022	192
Mean Runoff [mm]	1995 – 2004	238	1 165	722	712	327
Minimum Temperature [°C]	1995 – 2001	6.7	8.8	7.8	7.6	0.8
Maximum Temperature [°C]	1995 – 2001	21.3	23.9	22.1	21.7	0.9
Mean Temperature [°C]	1995 – 2001	14.2	16.4	14.9	14.8	0.8
Mean Solar Rad. [MJ m^{-2} day^{-1}]	1995 – 2001	16.8	18.2	17.3	17.2	0.5

Similar to the analysis carried out for the Mooi basin, individual years were investigated to provide knowledge on runoff generation dynamics. It was ascertained that a comparable temporal pattern regarding the hydrograph response resulting from water storage in the wetlands can be observed. Figure 7.23 shows a rainfall-runoff graph for the hydrological years 2000 and 2004. Analyzing the graphs, the first noticeable response of the hydrograph is about ten weeks after the first rainfall. The mean response time of the hydrograph, once the wetland storage capacity is achieved, is about 24 hours depending on the rainfall intensity. Some variations were identified analyzing low flow conditions. Very low runoff was observed during the dry season in 2000, while in May 2004 the Weatherley Creek completely dried up for the first time. Although 2004 was relatively dry, it is assumed that the planting in 2002 showed its first impacts on runoff generation. As observed in the field during intense events in 2004 and 2005, surface runoff was evidently reduced, especially on eucalyptus plantations, while interflow was still observed in the field. These phenomena were taken into account in the model application by calibrating surface runoff and subsurface water dynamics accordingly.

When examining a double mass plot of cumulated daily runoff between Weatherley Creek (lower weir) and the Mooi River (Maclear) and the Tsitsa River (Tsitsa River Bridge) (Figure 7.24 a, b) it was found that the curves show a relatively constant slope nearly a 45° line from 1998 - 2005. Thus, it is concluded that afforestation of Weatherley in 2002 seemed not to be significantly influential on the overall basin runoff when compared to runoff dynamics of the Mooi and Tsitsa rivers respectively. In contrast to the assumption outlined above, this also indicates that in the first two years of growing of commercial forests, afforestation shows no considerable impact on runoff behavior of the Weatherley Creek, when compared to the two rivers. Because field observation has indicated that changes have occurred, it is concluded that double mass plot analysis is not appropriate to capture these changes in that extent. However, further studies based on new data will show whether there is an effect of afforestation which can be recognized using double mass plots.

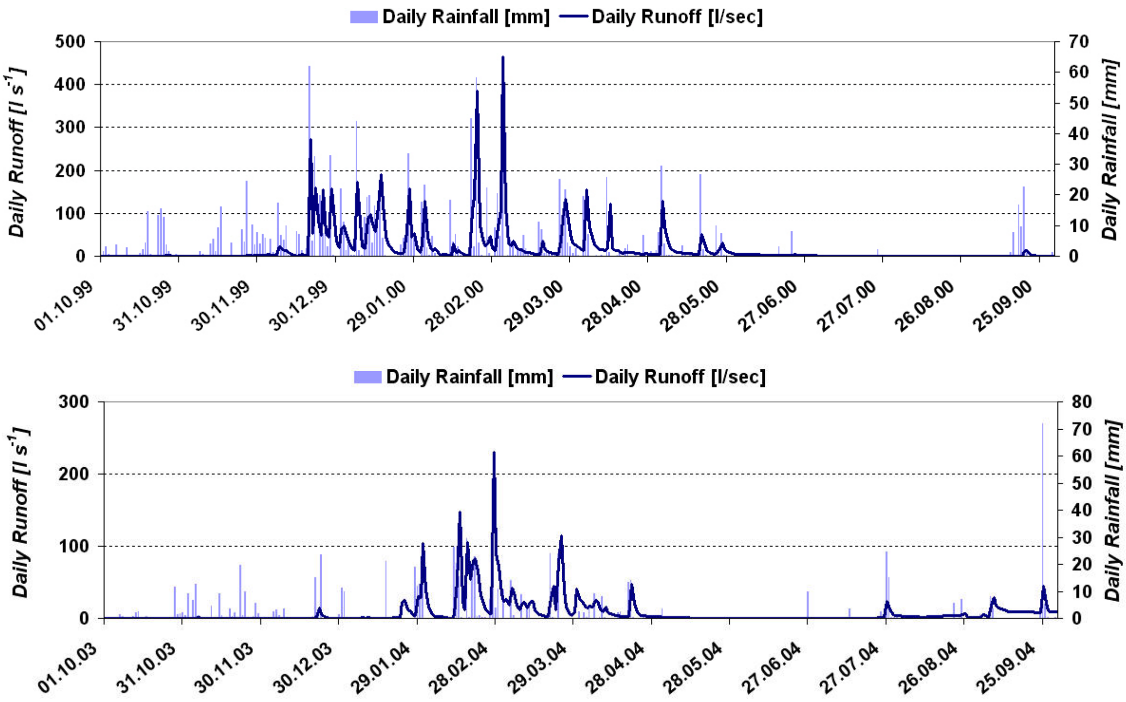


Figure 7.23: Rainfall-runoff graph for the Weatherley catchment for the hydrological years 2000 (wettest year) and 2004 (driest year).Between 10 and 20 % of the annual rainfall are required to fill the weltands at the beginning of the wet season

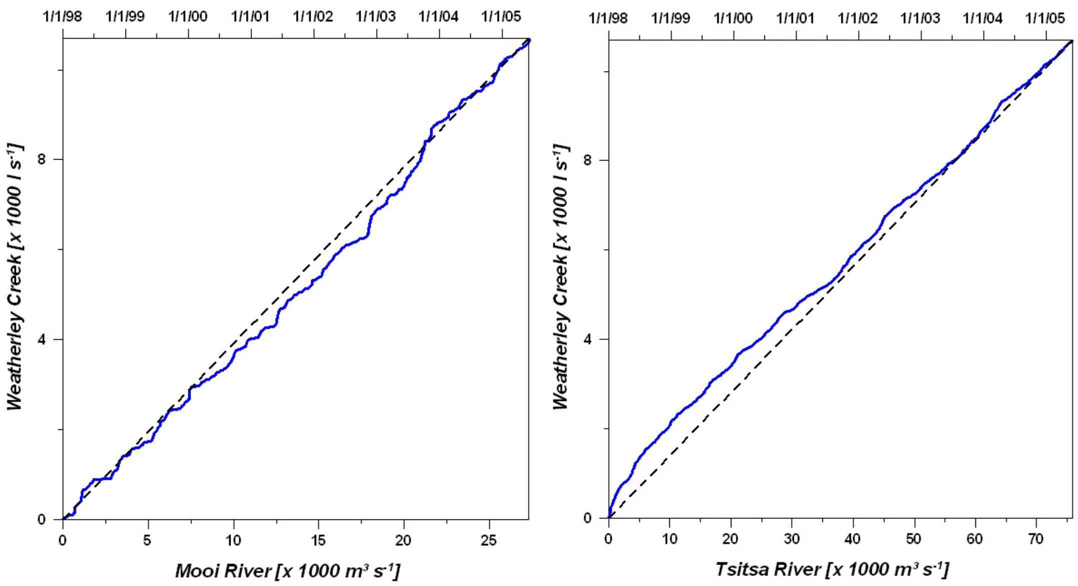


Figure 7.24: Double mass plot of daily runoff between a) Mooi River (weir Maclear) and b) Weatherley Creek (lower weir) from 1998 – 2005.

7.2.1.2 Soil Analysis

Combining existing soil data provided by ROBERTS *et al.* (1996), ESPREY (1997) and HERBERT (1997) with own field survey and laboratory analysis (Section 7.1.2), soil studies were conducted to provide *i) information on predominant soil types and their specific characteristics* and *ii) information on structure and formation of soils in wetlands*. These studies were mainly carried out in the Weatherley catchment, but supplementary work was also done in the Mooi, Gatberg and Wildebees catchments. The main results are summarized in the following sections.

Summarizing the soil survey it was found that a very complex soil distribution pattern exists within the research catchment Weatherley. According to the South African Soil Taxonomy (SOIL CLASSIFICATION WORKING GROUP, 1991), 15 soil types were identified showing a high spatial variability. Basically, the soils of the catchment included red and yellow apedal mesotrophic soils, and neocutanic and hydromorphic soils. Dependin gon landscape positions, the soil depths varied between 47 cm (*Regosol*) on upslopes to more than 4 m (*Gleysol*) in the valley bottoms. It was shown that the western slopes are mainly dominated by *Arenosols* and *Cambisols* (*Hutton* form). The *Arenosols* usually have brown to dark reddish brown A-horizons with medium to fine sandy loam to sandy clay loam topsoils overlaying a dark red to reddish brown, sandy clay loam subsoils. *Cambisols* are mainly characterized by bleached loamy sand to sandy loam topsoils on brown sandy loam subsoils. East-facing slopes have a greater variation and small scale distribution pattern. Soil forms range from *Regosols*, *Cambisols*, *Luvisols* and *Arenosols*. In addition, non-red duplex soils (*colluviums*) were found on more gentle parts of the eastern bottomslopes and in mid- and downslope depressions.

Depending on the relief position and the underlying geology, some of the identified soils showed a varying degree of wetness and color indicating periodic or permanent saturation with water. These indication ranges from mottling, thin horizons with bleached sand grains to well developed E horizons and gleyic soils. The latter show a considerable reduction of ferric oxides and hydrated oxides indicating anaerobic conditions. Consequently, the identified hydromorphic soils range from stagnic *Cambisols* and *Luvisols*, stagnic *Albeluvisols* to well developed *Gleysols* (Table 7.1). Differences were found with respect to the source of water affecting soil development. Stagnic soil types are found on moderate to steep slopes indicating that soil-chemical processes are caused by temporary lateral flows and fluctuations of perched groundwater, while typical *Gleysols* which are located in flat terrains are controlled by continuously fluctuating groundwater,

According to Table 7.2, non-wetland soils show relatively high percentages in the sand fraction comprising more than 50 %. Deeper soils have sand fractions ranging from 10 % to 45 % with clay fractions in excess of 35 %. As also shown by ESPREY (1997), sand fractions usually decrease both down the profile and in lower slope positions, while contrary clay content increases. With some exceptions, bulk densities generally increase slightly with depths due to the compact nature of these soils (ESPREY, 1997). Depending on the depth and the relief position, hydromorphic soils are mostly characterized by large percentages of clay with a maximum of 40 % in the lower part of the profile, with an increasing fine sand fraction towards the base of the profile. Bulk densities seem to be lower at depth than nearer the surface. As discussed by ESPREY (1997), this is related to the proliferation of macropores in these soils.

Since the data should be used for the HRU delineation and the model parameterization, the soils were reclassified to reduce the variability of soil types within the catchment. The re-classification was done merging soil types with similar soil-physical characteristics. Figure 7.25 shows the soil distribution of the Weatherley catchment integrating data from the previous studies (ROBERTS *et al.,* 1996; ESPREY, 1997; HERBERT, 1997) and own field data.

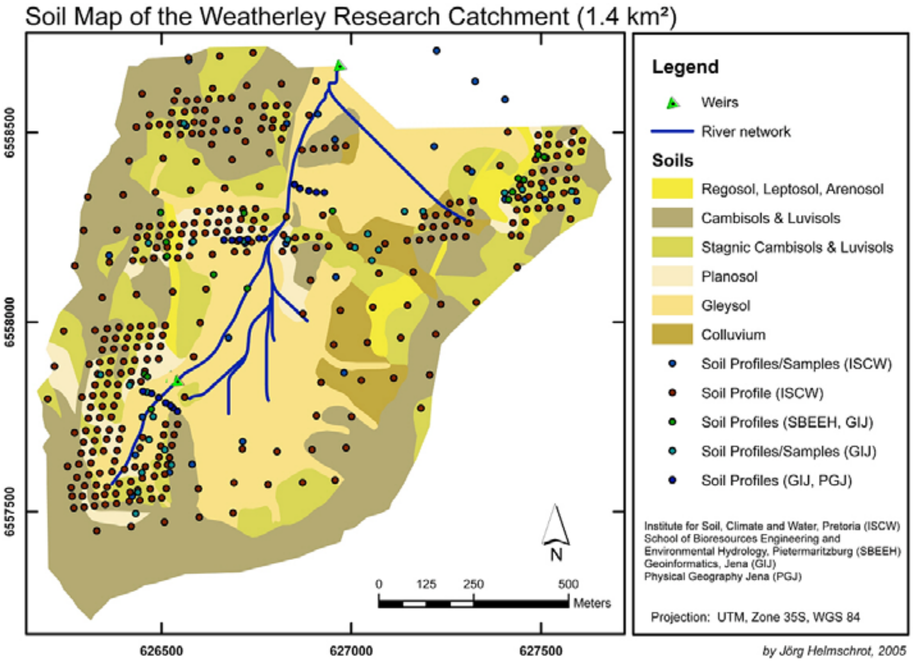


Figure 7.25: Simplified soil map of the research catchment Weatherley with contributions by the Institute for Soil, Climate and Water (ISCW, Pretoria) and the School of Bioresources Engineering and Environmental Hydrology (SBEEH, KZNU, Pietermaritzburg).

A more detailed description of the specific physical and chemical soil properties of different soils found in Weatherley is given in ESPREY (1997) and ROBERTS *et al.* (1996).

Information on soil distribution in the Mooi catchment has been obtained by correlating punctual soil data with a variety of landscape parameters. Since the soil types have shown a good correspondence with relief position, geology and land use, a generalized soil map was provided representing major soil types of the Mooi basin. Hereby, soil types were classified with respect to the underlying geology, land use and relief characteristics. For example, as found in Weatherley, *Regosols* are developed on sandy parent material in relatively steep positions with a land use usually characterized as poor grassland. Consequently, areas with *Molteno* sandstone and grassland in bad conditions and slopes steeper than 15 ° were defined as *Regosols*. On the other hand, areas planted with pine or eucalyptus indicate well-developed *Cambisols* or *Luvisols* on moderate slopes. In addition, wetland distribution has been developed from relief analysis as described in Section 7.2.3. From this effort, information on the distribution of wetland soils (*Gleysols*, stagnic *Cambisols* and *Luvisols*) were available. Overlaying all derived soil layers, a soil map was performed for the Mooi catchment.

7.2.1.3 Vegetation Analysis

The vegetation dynamics play an important role for the hydrological modeling, since the type of vegetation and its plant-biophysical characteristic control processes like evapotranspiration and interception. Consequently, intensive field work were carried out in order to evaluate and model vegetation dynamics in the study area and to develop model parameters for the plant growth and hydrological modeling. Since only two dominant vegetation types were identified, studies were focused on grassland including wetland areas which are predominantly covered by grassy vegetation and afforested areas.

7.2.1.3.1 Grassland and Wetland Ecosystems

The analysis of the vegetation composition and the relation of a specific species type with environmental conditions showed notable differences between the vegetation classes. Grassland areas are mainly dominated by annual grass species like *Themeda trianda, Alloteropsis semilata, Panicum natalense* and *Monocymbium ceresiiforme* on moister sites. These areas are mainly characterized by low vegetation heights and densities. Temporary or seasonal saturated areas (i.e. slope and plateau wetlands) are mainly dominated by *Scleria welwitschii*, but also *Pycreus uniolides*, *Rhynchospora barossiana*, *Arundinella nepalensis*, *Aristida junciformis*, *Pennisetum thunbergii* and *Helichrysum rugulosum* were found. Vegetation heights range between 20 and 50 cm, while densities vary between 70 and 100%. The valley bottom wetland type is mainly dominated by perennial sedges and rushes species. The occurrence of grass species is evident, but relatively limited to species which are more resistant to wet conditions. Typical vegetation of valley bottom wetlands is represented by *Juncus effusus*, *J. exsertus*, *J. oxycarpus*, *Cyperus fastigiatus*, *C. denudatus*, *Schoenoplectus brachyceras* and *Scleria welwitschii,* and grass species: *Arundinella nepalensis*, *Leersia hexandra* and *Phragmites australis*.

When examining soil moisture data taken along the transects it was found that the distribution of most species is strongly associated with water regime. With the exception of a few ubiquitous species with wide niches (e.g. *Kyllinga erecta* and *Phragmites mauritianus*) there was an almost complete turnover of species in a wetland along the soil saturation gradient from temporary wetness to permanent wetness. The analysis of the relationship between the distribution of the 8 predominant species and degree of wetness for different wetland sites showed that generally the relationship between commonly occurring species and degree of wetness, as determined by soil moisture measurements, does not vary significantly among wetlands (r^2=0.10). This is in agreement of findings presented by KOTZE & O'CONNOR (2000). Additional parameters such as soil type, soil texture and relief position were found to be less important, but nevertheless contributed to explaining variation in species composition. Figure 7.26 summarizes the distribution characteristics of dominant species within grassland and wetlands in relation to their environmental conditions expressed as soil moisture, drainage type and soil type.

Besides the vegetation composition, several relationships among the measured parameters were used to characterize the specific plant communities and to identify variables which can be used to improve the differentiation of wetland types. Moreover, the relations identified can be used to provide estimations of several parameters as long as one parameter is available. For example, from the measurement of vegetation height which is simple to measure, estimates of cover density or LAI can be provided. Plateau wetlands were mainly excluded from these analyses, because of the non-representative and small number of plateau wetlands surveyed. Hence, this type was assigned to the slope wetland class which is similar with respect to species composition and plant-biophysical parameters.

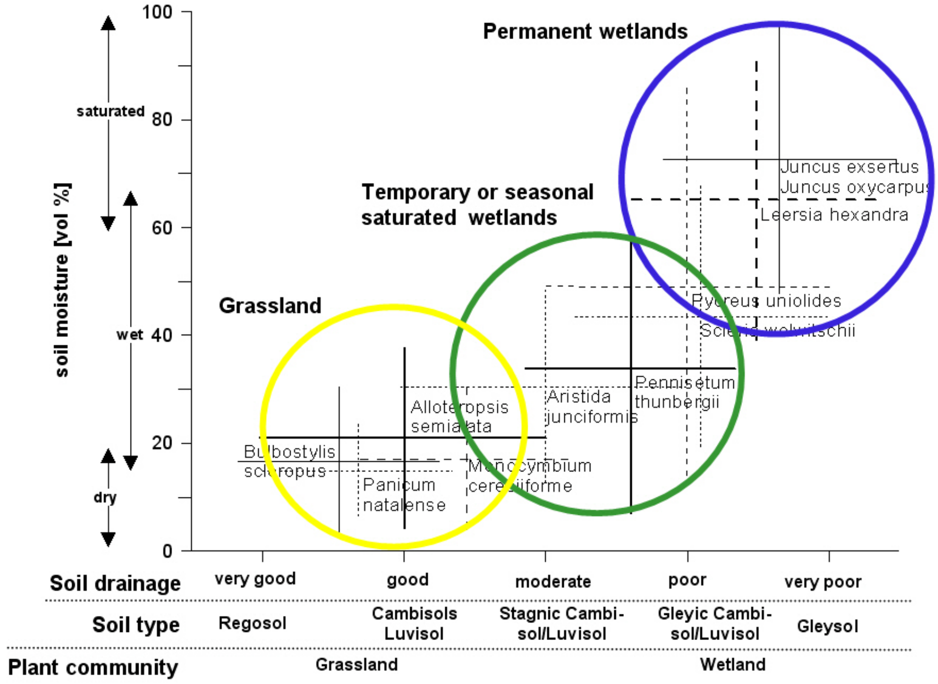


Figure 7.26: Two-dimensional ordination of selected dominant grassland and wetland species in relation to soil moisture, drainage and soil type classes (mod. after Dahlke et al., 2003).

The relationship between mean vegetation height and cover density is plotted in Figure 7.27. Basically, the mean height corresponds with the cover density ($r^2 = 0.67$) for all classes. While grassland generally shows smaller vegetation heights and densities, the slope wetland vegetation tends to be explicitly smaller than the valley bottom wetland vegetation, but shows similar densities. This might be caused by the occurrence of species dominating the transition areas and their specific adaptation (leaf structure) to the temporary water availability.

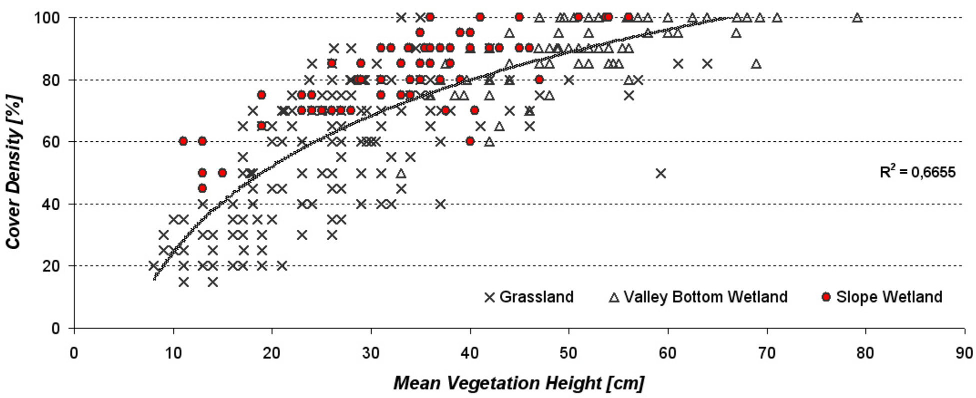


Figure 7.27: Relationship of mean vegetation height and cover density for grassland and wetland vegetation.

A significantly linear relationship ($r^2 = 0.64$) was found when mean vegetation height was related to LAI (Figure 7.28). As expected, the primarily lower grassland is characterized by lower LAIs, while wetlands show relatively high LAIs. According to LAI values, the slope wetland vegetation is slightly lower when compared to the valley bottom wetland, but shows notable smaller mean vegetation heights.

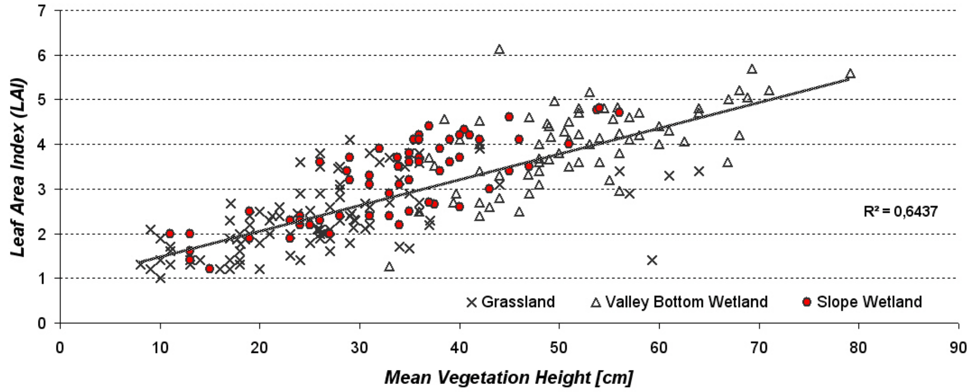


Figure 7.28: Relationship of mean vegetation height and LAI for grassland and wetland vegetation.

The relationship between mean vegetation height and mean root length is plotted in Figure 7.29. Although a linearity ($r^2 = 0.57$) has been identified between the two parameters, differences were found in terms of the scatter of parameters for each plant community. Grassland is evidently less scattered, while both wetland types show a relatively high variability. This can be explained since grassland areas are characterized by relatively, in terms of water availability homogeneous environmental conditions, while wetland areas are influenced by a wide range of environmental parameters (water availability, slope position, land management). The plot furthermore indicates that slope wetland vegetation develops longer roots, since this vegetation needs to be adaptive to fluctuating water availability.

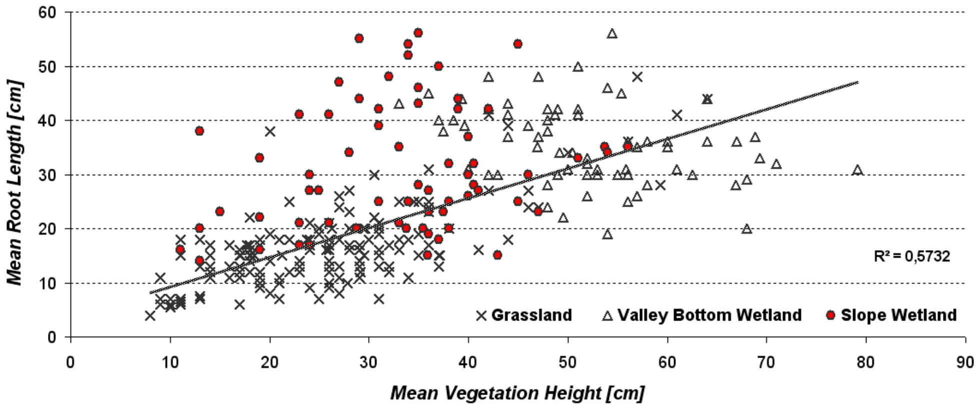


Figure 7.29: Relationship of mean vegetation height and mean maximum root length for grassland and wetland vegetation.

A more detailed analysis incorporating the plateau wetland class was used to characterize differences between the three wetland classes in terms of cover density, vegetation height and root length. The Box-Whisker plots shown in Figure 7.30 illustrate the spread of data groups around their medians using the minimum and maximum values and the 25/75 percentiles. The graphs demonstrate that cover density and vegetation height are clearly different among the three types, and thereby can be used as indicators to differentiate between them. The root length seemed to be similar between the three classes, but showing a higher range in the valley bottom wetland type.

In addition, the parameters cover density; vegetation height and LAI of all plant communities were related to four aspect classes in order to identify the influence of solar radiation, and thereby evapotranspiration, and temperature on these parameters. For this purpose, aspects were classified into 4 classes (N: 0°-45°, 315°-0°; E: 45°-135°; S: 135°-225°; W: 225°-315°).

As shown in Figure 7.31, south-facing slopes are assumed to show a noticeably higher cover density; vegetation height and LAI than northern slopes, while eastern and western slopes are characterized by relatively similar values between north- and south-facing slopes. Consequently, it is assumed, that a sparser vegetation density is developed on north-facing slopes resulting from lower water availability due to higher solar radiation, which in turn causes higher temperatures and evapotranspiration rates. Since the aspect obviously influences vegetation density and, thereby evapotranspiration and interception rates, the parameter aspect needs to be considered within the HRU delineation and the model application.

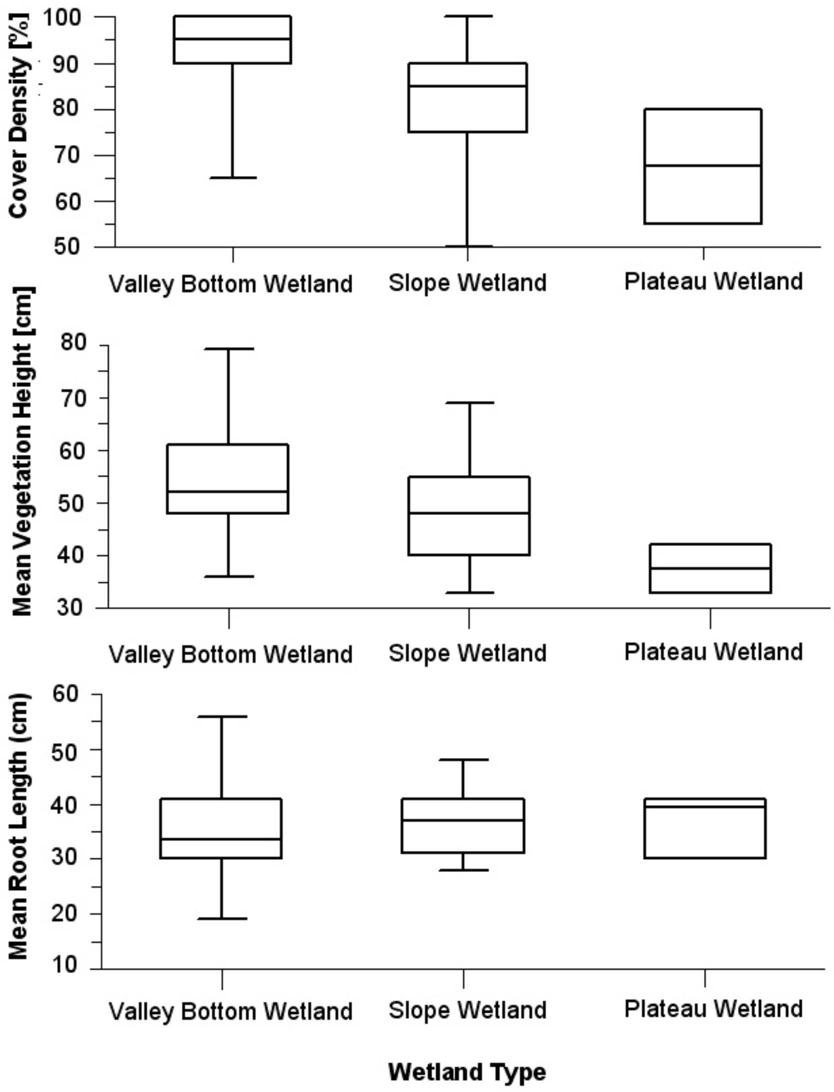


Figure 7.30: Box-Whisker plots illustrating cover density, vegetation height and root length for three wetland types. (The parameters used in the Box-Whisker plot are the Min, Max, Median and the 25/75 percentile of each data sample.)

Summarizing the vegetation studies in grassland and wetland communities, it was shown that plant-biophysical parameters like vegetation height, cover density, LAI and root length can be used to distinguish between wetland and grassland areas, and moreover to differentiate between different wetland classes. This information has been incorporated into the HRU delineation approach and was used to parameterize the hydrological model.

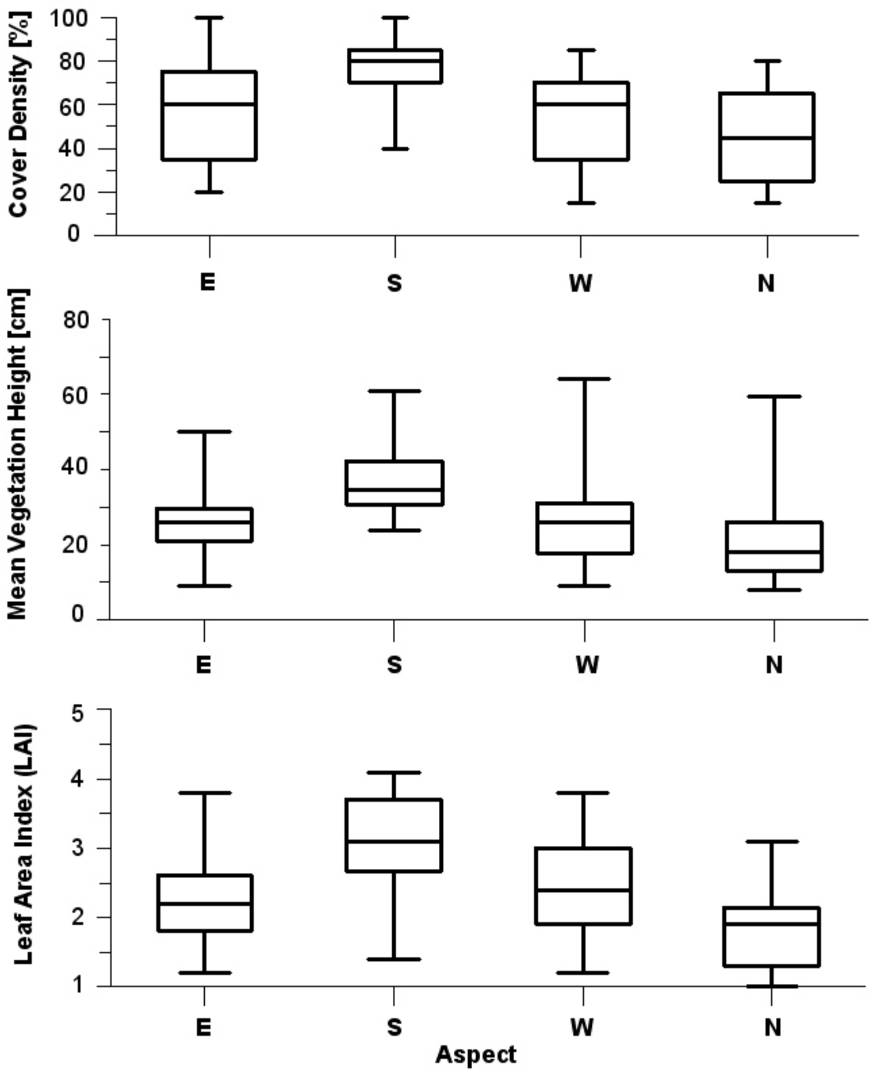


Figure 7.31: Box-Whisker plots illustrating LAI, vegetation height and cover density for four aspect classes. (The parameters used in the Box-Whisker plot are the Min, Max, Median and the 25/75 percentile of each data sample.)

7.2.1.3.2 Commercial Forest Plantations

Since the afforestation activities starting in 1989 are assumed to impact the water budget in general and the wetland dynamics in particular, pine and eucalyptus stands were surveyed during several field campaigns from 1997-2005. Knowledge of growth dynamics and a number of model parameters were provided for the parameterization and verification of 3-PG and PRMS model applications.

Measurements were firstly used to identify relationships between cover density and LAI, and stand-related parameters like stocking (tree density), DBH and tree height.

Once the relationships are established, they can be used to derive age-related cover densities and LAI from available forest stand parameters indirectly, because stand parameters like DBH and height are usually available from forest stand data bases. Following the main results which are of importance for the model applications are discussed briefly.

The relationship between tree density (stems ha^{-1}) and cover density (%) is plotted in Figure 7.32 showing a slight positive linear relationship between both parameters. Nevertheless, the sensitivity of cover density to stocking tends to decrease with increasing ages which in turn is related to silvicultural practices (thinning). As a consequence, the 15-22 years old stands show a relatively high scatter in terms of cover density, while the younger stands seem to be proportionally homogenous distributed. Given tree density is consistent due to planting practices (3 m spacing interval), little variations within the younger classes are only addressed to the variability of stand parameters such as soil type, slope, aspect and relief position affecting plant growth dynamics.

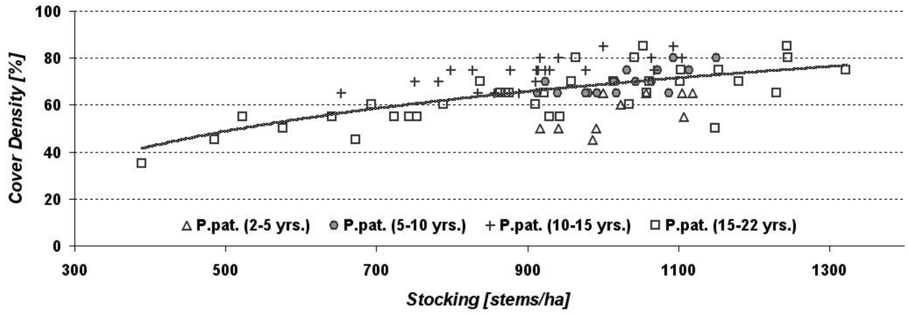


Figure 7.32: Relationship between stocking (stem ha^{-1}) and cover density (%) for Pinus patula stands grouped into four classes of different ages.

In Figure 7.33 the relationship between tree height (m) is plotted against cover density (%). The plot shows a high scatter for each age class, and hence it can be concluded that the mean tree height is little related to the cover densities. Although a relation basically seems to be evident between both parameters ($r^2=0.33$), the large spread indicates a high level of uncertainty especially in old stands. Nevertheless, it is shown, that older stands are characterized by higher tree heights which in turn are associated with decreasing cover densities. This effect also needs to be related to forest management practices. Younger trees can be easily separated from the other classes, since mean heights are significantly lower than in the other groups, even though cover densities are in the same range like the others.

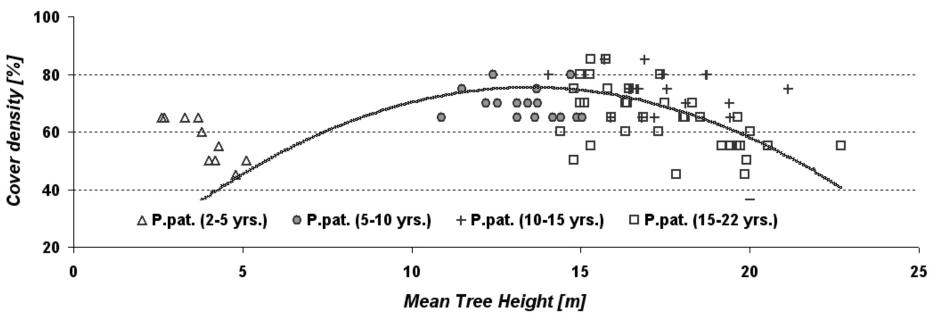


Figure 7.33: Relationship between mean tree height (m) and cover density (%) for Pinus patula stands grouped into four age classes.

Figure 7.34 illustrates the relationship between mean DBH (cm) and cover density (%). With the exception of the oldest stands, which show a high variability in cover density, there seems to be a reasonable relation between the two parameters (r^2=0.51) in each of the other age class. Similarly to the effect illustrated in Figure 7.33, the older stands show an increasing DBH when cover density decreases.

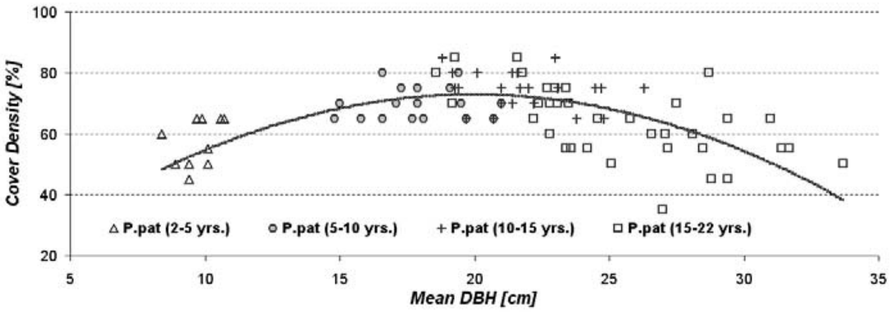


Figure 7.34: Relationship between mean tree height (m) and cover density (%) for Pinus patula stands grouped into four age classes.

As discussed by several studies (HELMSCHROT, 1999; WATSON, 1999), a strong relationship is evident between DBH (cm) and mean tree height (m) in pine stands. These findings are supported by the plot shown in Figure 7.35. Based on the measured parameters it is concluded that the DBH shows a high correlation (r^2=0.84) with mean tree height in *Pinus patula* stands represented by the linear curve. As a consequence, if one of the parameters is unknown, the residue can be estimated from the knowledge of this relation, and thereby used for further forest and hydrological analysis (e.g. biomass studies or growth modeling).

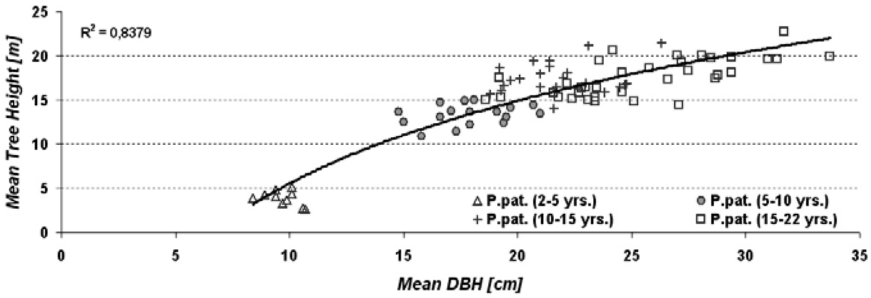


Figure 7.35: Relationship between mean DBH (cm) and mean tree height (m) for Pinus patula stands grouped into four age classes.

Finally, age-related mean LAI values of *P. patula* and *E. nitens* stands were plotted against their mean DBH as illustrated in Figure 7.36. Since the plot indicates a good correlation between the parameters ($r^2_{P.pat}$=0.61, $r^2_{E.nit}$=0.56), those curves are appropriate to estimate age-related LAI from given DBH values. Using the relationship given in Figure 7.36 and the relationship between LAI, crown diameter and cover density within *P. patula* stands provided by HELMSCHROT (1999), cover densities and LAI vice versa can be roughly estimated within *Pinus patula* stands applying relations plotted in Figures 7.33, 7.34 and 7.35 respectively.

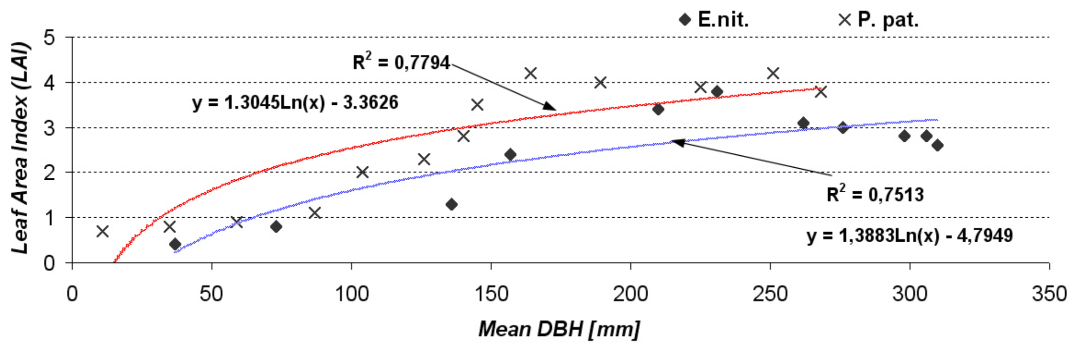


Figure 7.36: Age-related relationship between mean DBH (cm) and LAI for Pinus patula stands.

Summarizing studies conducted in forest stands, a reliable data base has been created which was used to develop relationships between selected parameters and for the later model applications. The above observations were used to construct a model enabling the prediction of LAI and its associated cover density of any pine or eucalyptus stand given its mean DBH. This information could be used to calibrate the models and to verify model results derived from the plant growth modeling using 3-PG.

7.2.1.4 Land Use Change Analysis

As shown by many studies, an integrated assessment of land use impacts on water balance and streamflow needs to be based on reliable information on land use. In particular when physically-based, distributed models are used, the spatial and temporal resolution of land use data needs to consider the explicit spatial and temporal scale of the model. BRONSTERT *et al.* (2002) give a thorough background on the present knowledge and modeling capabilities to simulate the effect of land-use change on runoff generation.

To evaluate the impact of land use change on runoff generation, in this case afforestation, land use change analysis reflecting land use dynamics over a specified time is a prerequisite for a sound hydrological modeling. A variety of approaches exists to identify land use and cover change. As emphasized in numerous studies, innovative techniques like neural networks, knowledge-based expert systems, and object-oriented classification have shown their potential in providing sufficient data on land use dynamics in heterogeneous areas like urban environments or complex landscapes, while traditional post-classification can be used in relatively homogenous environments (*inter alia* CIVCO, 1993; GREEN *et al.*, 1994; HEROLD, 2004). Thus, in the present study, a post-classification approach utilizing multi-temporal land use information derived from optical satellite data was chosen to characterize afforestation dynamics from the beginning of afforestation in 1989 until the complete closing of canopies of the dominant species and first clearcuts in 2001.

Table 7.11 summarizes land use distribution at level 3 for autumns 1989, 1995, 1999 and 2001 which is derived from land use classification as described in Section 7.1.5. Table 7.12, moreover, gives information on land use changes at level 1 between 1989 and 2001.

Table 7.11: Level 3 land use distribution within the Mooi catchment based on the analysis of land use classifications derived from combined multi-temporal Landsat TM images from 1989, 1995, 1999 and 2001, contemporary forest data and field-based land use maps.

Land use class	09 Mar 1989		29 05 1995		09 Apr 1999		10 Mar 2001	
	Km²	%	Km²	%	Km²	%	Km²	%
Arable land, cultivated]	8.58	2.79	2.05	0.67	0.76	0.25	2.74	0.89
Arable land, not cultivated	1.82	0.59	0.47	0.15	1.36	0.44	0.32	0.10
Indigenous forest	2.49	0.81	1.93	0.63	1.63	0.53	1.63	0.53
Poplar	0.13	0.04	0.1	0.03	0	0	0	0
Euc. < 1 year	0.24	0.08	0.21	0.07	0	0	0	0
Euc. 1 – 2 years	0	0	0.89	0.29	0	0	1.15	0.37
Euc. 3 – 4 years	0	0	0.28	0.09	0.76	0.25	0	0
Euc. > 4 years	0	0	1.33	0.43	1.04	0.34	1.00	0.33
Pinus < 3 years	4.50	1.47	15.18	4.95	11.84	3.86	6.18	2.01
Pinus 3 – 6 years	0	0	17.76	5.79	17.62	5.74	19.18	6.25
Pinus 7 – 10 years	0	0	0.19	0.06	23.36	7.60	22.29	7.26
Pinus 11 – 15 years	2.12	0.69	0.82	0.27	1.31	0.43	8.32	2.72
Pinus 16 – 20 years	1.09	0.36	0.31	0.10	0.11	0.03	0.10	0.03
Pinus > 20 years	0	0	4.52	1.47	2.61	0.85	0.12	0.04
Deforested	0	0	0.96	0.31	0.02	0.01	0.90	0.29
Grassland, open	69.53	22.65	51.80	16.88	79.67	25.96	30.26	9.86
Grassland, moderate	65.81	21.44	120.25	39.17	67.13	21.87	72.00	23.46
Grassland, closed	100.11	32.61	47.31	15.41	54.52	17.76	96.51	31.45
Water	0.04	0.01	0.04	0.01	0.05	0.02	0.05	0.01
Wetlands, valley	19.85	6.48	19.19	6.25	18.98	6.18	18.81	6.13
Wetlands, slope	16.77	5.46	13.05	4.25	12.82	4.18	12.51	4.08
Wetlands, plateau	2.05	0.67	1.99	0.65	1.97	0.64	1.78	0.58
Bare soil	10.72	3.49	5.24	1.71	8.29	2.70	9.99	3.25
Bare rock	1.11	0.36	1.09	0.36	1.11	0.36	1.12	0.36
	996	**892**	**1284**	**991**	**1293**	**1090**	**1095**	**793**

Table 7.12: Level 1 land use change analysis within the Mooi catchment between 1989 and 2001 based on the analysis of land use classifications derived from combined multi-temporal Landsat TM images from 1989 and 2001, contemporary forest data and field-based land use maps.

Land use class	1989		2001		Total Change	
	Km²	%	Km²	%	Km²	%
Agricultural land	10.04	3.38	3.06	0.99	-7.34	-2.39
Indigenous forest	2.49	0.81	1.63	0.53	-0.86	-0.28
Forest Plantations	8.08	2.64	59.24	19.30	51.16	16.67
Grassland	235.45	76.7	198.77	64.77	-36.68	-11.95
Water	0.04	0.01	0.05	0.01	0.01	0
Wetlands	38.67	12.61	33.1	10.79	-5.57	-1.81
Bare soil	10.72	3.49	9.99	3.25	-0.73	-0.24
Bare rock	1.11	0.36	1.12	0.36	0.01	0
	564	**433**	**591**	**496**	**339**	**336**

Regarding the objective of this study, the main focus of the comparison between the given land use data sets is on changes resulting from the transformation of rangeland to commercial forest plantations. Moreover, the dynamics of wetland areas were specifically investigated, since it is assumed that afforestation affect wetland extent either directly by planting in wetlands, or indirectly by reducing water inflow and the subsequent drying out of wetland patches.

Summarizing land use dynamics identified, following main conclusions can be drawn from Table 7.11 and 7.12 respectively:

- A significant increase of the extent of total forest area (+ 16.7 %) has been identified. Moreover, a simultaneous decrease of all other land uses was detected with the exception of water and bare rock.
- In the forest areas, the main increase was found for pine plantations (+ 12 %) with some age-dependent variations. The relatively constant occurrence of eucalyptus stands since 1995 can be explained by the cessation of eucalyptus planting since 1992 due to economic reasons. In 2000, the forest company decided to re-establish eucalyptus forestry in the area causing an increase of eucalyptus stands.
- Deforestation i.e. clear-cuts of forest stands took place from 1993 - 1995 when old pine stands (ZWOLINSKI *et al.*, 1997) have been harvested and in 2001 when mature eucalyptus plantations have been cleared. Moreover, small stands of poplar were removed in in 1998.
- Indigenous forest loss is addressed to the clearing of wattle tree areas resulting from an initiative to reduce the prevalence of alien vegetation (BUTT, 2000, pers. comm.).
- Primarily, grassland (- 12 %) received areal losses followed by agricultural lands (- 2.39 %). This is explained because trees have been usually planted on abandoned farm land which was primary used for rangeland or crop farming.
- The wetland loss (- 1.81 %) is addressed to planting trees in either transition areas between wetlands and uplands or in wetland areas directly. In addition, it is assumed that areas which are surrounded by afforestation are affected by the reduction of water inflows. An indication for wetland loss is also given when rainfall dynamics are considered. Lower rainfalls in the wet season 1995/96 caused a decrease of total wetland area. Although the intense rainfalls were observed in the 1998/99 season, a further reduction of total wetland area was detected. Moreover, continuous monitoring of soil wetness in selected areas leads to the assumption that individual slope wetlands surrounded by eucalyptus stands receive less water than in the past. For example, one wetland site in the Glen Cullen estate was continuously surveyed by soil drills carried out during the field campaigns. This specific wetland never showed signs of wetness, not even at the end of the rain season, since 1998. Thus it is indicated that the lateral water inflow was reduced as a consequence of planting the wetland uplands.
- The inter-annual variations within the soil class can be explained by the preparation of former rangeland for afforestation by contour ripping, burning etc., while variations within the bare rock class are addressed to the miss-classification.

In Weatherley, land used was derived from field-based land use maps and forest planting maps. As shown in Table 7.13 land use has changed in 2002 by planting 17.2 ha with eucalyptus and 31.4 ha with pine species so that a total of 48.6 ha (35.09 %) was transformed from grassland to forest plantation. Since wetland area was not affected by plantations, its extent remained with 27.46 %.

Table 7.13: Land use distribution within the Weatherley experimental site prior to and after afforestation (2002) based on field-based land use and contemporary forest maps.

Land use class	Before 2002		After 2002		Total Change	
	ha	%	ha	%	ha	%
Eucalyptus	0	0	17,2	12,42	17,2	12,42
Pinus	0	0	31,4	22,67	31,4	22,67
Grassland	100,7	72,71	52,1	37,62	- 48,6	-35,09
Wetlands, valley	16,2	11,70	16,2	11,70	0	0
Wetlands, slope	21,0	15,16	21,0	15,16	0	0
Wetlands, plateau	0,6	0,43	0,6	0,43	0	0
	138,5	**100**	**138,5**	**100**	**0,0**	**0,0**

7.2.1.5 Terrain Analysis

Topography significantly influences hydrological processes such as evapotranspiration, surface and subsurface flow dynamics and groundwater recharge (KIRKBY, 1978). As discussed by WALLACE & OLIVER (1990), the primary effects of slope and aspect are to alter the radiation balance and this in turn might change the potential evaporation rate to a significant extent. For example, JACKSON (1967, cit. in WALLACE & OLIVER, 1990) demonstrated for southern hemisphere conditions that the potential evaporation rate on north-facing slopes was greater than on south-facing ones. The slope angle also affected evaporation with increasing slope tending to decrease evaporation on a south-oriented aspect and vice versa on a northerly one. Thus, the given DEM was analyzed to explore slope and aspect distribution and the characteristics of slope shapes and curvatures. This information was taken into account in characterizing dominant hydrological processes in the two catchments and, subsequently, in the delineation of the HRUs.

As illustrated in Figures 7.37 and 7.38, slope and aspect was computed from DEMs for the Mooi catchment (25 x 25 m²) and for the Weatherley catchment (5 x 5 m²).

From the analysis of the distribution of slope and aspect in the Mooi basin it is concluded that

- about 20 % of the basin are characterized by relatively flat terrain (0 - 5 °), while about 40 % are dominated by moderate (5 – 15 °) and another 40 % by steep (> 15°) slopes,
- highest gradients are observed along the escarpment, in particular at the interface of the Drakensberg Basalts and the Elliot and the Clarens Sandstone,
- the aspect is uniformly distributed in the catchment (N: 26 %, E: 30 %, S: 24 %, W: 20 %).

Relating both parameters it was found that south-facing slopes are usually steeper than north-facing slopes. This confirms findings of MEIKLEJOHN (1992) and BOULHOEWERS (1988). Both authors associated these differences to varying wetness conditions which result from distinctive incoming radiation intensities which, in turn, cause different erosion process dynamics.

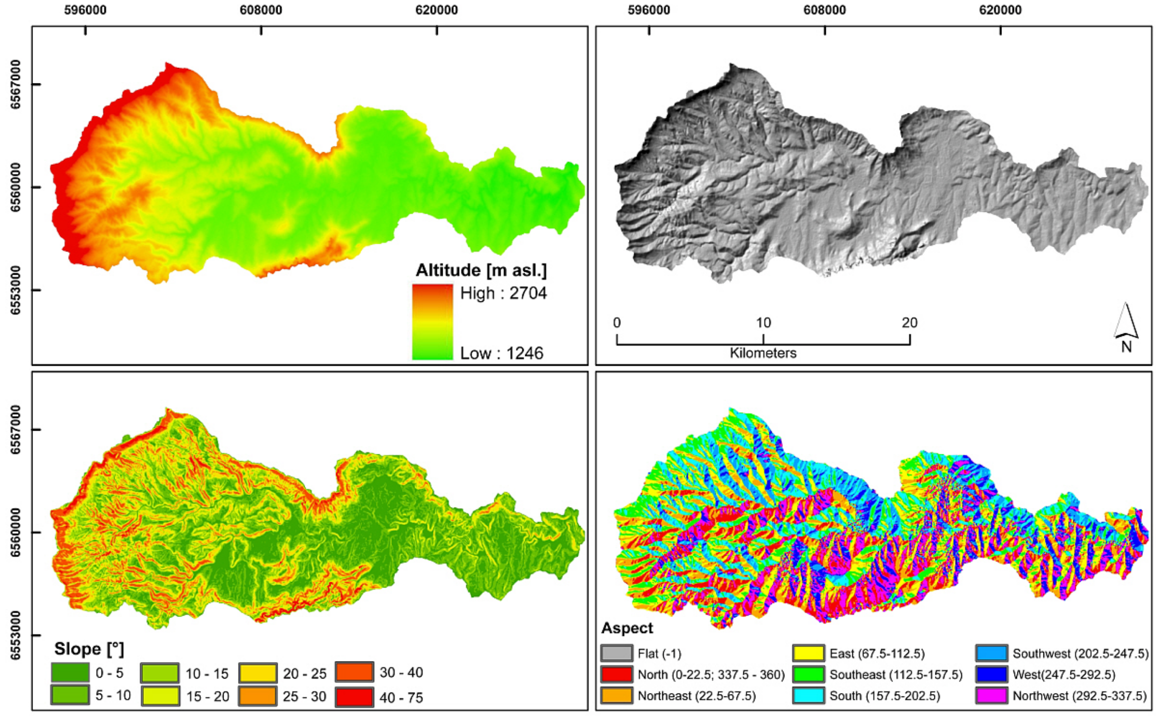


Figure 7.37: Digital Elevation Model with 25 × 25 m² resolution (upper left) and delineated maps of hillshade (upper right), slope (lower left) and aspect (lower right) of the Mooi catchment.

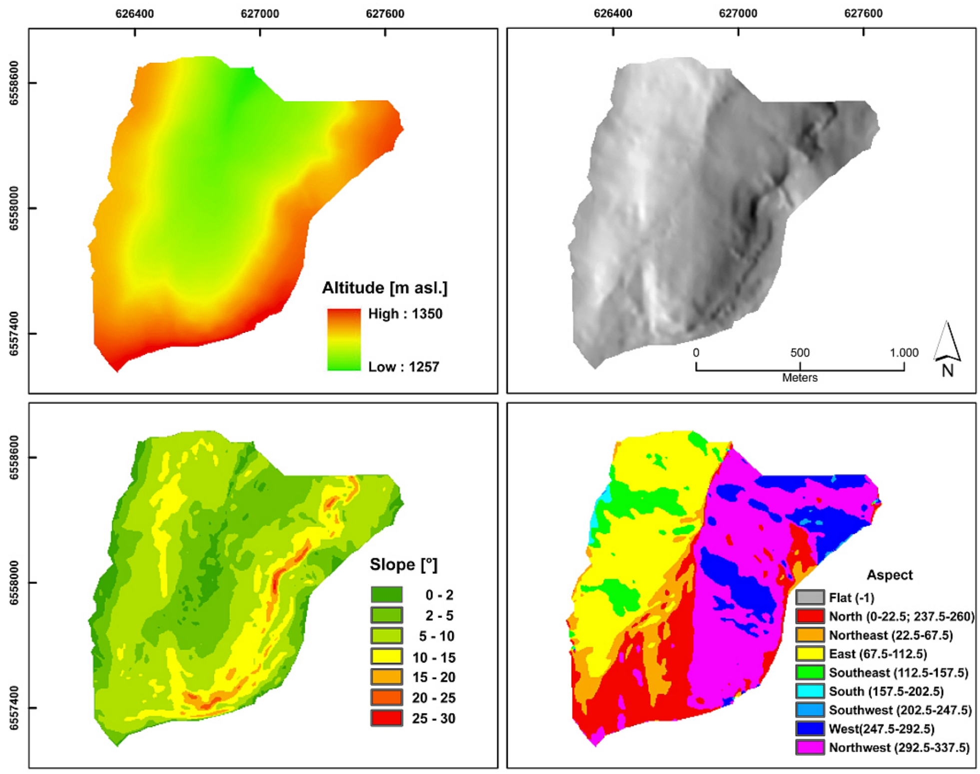


Figure 7.38: Digital Elevation Model with 5 × 5 m² resolution (upper left) and delineated maps of hillshade (upper right), slope (lower left) and aspect (lower right) of the Weatherley catchment.

The analysis of topographic features in Weatherley has shown that

- about 54 % of the catchment area is characterized by moderate (5 – 15 °) and about 32 % by steep (>15 °) slopes, while only 14 % of the basin are flat areas (0-5 °),
- in contrast to the Mooi basin, slopes are only north-facing (35 %), west-facing (31 %) and east facing (33 %), while less than 1 % are south-oriented.

Since studies of hillslope hydrology has shown that hydrology is significantly different at different terrain position, terrain units were delineated from the DEM. Combining the parameters height below culmination and height above drainage channel on a trial-and-error basis, three terrain units were distinguished regarding their importance for catchment hydrology:

i) ***Valley floors*** are located in lower positions in the catchment. They are generally flat, but may be slightly concave. Valley units are usually associated with a river channel which tends to meander because of the flat terrain. Hydrology is characterized by a variable groundwater level.

ii) ***Slopes*** are characterized by a gradient higher than 5 ° showing either convex or concave shapes. Slope units are usually directly connected to the valley unit. Hydrologically, slopes are mainly controlled by lateral subsurface flow.

iii) ***Plateaus*** or interfluve crests are found on top of slopes which separates two adjacent valleys. Thus, slopes are always convex. They are small in size and characterized by a relatively independent water cycle, i.e. groundwater is exfiltrating occurring as toeslope seepage.

From this effort, a terrain unit map were created which found consideration in the the delineation of HRUs (Section 7.2.4).

Furthermore, basic watershed parameters such as catchment boundary, river network, flow accumulation and direction were delineated for each catchment using standard methods implemented in ARGGIS 9.0.

7.2.2 Analysis of Hillslope Hydrological Dynamics

Considerable progress was made in hillslope hydrological research, since it is recognized in particular in headwater catchments that runoff generation is mainly controlled by hillslope processes (KIRKBY, 1978; ANDERSON & BURT, 1990). This is mainly due to the increase of field catchment studies incorporating dense instrumentation in relatively small areas. Such an analysis of the hydrometric data measured along several transects formed the base of the understanding of the hydrological functioning in Weatherley. Integrated studies on subsurface and surface water dynamics led to the development of a model that characterizes major runoff generation processes on hillslopes in Weatherley. The developed model was considered to differentiate HRUs with respect to hydrological process dynamics and for the classification of wetlands regarding their water transport dynamics. The presented findings result from the close cooperation with Dr. Simon Lorentz from the School of Biological and Environmental Engineering and Hydrology in Pietermaritzburg.

7.2.2.1 Event-based Analysis of Hillslope Processes

Complementing the work published by LORENTZ *et al.* (2001, 2004), subsurface soil moisture status measured along the transects combined with rainfall, runoff and groundwater observations were used to study runoff generation mechanisms at hill-slopes in detail. Herein, soil water status measurements (capillary pressure head responses) at different depths of the profile were compared before, during and after rainfall events. An example of a typical slope sequence is given in Figure 7.39 showing capillary pressure head responses in three soil profiles beginning at the dry upslope area (nest 10) through the transition zone (nest 9) down to the wetland and riparian zone (nest 8). The sequence was recorded during February and March 2001. The mechanisms described below were observed throughout the record of measurements. The location of the nests is illustrated in Figure 7.40.

It is shown that saturated conditions rarely occur at any depth in the profile in upland areas (nest 10, Figure 7.39b), even after intense rainfalls (Figure 7.39a). Even though the response at 400 mm is more dynamic than at 700 mm and 1 200 mm, the capillary pressure head never becomes negative which would indicate a positive hydraulic head at 400 mm and hence saturated conditions. The rate at which the capillary pressure head reduces indicates a freely conducting macro-pore structure. The water is assumed either to move immediately downwards by rapid lateral flow which occurs in some cases as piping or evaporates by interception in dense grassland. The dry phase observed during the end of February and the middle of March resulted in a continuous increase of the capillary pressure head. At 700 mm, only more than 40 mm of rainfall causes short-term saturated conditions, evidently from direct and upslope contributions. Moreover, a second wetting phase arrives 1 – 3 days after intense rainfalls. With a delay ranging between 3 hours and 1 day, short-term saturation is observed close to the soil-bedrock interface (1 200 mm) after intense rainfalls, but recovers to unsaturated conditions within 12 hours. It should be noted that the second intense rain event (47.5 mm) produces a lower peak and smaller volume of runoff than the first. The second comes after a longer dry period with lower antecedent rain in the previous 7 days and highlights the importance of antecedent moisture content (AMC) and age duration for the volume and timing of runoff response.

Analyzing these effects by plotting runoff data against soil moisture records, it was shown that with no aging, runoff volume increased with an increase in AMC. This is due to the enhanced aggregates breakdown. Further examples have shown that runoff decreased with the increase in aging duration. When compared to soil analysis, the smallest runoff volumes were obtained at the intermediate AMC levels, generally between wilting point and field capacity. As a consequence it is concluded that the AMC dynamics have a significant impact on runoff generation, and thereby control surface and subsurface flows on hillslopes and their potential to support floodflows.

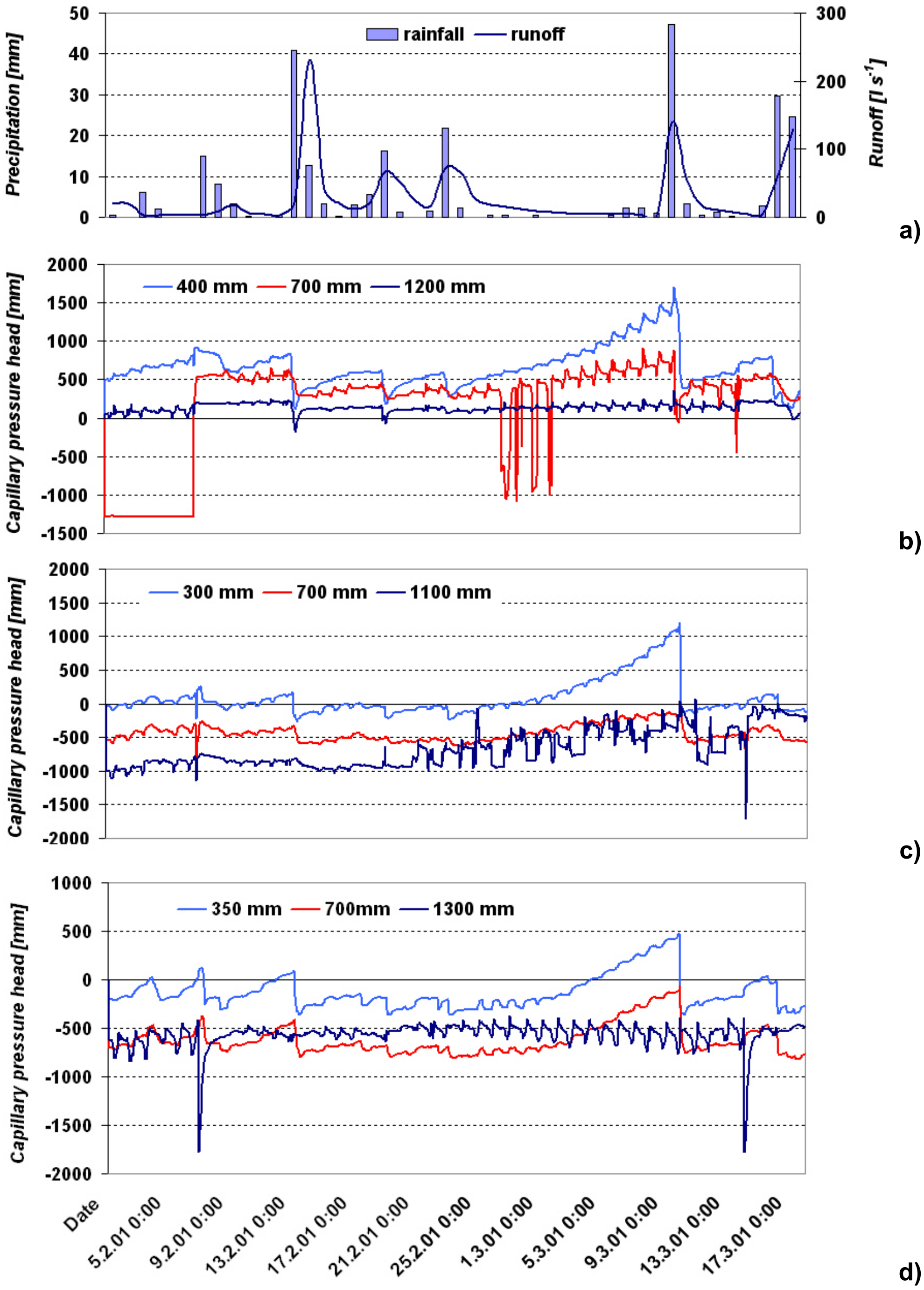


Figure 7.39: Tensiometer response during February and March 2001 in a typical slope segment representing the transition from the uplands to the wetland and riparian zones in the upper Weatherley catchment. The figure shows: a) Rainfall-runoff record; b) upland area (nest 10); c) transition zone (nest 9); wetland and riparian zone (nest 8).

Note: The drops in the 700mm tension in b) reflect the time when the ceramic lost contact with the soil, and thereby need to be excluded from the interpretation.

In the transition zone (nest 9, Figure 7.39c) the entire soil profile is inundated during the observed period except near the surface at 300 mm where unsaturated conditions occur after a minimum of three days without rain. The response of the capillary pressure head at 300 mm and 700 mm shows a similar temporal behavior, while the response at 1 100 mm is more dynamic. Although the capillary pressure head seems to respond to the rainfall event at the 10^{th} of March immediately, the highest negative peak is observed about 3-5 days after the event. Thus, it is assumed that lateral flow along the soil-bedrock interface which comes from upslope areas is more influential than direct vertical water flow.

A similar behavior was observed in the wetland soil profile in the valley bottom. The signal at nest 8 (Figure 7.39d) indicates dry-outs near surface (350 mm) only at three times during the observed period. The capillary pressure head at 350 mm and 700 mm seems to respond with the same temporal dynamics, but with lower values at 700 mm. In contrast, the tensiometer signals at 1 300 mm show a different dynamic. Comparing the measurements with soil data it is concluded that a low permeability barrier between the 700 mm and 1 300 mm deep sensors causes a disconnected system. Additionally it is indicated that the dry phase does not affect the water level dynamics at 1 300 mm depths and thereby confirms the theory of a disconnected system. Thus, it is concluded that the near bedrock water level is more controlled by lateral inflow from upper areas than by vertical transfers within the profile. The occurrence of permanent saturated conditions indicates that this inflow is continuously and independently from rain volumes and intensities. As shown by soil studies, water retention capacity measured in these layers is very high, while the terrain is relatively flat. This combination results in the formation of a groundwater aquifer with a fluctuating water table (phreatic surface) which is controlled by the subsurface inflows generated on the upslope areas. It is indicated that the dynamic of this groundwater aquifer supports flood attenuation, but, more important, controls the low flow conditions during the dry season by the continuous release of water.

7.2.2.2 Modeling of Hillslope Processes

In addition to the analysis of hydrometric data, two modeling exercises have been undertaken by LORENTZ *et al.* (2001, 2004) to simulate the complex hillslope flow dynamics in Weatherley. In this regard, one segment of the transect in the lower catchment was simulated using the HYDRUS 2D (SIMUNEK *et al.*, 1999) model. The model is a finite element soil physics model and can be used for the analysis of unsaturated, variably saturated, and saturated flow and solute transport through porous media. The HYDRUS 2D model numerically solves Richard's equation for saturated-unsaturated water flow. Richard's equation, the governing flow and transport equation, is solved numerically using a Galerkin-type linear finite element scheme (SIMUNEK *et al.*, 1999). Moreover, HYDRUS 2D uses unsaturated soil hydraulic properties that are incorporated into the governing flow equation. The user may choose from three different analytical models to solve for unsaturated soil hydraulic properties (SIMUNEK *et al.*, 1999). The model incorporates a sink term for root water uptake, and uses an anisotropy tensor to account for an anisotropic medium.

Complementing the model efforts, the two-dimensional physically-based hillslope hydrology model HILLS model (HEBBERT & SMITH, 1990) was utilized for a sequence in the upper catchment. The model describes water movement through a two-layered soil profile where important soil parameters, such as the hydraulic conductivity, soil depth and porosity need to be defined. It operates on a timescale varying from minutes to days. Applying a kinematic wave function, the model quantifies surface runoff and saturated overland flow. According to Richard's Equation, water is assumed to move as unsaturated vertical flow when it infiltrates into the topsoil. Saturated lateral flow occurs, at a rate determined by the *Dupuit* approximation of Darcy's Law if saturation occurs in the topsoil. Evapotranspiration rate is a function of root depth, potential pan evaporation, and moisture content and occurs between rainfall events from both the saturated and unsaturated soil. A more detailed description of the model concepts and their parameterization can be found in LORENTZ *et al.* (2001).

From all these efforts, three dominant runoff generation mechanisms that contribute to the runoff generation were identified: *i) overland flow, ii) near-surface macro-pore flow*, and *iii) groundwater flow*. As presented by LORENTZ *et al.* (2004), these mechanisms were quantified using simple physical-based algorithms applied to measured soil water dynamics and runoff data. In addition, simple unit response functions comprising an advection-dispersion model (ADM) and an Overland Flow Model (OFM) were applied to simulate residence times and fluxes of runoff sources.

Based on this work (LORENTZ *et al.*, 2004) and own observations, a model was developed describing streamflow generating mechanisms and their occurrence in the Weatherley catchment. The descriptions were generalized and illustrated in Figure 7.40. Its implications for wetland hydrology are explained in the following sections.

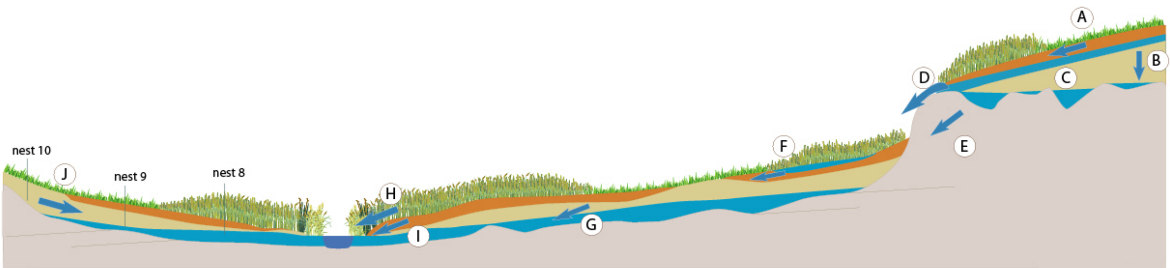


Figure 7.40: Schematic diagram of dominant flow processes and their occurrence on the hillslopes (mod. after LORENTZ *et al. 2004;* HELMSCHROT *et al., 2005).*

Combining field survey, hydrometric monitoring and process modeling, the following conclusions can be summarized regarding the streamflow generation mechanisms and their spatio-temporal occurrence in the Weatherley catchment:

A. Resulting from macropore conductance, rapid lateral flow near the surface is observed in the upper slope segments of the downstream catchment during high intense events and some low intense events with large volumes (>30 mm d^{-1}). Depending on the substrate and the subsurface morphology, local perched water tables can arise for short durations. Surface runoff only occurs during intense rainfalls in areas of sparse vegetation cover.

B. Slow percolation of water towards the bedrock and soil interface occurs in all slope segments for most events with the exception of events of low intensities and volumes.

C. Depending on subsurface morphology, time of the year and slope position, water is accumulated on sinks and hollows in bedrock. This water is disconnected from soil water in upper slopes of the downstream catchment, but often connected in concave slope segments and in upstream catchment during intense and moderate rainfalls.

D. Exfiltrating groundwater is accumulated at the toe of the slope near the crest with emergence and flow over bedrock. These areas are usually considered as plateau wetlands occurring in upper slope segments on top of the crests. They are temporary in nature and in most cases result from intense events during summer.

E. Water percolates through bedrock fractures and reappears as seasonal springs in lower hillslope positions or as recharge to local bedrock groundwater.

F. Rapid macro-pore, lateral flow and infiltration to groundwater aquifers controlling the valley bottom wetlands are observed in slope wetlands. It was often recognized that vertical recharge is more rapid than lateral movement in lower slope except when groundwater rises into macro-pore layers. During intense rainfalls surface runoff was observed on steep slopes that in turn infiltrates on gentler slope segments. These areas are often affected by piping processes.

G. The hydrology of the valley bottom wetlands is controlled by groundwater level fluctuations. Once the groundwater aquifer is filled which usually occurs about six weeks after the beginning of the rainy season, groundwater table response is rapid for most events in the lower downstream catchment, but with a response time of 1-2 days. In the upper catchment the dynamic of fluctuations are slower, but first response is observed earlier than in the lower catchment. Since the wetland seems to be connected to the creek during the entire year in the lower catchment, groundwater aquifer controls the baseflow of the creek. In the upper catchment the aquifer is assumed to be disconnected from the creek in very dry years.

H. Exfiltration, surface runoff and macro-pore discharge from the wetland areas to the incised stream occurs during the entire rainy season in the downstream catchment. Depending on the rainfall intensity and micro-topography, rapid surface runoff is generated in the steeper wetland zones and directly transferred to the stream. When the slope gradient is gentler, the water infiltrates generating lateral subsurface flow which drains into the stream. In the lower catchment surface runoff usually occurs about six weeks after the beginning of the rainy season, i.e. when the wetland retention capacity is achieved. This phenomenon is rarely observed to a similar degree in the upper slopes. During and after extreme rainfall events, these areas are temporary affected by oberbank flooding of the river that in turn leads to the accumulation of open water surfaces. During these times, water is either transferred as subsurface flow or infiltrates slowly re-filling the groundwater aquifer.

I. Groundwater discharge into the stream is assumed to occur along the creek and its tributaries when the creek is water-bearing. This input is very low during the dry season so that only little runoff values are generated with the tendency to run dry in extremely dry years.

J. In the upper parts of western slopes, soil water is vertically and laterally redistributed in the unsaturated soil zone, but water is usually not accumulated at the soil-bedrock interface. The water generates slowly downwards to the groundwater aquifer in downslope areas.

7.2.3 Wetland Ecosystem Analysis

The wetland ecosystem analysis focuses on providing detailed information on the characteristics of prevalent types of wetlands found in the study area. Based on the analysis of wetland structure, soils and vegetation in combination with findings from catchment and hillslope studies as discussed above, different types of wetlands were identified. Since the identified wetland types are distinguishable by their relief position and hydrological dynamic, wetland distribution was derived by developing a delineation approach based on terrain analysis.

7.2.3.1 Structural and Physical Properties of Wetland Sediments

Refraction seismic was used in selected wetland sites to obtain information on structural and physical properties of wetland sediments. The analyses of wave velocities indicate that relatively homogenous sediments with a varying thickness of 2 – 4 m overlay the triassic sandstone in all wetlands. As shown in several studies (BURGER, 1992; PULLAN & HUNTER, 1999), unconsolidated sediments usually provide low wave velocities in the range of up to 600 m s^{-1} of. Thus, measured velocities of 300 - 500 m s^{-1} are assumed to represent the overburden. Since the variation of wave velocities is very small, the variation of the physical properties of the sediments seems to be very small too. As a consequence it is assumed that the sediments are very homogenous generally. Those assumptions indicate relatively constant conditions during the deposition of the sediments. Although sediment thickness varies slightly due to topographic effects and wetlands sub-morphology, no indication was found that sediment thickness is related to a specific wetland size, type or relief positions. The interface to the underlying sandstone and thereby the sediment thickness was detected resulting from a sharp increase of wave velocities. Its variation between 2 200 and 4 800 m s^{-1} is associated to jointing and unsteady weathering of the sandstone which could be surveyed at several outcrops. Significant inhomogeneities of traveltimes indicate weathered and fractured or non-weathered zones. Those zones were not measured in detail, since it was not of interest to this study and refraction seismic techniques are limited in reliably modeling such structures.

Slope and valley bottom wetlands were investigated in detail in order to identify characteristics of their specific hydrological behavior and thereby their evolution. Thus, two slope wetlands with different flow dynamics (with/without flow channel) were studied in Weatherley along longitudinal and cross sequences (see Section 6.2.2). It was found that slope wetlands are strongly controlled by the underlying sandstone and specifically its gentle dipping. The profiles indicate that wetlands are developed at positions, where either surface or subsurface flow respectively is perched by sub-morphological structures. The layer thickness however was assumed not to be related to wetland occurrence. Figure 7.41 illustrates two sequences measured in Weatherley. Hereby, WSeis1 shows a sequence of a valley cross profile, while WSeis2 represents a longitudinal sequence.

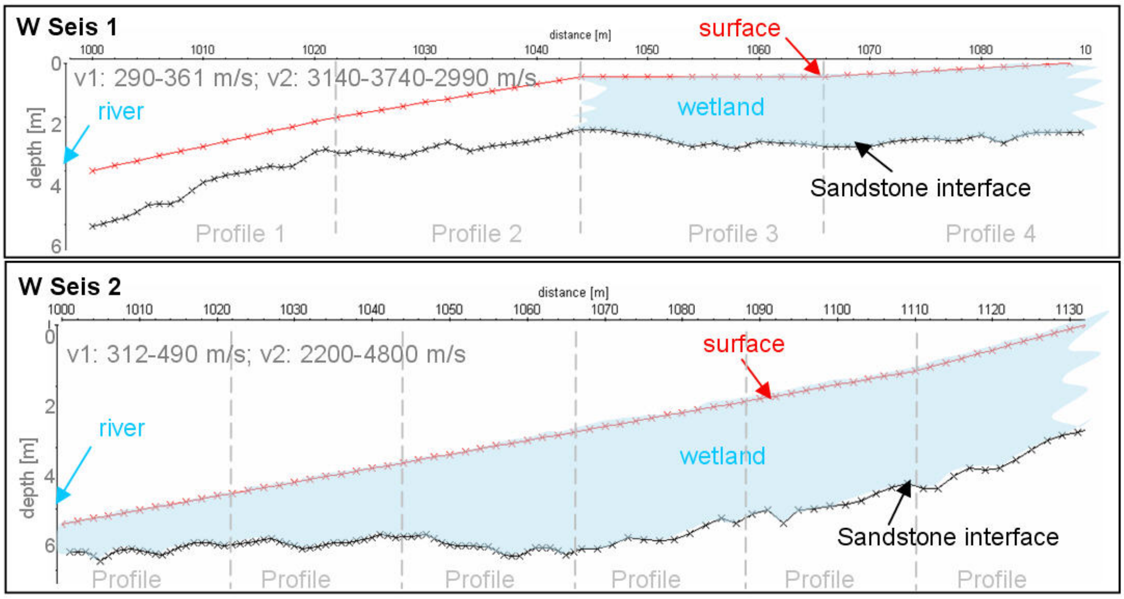


Figure 7.41: Refraction seismic profiles of two slope wetlands in Weatherley (exaggerated). WSeis1 (top) illustrates a cross-profile of a slope wetland, while WSeis2 (bottom) characterizes a typical longitudinal profile. The wetlands (blue) are limited by seismic boundary at the interface derived from the model (black line) and the surface topography (red line) which was delineated by topographic correction.

Sub-morphological structures are less important for the evolution and water dynamics of valley bottom wetlands, since the underlying sandstone is completely covered by unconsolidated sediments. Those sediments were accumulated by fluvial dynamics during the Holocene and associated phases of erosion and deposition. As a consequence of the deposition of fine sediments and clays and high groundwater fluctuation rates, relatively impermeable layers have been formed controlling hydrological dynamics of these wetlands. Nevertheless, the dipping of the sandstone has influenced the wetland dynamics in terms of a successive movement of the river channel following dipping. Figure 7.42 gives two examples of delineated sequences in valley bottom wetlands, where ChillSeis1 shows a sequence of a valley cross profile without a channel, while ChillSeis 2 represents a sequence from the channel up to the downslope.

Plateau wetlands were not considered for refraction seismic measurements, since their extent and distribution is usually restricted and thereby not appropriate for such studies. Those wetlands were surveyed by soil drilling instead.

Summarizing refraction seismic survey it was shown that wetland related sediments are relatively homogeneous in terms of layer thickness and physical properties. Moreover, it is assumed that the layer thickness is not related to the size of the watershed of the specific wetland. Neither the slope wetlands nor the valley bottom wetlands showed significant changes in sediment layer thickness due to variations in extent of their associated catchments. Differences between wetland types could be found due to the influence of subsurface topography. Slope wetlands are originated in hillslope positions, where sub-morphological structures allow water retention of subsurface water. Valley bottom wetlands are developed as a result of Holocene deposition of fine sediments, groundwater dynamics and soil development processes.

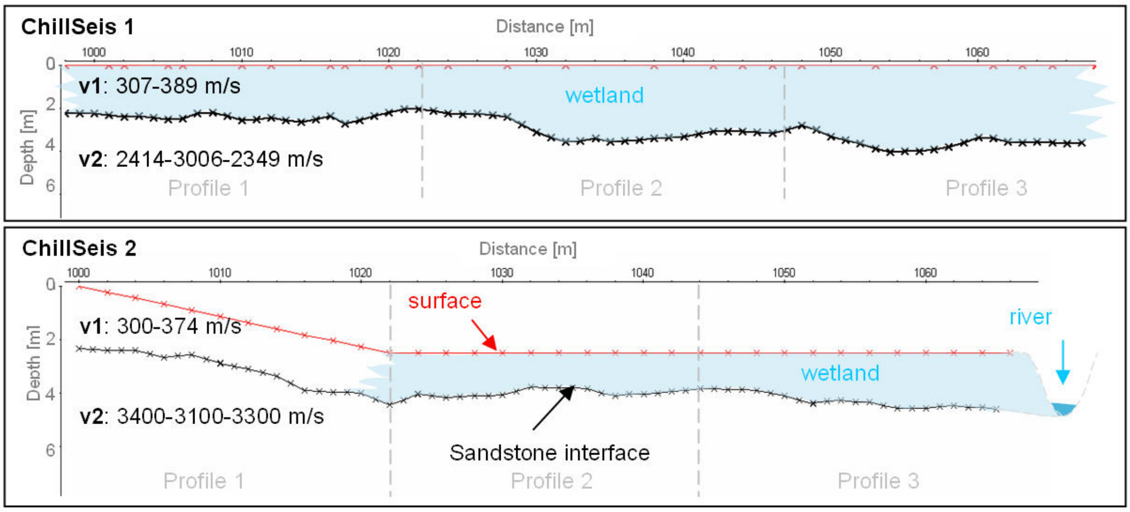


Figure 7.42: Refraction seismic profiles of 2 valley bottom wetlands in the Mooi basin (exaggerated). ChillSeis1(top) illustrates a cross-profile of a valley floor situation within the Ku'Ntombininzinzi Vlei, while ChillSeis2 (bottom) characterizes the whole sequence from the river to the bottomslope. The wetlands (blue) are limited by seismic boundary at the interface derived from the model (black line) and the surface topography (red line) which was delineated by topographic correction.

7.2.3.2 Wetland Soils

Wetland soils were specifically investigated, since these soils control the wetland water retention capacity and thereby runoff dynamics of their associated rivers. As described in Section 6.2.1 a number of open soil pits and soil cores were investigated in several wetlands in the field. Moreover, soil samples from different profiles were analyzed in the laboratory.

In general, all analyzed profiles and cores of wetland soils showed a similarity in terms of structure and soil physical and chemical properties. Mean soil depths of the investigated wetland areas ranged from 0.80 to 3.80 m, but showed high standard deviations and substantial variations between minimum and maximum values in soil depths especially in boundary areas of slope wetlands. This is addressed to their specific landscape and slope positions and shapes. Soils on concave shaped slopes (depressions) are usually deeper compared to these on convex-shaped slopes.

The wetland soils observed in the study region are principally mineral wetland soils, i.e. soil organic content is less than 20 – 35 % (MITSCH & GOSSELINK, 2000). Depending on the hydrological conditions, the wetlands soils are either affected by fluctuating or temporary perched subsurface water. Soils assessed by fluctuating groundwater occur as proper *Gleysols* with well-developed horizons characterized by grey colors and mottles of grayish, yellowish or reddish colors (Figure 7.43). This indicates that the sesquioxide of iron, ferric oxide is reduced to ferrous oxide by the removal of oxygen during saturation and that re-oxidation takes place when the water table (phreatic surface) drops down. Since *Gleysols* are usually found in valley bottom situations, they are assumed to be water-logged for long periods. In downslope situation when lateral moving water is perched by impermeable soil layers or bedrock, hydromorphic soils such as stagnic *Luvisols, Cambisols* or *Planosols* were identified (Figure 7.43). These soils also show signs of wetness but to a lower degree indicating more frequent changes between saturated and unsaturated conditions.

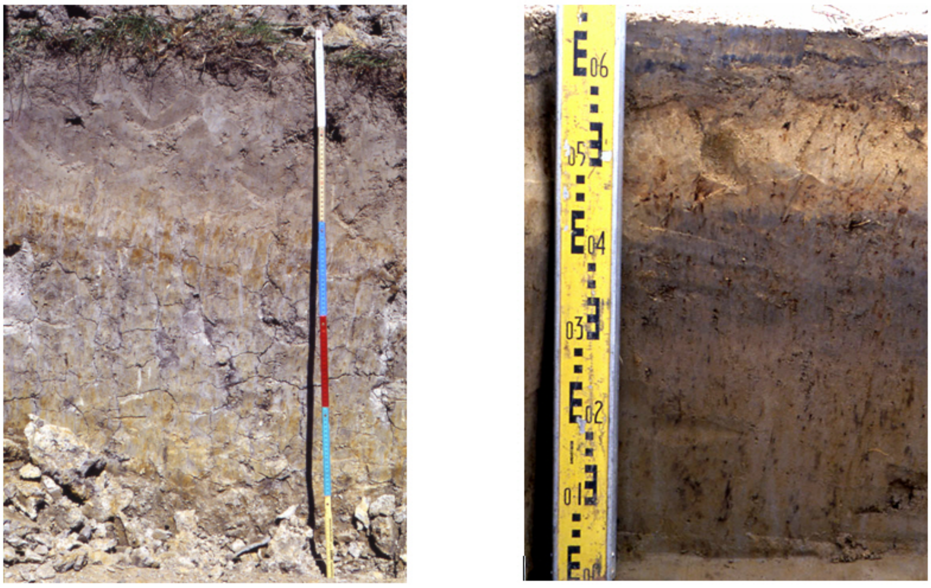


Figure 7.43: Two examples of typical wetland soils found in the study area: Typical Gleysol affected by fluctuating groundwater in a valley situation (left) and stagnic Luvisol influenced by temporary perched groundwater on a downslope (right) (Photographs: HELMSCHROT, 1997, 2001).

The wetland soils usually show high values for the silt fractions, followed by clay and sand. The fairly high clay contents and relatively heavy texture of the soils are assumed to be effective in retaining water during drier periods. From hillslope transects it was found that in plateau and slope wetlands the percentage of sand decreases both down the profiles and down the hillslope transect, with the inverse trend for percentage clay. The soils of valley bottom wetlands are characterized by a silty-sandy upper horizon, whereas clay increases down the profile resulting in the formation of an impermeable clayey horizon. Below this compacted clay layer fine, medium and coarse sand fractions increase towards the base of the profile.

The distribution of organic matter in the sediments was variable both spatially and along depth gradients. Organic carbon levels were relatively high (for mineral soils) at all sites. The highest concentrations of organic matter (with a range of 1.5 - 11.4 %) were found in the upper 30 cm and significantly decreased with increasing profile depth. Significantly lower concentrations of organic matter were recorded in the upper parts of the profiles in permanent saturated areas covered by wetland vegetation and open water (1.5 – 7.1 %) compared with temporary saturated areas dominated by mixed grassland and wetland species (6 – 11.4 %). With respect to MITSCH & GOSSELINK (2000), the relatively high proportion of organic matter near the surface is nevertheless likely to be effective in water retention in these wetlands. Bulk densities were lower at depth than nearer to the surface confirming findings by ESPREY (1997).

The wetland soils show little variation in hydraulic conductivities (k-values). Slightly higher hydraulic conductivity was found in shallow soils of the plateau wetlands (0.8 to 13 cm d^{-1}) and in slope wetland soils (0.2 to 19 cm d^{-1}) compared to that in deeper soils found in valley bottom wetlands (1 x 10^{-3} to 8 cm d^{-1}). In general, k-values decreased down the profile. It also was observed that k-values are significantly lower when silt and sand increased and organic matter decreased. HARVEY *et al.* (1995) found increased k-values in sediments resulting from the presence of roots and rhizomes in the upper horizons. Since roots and rhizomes create large diameter pores (> 100 µm), water is transferred at a faster rate than the surrounding sediments (HARVEY *et al.*, 1995). This partially explains the high rate of macro-pore flow determined by the hydrometric monitoring on hillslopes. The hillslope process studies also revealed that permeability is low to very low particularly in soils in the valley bottom wetlands. Although there appeared to be a trend of the measured k-values in the soils of different wetland types, the variation was not statistically significant (possibly due to insufficient sample size). Consequently, hydraulic conductivity can not be used to differentiate individual wetland types. However, wetlands were different in terms of hydraulic conductivity compared to the soils of the non-wetland areas, since the latter showed significantly higher k-values (6-49 cm d^{-1}) than the wetland soils.

These findings were confirmed by analyzing pF-curves received for soils of different wetland types (Figure 7.9). It is concluded that slope wetlands are usually characterized by highly compressed subsoils. The clay fraction and wilting points increase with depth, while the field capacities decrease. The topsoils are characterized by better drainage properties which refer to the high fine sand fraction. Valley bottom wetland soils show a different characteristic, i.e. high fraction of clay were found in the topsoil which can be associated with low field capacities and high wilting points. The subsoils tend to be sandier and show better drainage properties with increasing depths.

In the Gatberg Vlei three different sequences overlaying the bedrock (sandstone or weathered sandstone) were identified in the soils of the valley bottom wetlands. At the base, the bedrock is overlain by a usually thin layer of grayish sand. Comparing soil profiles along the cross-sectional transect it was found that this layer is partially or completely eroded before the deposition of the overlain sediments. Additional soil drillings taken in areas surrounding the Gatberg Vlei, gave evidence that these gray sands formed terraces higher than the recent floodplain level. Consequently, these sands are expected to be older than the recent wetland forming sediments (MÄUSBACHER, 2004, pers. comm.). The gray sands are overlaid by a layer of gravel, which in turn is overlaid by a relatively thick sequence of sandy-loamy silt. The thickness of this upper layer usually varies between 1.5 and 2.7 m. The clay content ranges between a minimum of 10% and a maximum of 60 %. Since only this upper layer is still evident in most profiles, this layer was characterized further. It shows a clayey-silty sequence ranging from 0.3 to 1 m thickness and a second underlying horizon which includes notable Iron and Manganese concretions (see Figure 7.7). Both sequences of the upper layer are expected to indicate soil-forming processes (MÄUSBACHER, 2004, pers. comm.), which in turn are associated with a relatively constant phase during or after the sediment deposition. According to FEY (2004, pers. comm.), it is assumed that the development of such soil sequences and its associated features require a minimum of 600 years of a steady phase without erosion or sedimentation.

A surprisingly high incidence of soil faunal activity was noted within the wetlands which need to be considered as being of importance for soil formation processes (re-deposition) and water transport processes within the sediments (DE BRUYNL & CONACHER, 1990). Vertebrate species like vlei rates (*Othomus spp.*), shrews (*Crocidura spp.*), crabs (*Brachyura*), snakes (*Viperidae*) and lizards (*Lacertilia*) and numerous invertebrate species like crustaceans (*Crustacea*), earthworms (A*nnelida*) and termites (*Pterygota*) were sighted in the wetlands. Their occurrence is assumed to impact vertical soil water fluxes along rootcasts and animal burrows as reported by BECKEDAHL (1996). The concentrated flow of water and associated turbulence along a soil conduit increases the potential for erosive scour, consequent enlargement and hence pipe formation. As outlined by FERNANDEZ *et al.* (1994), earthworms and ant activity may increase soil permeability and hence infiltration, increasing the incidence of saturated matrix flow and consequent piping. These fauna are most likely seasonal visitors to the wetland environments, colonizing wetlands during drier periods and avoiding wet periods. Mole hills, termite mounds and rodent warrens were significantly more often observed in temporary and seasonal wetlands than in permanent inundated wetlands. From this observation it is concluded that wetlands displaying a larger proportion of permanently wet zones appear to display reduced faunal activity.

Since piping was observed particularly in temporary slope wetlands, it is resumed that temporary wetlands are more prone to processes like piping as result of biotic initiation than other wetland types. Further investigations are, however, required to ascertain the impact of biotic factors on wetland dynamics. Moreover, the detailed analysis of the flora and fauna may provide indicators of changes in terms of the loss of wetland areas or their drying-out.

7.2.3.3 Wetland Characterization, Dynamics and Functioning

The studies presented above have shown that wetlands occur in different relief positions having different soils, vegetation and main water sources. Furthermore differences were found regarding their hydrodynamics, since wetlands occur as permanent, seasonal or temporary landscape features. Integrating results presented in this study, following generalized conclusions regarding dynamics and functioning of specific wetland types in the study region can be drawn with respect to their landscape position.

i) Plateau wetlands

Small wetland patches located in plateau and bench positions occur either as saddle wetlands (referring to flat land between two sideslopes) or interfluve wetlands (referring to an area of high ground which separates two adjacent valleys belonging to the same drainage system) or shelf wetlands (referring to a break or crest in a slope). Those relatively flat wetlands are small in size (less then 1 ha) and formed in depressions or topographic lows or areas underlain by impermeable material. When patches are restricted to depressions, they sometimes appear as tarns characterized by standing water over longer periods and peat accumulation.

The plateau wetlands are hydrologically driven by fluctuations of water perched on bedrock and in bedrock hollows. The water has its origin in percolating water during medium and high intense rainfall events, but they also receive their inflow from groundwater recharge at the toe and/or from rainfall directly. Rapid lateral surface flows are rarely observed during intense rainfall events and are restricted to areas of sparse vegetation densities, while lateral subsurface flow occurs in dense vegetated zone after intense rainfalls. These patches usually dry out during dry seasons because of the macro-pore structure of the relatively shallow soils causing a little water retention capacity. Consequently, they are temporary or seasonal. Plateau wetlands are usually not connected to the fluvial system directly, since outflowing water either percolates through fractured bedrock contributing to groundwater recharge or overflows crests in order to re-infiltrate in underlying areas. Micro-relief features affecting hydrology were not observed in these wetlands.

Depending on landscape position, substrate thickness varies between 0.4 m up to a 2 m maximum. Although soil texture is variable, the substrate is characterized by relatively high percentages of silt and sand (up to 90 %) allowing a good drainage of the soil. They rarely show evidence of mineralization of clay. Organic content is high in surface horizons, with highest values observed in tarns (4.5 - 13.1 %).

The vegetation is dominated by short sedges and grasses, but also subaquatics or marsh vegetation including *Cyperus spp., Eleocharis spp.* and *Eriocaulon spp.* were found in narrow zones of the margins. In general, mean vegetation density (68 %) is sparser than other wetland types, while mean vegetation height (37 cm) is lower than in valley bottom wetlands, but slightly higher than in slope wetlands. Nevertheless, observations have shown that density and vegetation height is increasing with increasing soil moisture and water availability and thereby shows a high intra-annual and inter-annual variability. In addition, invasive grass and herbaceous species were observed at different investigated sites indicating longer periods of dryness or the progressive drying out of the wetland sites.

An example for a plateau wetland is given in Figure 7.44.

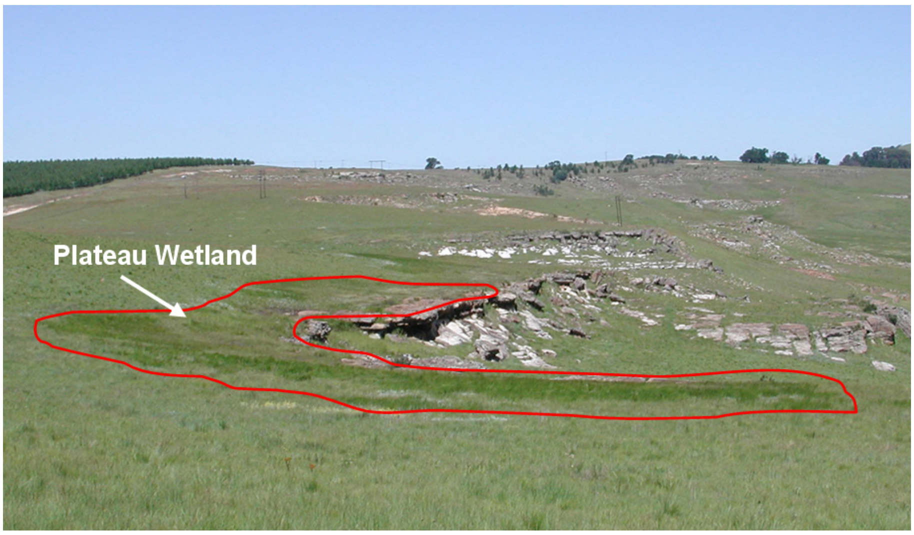


Figure 7.44: Example for a plateau wetland located on top of a crest at the Weatherley experimental catchment site (Photograph: HELMSCHROT, 2001).

ii) Slope wetlands

The slope wetlands were mainly found at hillslope sections with steep gradients (>5°), but also occur on slight slopes steeper than 1°. They are either isolated or interlinked to both the fluvial system and adjoining slope wetlands, whereas isolated patches are smaller in size (1 – 5 ha) than interlinked wetlands (< 15 ha). In some interlinked wetlands channels were observed which seem to control either inflow and outflow or both. With respect to the relief and the geology, cascading systems may have developed on slopes with varying gradients. The upper slopes mainly showed convex shapes, while the mid- and downslopes were concave.

Since water sources are primarily groundwater return flow and interflow from surrounding uplands and precipitation, these wetlands show a seasonal or temporary dynamic. When directly connected to the valley bottom, fluctuating groundwater may also affect wetland hydrology in downslope zones. These areas are often described as transition zones between the valley bottom and the slope wetlands (MITSCH & GOSSELINK, 2000). The slope wetlands lose water primarily by saturation subsurface and surface flows and by evapotranspiration. In addition, seepage was observed at the toeslope of steeper slopes (>5°) during and after intense events. Standing water was only observed in micro-topographical depressions in the more flat slope sections for a short time in the rainy season. It arrives as either surface runoff or recharged groundwater from upper areas during and after intense rainfalls. Temporary open water bodies are emptied by infiltration or surface runoff. The analysis of the soil moisture gradient reveals that near surface soil moisture is significantly lower in the upper, mostly steep areas than in the toeslope zone. The low values on upslopes are addressed to rapid surface and subsurface flow occurring after heavy rainfalls. Because of its smoothness, the micro-relief of these wetlands has little influence on the hydrological dynamic.

Soil depths vary in the range of 0.8 and 3.2 m, but are generally shallower on steep slopes compared to more flat zones. Since shallow soils are not particularly effective in storing large quantities of water, shallow zones within slope wetlands are assumed to be only controlled by return flow from the up-slopes. In general, the soils tend to be sandier than in other wetland types, but also show higher fractions of sand in the up- and midslope areas compared to decreasing values in the downslope areas. Depending on the intensity and volume of rain, silt and clay is continuously mobilized on the upper slopes. It is then transported by surface and subsurface flow following the gradient and is accumulated in the lower downslope areas. Total organic carbon content is lower than in other wetland types, most likely lower than 5 %, resulting from low biomass production and high entrainment by both surface and subsurface flow. As a consequence, only thin A-horizons that not exceed 35 cm are developed in slope wetland soils.

Depending on the hydrodynamics vegetation is dominated by seasonal to temporary or perennial hydrophytic vegetation. Former is characterized by a species-rich vegetation composition with sedges, herbaceous plants and hygrophilous grasses (Juncus spp., Pennisetum spp., Isolepsis spp.), while latter is mainly dominated by Phragmatis spp. and *Typpha spp.* Vegetation densities vary in slope wetlands (45 – 100 %), but are generally denser in areas where soil moisture is high. Mean vegetation height (33 cm) is lower than in the valley bottom wetlands, but higher than in the plateau type. Density and vegetation height are also affected by aspect and slope. Highest values were recorded from moderate south-facing slopes, because these slopes are wetter than north-facing slopes, since they receive less solar radiation. The occurrence of invasive grass species (*Alloteropsis semialata, Diheteropogon filifolius, Melinis nerviglumis* and *Panicum natatalense*) were recorded at seven wetland sites. Since all of these sites were surrounded by forest plantations it is indicated that the reduction of inflow by an increasing water uptake of the adjacent forest trees cause the progressive drying out of these wetlands. Further studies are needed to verify this assumption.

An example for a slope wetland is given in Figure 7.45.

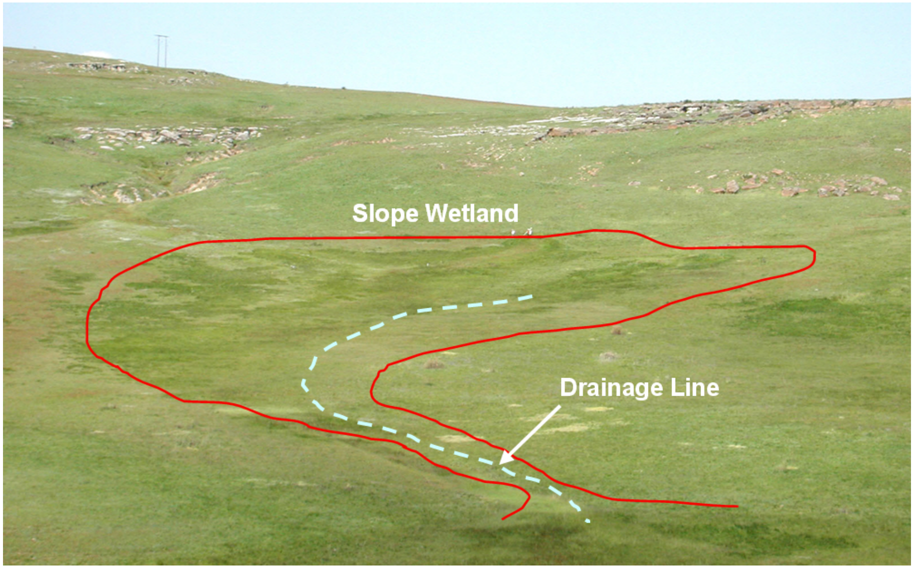


Figure 7.45: Example for a slope wetland located on a midslope (Photograph: HELMSCHROT, 2001).

iii) Valley bottom wetlands

The valley bottom wetlands are located in floodplains and riparian corridors in association with stream channels at the bottom of valleys. They are characterized by a negligible gradient. They are larger than other wetland types (> 10 ha) and are either associated with a stream (channelized) or diffuse with temporally and spatially variable channels which drain the wetland. Because of the flat terrain, streams usually tend to meander. From terrain analysis it was found, that streams often run along the lowest point of the valley given by the gentle dipping of the underlain geological parent material (sandstone). In broader valleys, oxbow lakes have been formed resulting from the cut-off of former river bends.

Water sources controlling wetland dynamics are groundwater, return flow from adjacent uplands, occasional interflow and overland flow, tributary inflow, and precipitation. The hydrology of channelized valley bottom wetlands is also directly affected by overbank flow from the channel or subsurface hydraulic connections between the stream channel and wetland. Primary sources of water output are groundwater re- and discharge, overland and subsurface flow, evaporation (from inundated areas) and evapotranspiration from vegetated areas. When overbank flow occurs, surface flows down the floodplain also affect hydrodynamics. With respect to the findings of other studies (COWAN, 1995) and own observations, the high water retention capacity of these wetlands is of notable importance for the regional water cycle. The storage and slow release of water maintain the perennial flow of the major rivers and streams in the study area, especially during the low season.

As observed in the field, the micro-topography plays an important role for the hydrological process dynamics in valley bottom wetlands. The micro-relief is often characterized by tussocks (also called hummocks). The channels between these tussocks act as drains and storages because the tussocks are higher and have a larger surface area exposed to the air. Once the hollows were filled, rapid surface runoff was observed in these channels during and shortly after intense rainfall. When the vegetation is dense and overlaps the channels, these channels also tend to store water for long periods. Then the water infiltrates and thereby contributes to groundwater recharge or evaporates slowly. The formation of tussocks is controversially discussed in the literature (KOTZE & O'CONNOR, 2000). For example, trampling by domestic stock often caused wetland surfaces to become more tussocky. Other factors may, however be more important for the formation of tussocks; mounds built by ants and termites or earthworms and inherently tussocky growth forms of some commonly occurring plant species. In altitudes higher than the study area, climatic factors (temperature and temporal rainfall variability) are also recognized to affect tussock formation (GRAB, 1994)

The soils of the valley bottom wetland seemed to be slightly deeper than in other wetland types, occasionally in the range of 1.2 to 4.3 m resulting from the larger tributary catchments. As described above textural characteristics are variable within the soils. When the soil is affected by fluctuating groundwater, massive, impermeable layers (- 1 m) with high clay fractions and crusted Fe and Mn concretions have been formed. This layer is overlain by a silty-sandy toplayer with good drainage properties. Underneath the impermeable layer, sand fraction increases down the profile. Total organic content is moderate in topsoils (5 – 8 %), but decreases significantly down the profile (< 2 %). Permanently inundated areas as well as oxbow lakes and pools are assumed to represent initial phases of peat accumulation, since high values of TOC (8 – 13 %) were found.

In the core zones, occasionally along the river, the vegetation is dominated by perennial wetland vegetation (*Juncus spp., Phragmatis spp., Typha spp., Cyperus spp.*), while annual or seasonal vegetation (*Aristida spp., Pennisettum spp.*) is observed in the narrow margins. Invasive plants were observed in the margins, but seemed to be related to water availability and season. Vegetation composition, density and height are significantly affected by land management. When the site is used for stock-farming the mean vegetation cover is sparse and the mean vegetation height low due to annual burning, drainage and continuous grazing. Also the biodiversity is reduced as shown by several studies (see Section 2.4.2). Restored valley bottom wetlands like the Ku'Ntombininzinzi Vlei, however, showed very dense (up to 100 % coverage) and high (80 cm) vegetation. In addition, woody vegetation dominated by *salix* and *poplar* was recorded along the river margins in particularly along the Wildebees and the Mooi rivers and their tributaries.

An example for a valley bottom wetland is given in Figure 7.46.

Figure 7.46: Example for a valley bottom wetland surrounded by pine and eucalyptus plantations (Photograph: HELMSCHROT, 2003).

7.2.3.4 Integrated Wetland Classification Approach and Regionalization

Since one objective of this study referred to the evaluation of the impact of afforestation on different wetlands types, a wetland classification was developed to characterize specific wetland types. As discussed in Chapter 2, most classification approaches consider differences and changes in soils, vegetation and hydrological behavior as the most powerful criteria to distinguish wetland types (MITSCH & GOSSELINK, 2000). In contrast, landscape-related approaches take the variability of wetland occurrence resulting from their landscape positions into account (BRINSON, 1993; MARNEWECKE & KOTZE, 1999; SMITH *et al.*, 1995).

Addressing the integrated nature of the presented research, a wetland classification was developed to differentiate wetland types by combining findings from wetlands soil and vegetation analysis, hillslope studies, regional hydrological and terrain analysis. From this effort, a conceptual model representing main wetland types and their associated subtypes was developed. The identified wetland types are representative for palustrine wetlands in the Eastern Cape, and thereby can be used for regionalization. Recognized wetland types are illustrated in Figure 7.47 with respect to their landscape positions. In addition, Table 7.14 summarizes identified wetland types and their generalized characteristics that are used in this study for HRU delineation and wetland modeling.

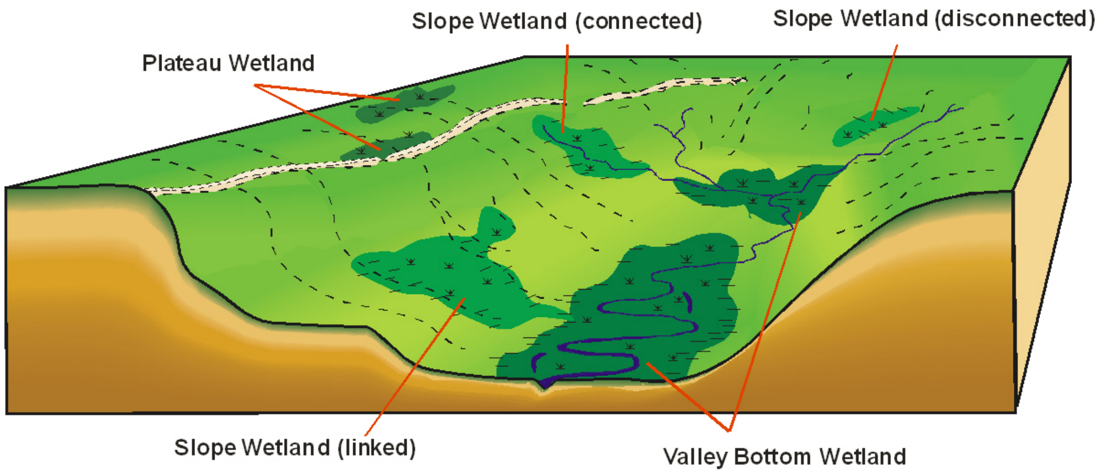


Figure 7.47: Schematic illustration of wetland types identified and their respective position in the landscape.

7.2.4 HRU Delineation

Integrating data and knowledge derived from empirical observations and system analysis, various sets of HRUs were created which were used as model entities for the hydrological modeling of the Weatherley and Mooi catchments.

7.2.4.1 Weatherley Catchment

With respect to the empirical data derived from this study and the system analysis described above, following assumptions were made to provide the hydrologically relevant information layers which finally were used for the HRU delineation for the Weatherley catchment:

- ***Landuse*** information which has been derived from field maps was used to differentiate four landuse classes (Grassland, Plateau wetland, Slope wetland, and Valley Bottom wetland) representing the pre-afforestation conditions (before 2002). Those areas which were considered to be planted by eucalyptus and pine were extracted from the forest data base in Weatherley. These data were overlaid on the existing land use map, and consequently six land use classes could be finally considered for the HRU delineation to simulate post-afforestation land use pattern.
- As shown by LORENTZ *et al.* (2004) and own studies, topographic landscape features resulting from the geological basement (such as crests) control the hillslope hydrology notable. For example, water overflowing crest needs to be considered as return flow in the model application. Based on a digital terrain analysis by utilizing a combination of morphometric parameters (DAHLKE ET AL., 2005), three ***terrain units*** were delineated from the DEM representing up-crest areas, down-crest areas and flat areas. Up-crest areas are considered as being disconnected to the river with an isolated groundwater reservoir. Thus, water from these areas flows either to the underlying down-crest or flat areas, and thereby fills their subsurface reservoirs.

Table 7.14: Generalized wetland classification resulting from field studies, laboratory analysis and analysis of hillslope process dynamics.

Type	Subtypes	WA [ha]	Depth [m]	RD [cm]	Soils	Vegetation	Hydro-dynamics	Main Water Source	Main Hydrological Processes
Plateau Wetland		1-5	0.4-1.6	10-50	stagnic Luvisols, stagnic Cambisols, stagnic Arenosols and Regosols	temporary hydrophytic vegetation, invasive grass species	temporary, seasonal	**pGW,** RF, ovFl	ovFL, Infil, IF, ET
	Description: Small wetland patches in plateau situations, which are associated with perched groundwater and/or precipitation input. These wetlands are usually disconnected from the fluvial system.								
Slope Wetland	Surface inlet/outlet	> 5	0.9-2.8	45-180	stagnic Luvisols, stagnic Cambisols	perennial species rich hygrophilous grass and sedge community	permanent, seasonal	**IF**, GW, RF,chINF, ovFl	ovFL, IF, ET, chRUN, pipeFL
	Only surface outlet	1-15	0.8-3.2	40-125	stagnic Luvisols, stagnic Cambisols		seasonal, temporary	RF, **IF**, retF, ovFl	ovFL, IF, ET, chRUN, pipeFL
	No surface inlet/outlet	1-5	1-1.8	25-125	stagnic Luvisols, stagnic Cambisols, stagnic Leptosols	annual and perennial hygrophilous grass vegetation, invasive grass species	temporary	**IF**, RF, ovFl	ovFL, IF, ET, pipeFL
	Description: Slope wetlands are medium-sized wetlands located at downslope areas and mainly controlled by rapid lateral water flow (surface runoff and/or interflow). They are characterized by permeable topsoil layers with high infiltration capacity. In some cases, subsurface topography supports the occurrence of perched groundwater. They can be isolated or connected either to the downslope valley bottom or an adjoining slope wetland. In some cases, cascading systems are established.								
Valley Bottom Wetland	floodplain (channelized)	> 10 (max. 20 km²)	1.5-4.3	45-210	Gleysols	narrow perennial hydrophytic grass species and sedges (*Phragmites spp., Typha spp., Cyperus spp.*) Woody vegetation may occur along river margins	permanent, seasonal	**GW, IF, retF,** chINF, RF, inflF, effF, ovFl	ovFL, E, ET, GWR, GWF, IF, chRUN
	floodplain (diffuse)		1.2-3.8	30-140	Gleysols, gleyic Planosols	annual and perennial hydrophytic grass species and sedges (*Phragmites spp., Typha spp.*)	seasonal	**retF,** GW, **IF**, effF, ovFl	ovFL, E, IF, ET, GWR, GWF, Infil
	Description: Valley bottom wetlands comprise large wetlands in valley situations which are generally very flat by a negligible gradient. They are associated with a significant river channel that is either a first order stream by itself or directly connected to a first order stream. The floodplain wetland type is mainly controlled by groundwater dynamics, but partially associated with interflow and rainfall. They show a high retention potential. In some cases these types are characterized by complex groundwater systems including different aquifers. They are also subject to effluent seepage, i.e. reach receives discharge from adjacent floodplain and influent flow from overbank flooding. Relics such as oxbow lakes and back swamps occur in the floodplains holding water for a long time and are characterized peat accumulation. The diffuse types are smaller in extent and mainly controlled by return flow and interflow from low order tributaries, but also are affected by fluctuating groundwater.								

WA ... Wetland area; RD ... Root Depth; GW ... Groundwater; GWR … Groundwater recharge; GWF … Groundwater fluctuation; ovFL … Overland Flow; Infil … Infiltration; IF ... Interflow; RF … Rainfall; E … Evaporation; ET … Evapotranspiration; pGW … perched Groundwater; chINF … channel inflow from adjacent areas; retF … Return Flow, inflF … influent flow, effF … effluent flow, chRUN … channel runoff; pipeFL … concentrated pipe flow

- The existing ***soil*** map representing 15 soil types according to the South African Soil Taxonomy (SOIL CLASSIFICATION WORKING GROUP, 1991) was provided by ROBERTS *et al.* (1996) and completed by own soil survey. The soil types were converted to the FAO classification system (FAO, 1998) and thereby reduced to 11 soil types. These 11 soil types were compared regarding grain size distribution, porosities, water holding capacities and hydromorphic characteristics to further reduce the number of soil types. Consequently, similar soil types were merged and after reclassification four groups of soil types were finally considered for the HRU delineation.
- ***Slope*** is an important factor to simulate lateral water fluxes on hillslopes, while the aspect is considered as being important for the energy budget calculation in PRMS. With respect to the system analysis and other studies in similar environments (STAUDENRAUSCH, 1996), 3 ***aspect*** groups (N: 0-45°, 315-360°; S: 135-225°; E-W: 45-135°, 225-315°) were differentiated in order to satisfy differences in evapotranspiration and soil moisture distribution. Resulting from hillslope studies which indicated slope-related differences of hydrological processes, *slopes* were grouped into four gradient classes (0-2%; 2-5%; 5-15%, and >15%). Thereby, the areas with negligible gradients (0-2 %) are assumed to be mainly controlled by groundwater dynamics, while low gradients (2-5 %) are mainly driven by a combination of groundwater processes and interflow. Steeper slopes (5-15 %) are controlled by interflow and surface runoff (after intense rainfall events), while the slopes with steep gradients (< 15 %) are subject to surface runoff (heavy rainfall) and subsurface flow (longer rainfall with high volumes but low intensities).
- Since the comparison of ***rainfall*** *data* from three rainfall gauges which were located in the watershed showed little variation, rainfall was assumed to be homogeneously distributed within the catchment and therefore not considered for the HRU delineation.
- To reduce the number of classes, the ***geology*** was assumed to be uniform, and therefore excluded from the overlay analysis.

Table 7.15 summarizes the input data layer and its associated classes which were used for the HRU delineation within the Weatherley catchment representing the pre- and post-afforestation condition.

As a result of the overlay analysis, two HRU maps with 84 classes (pre-afforestation) and 131 classes (post-afforestation) respectively were generated for the Weatherley catchment. As emphasized by several studies (BONGARTZ, 2001; MICHL, 2000; STAUDENRAUSCH, 1996), the total number of HRUs was reduced by grouping and reclassifying redundant HRUs.

Table 7.15: Summary of used input data layers and associated classes for the Weatherley catchment.

	Landuse	Terrain Unit	Soil	Aspect	Slope [%]
Pre-afforestation	Grassland	up-crest	Luvisol, Cambisol, Alisols (L,C,Al)	N	0 - 2
	Plateau Wetland	down-crest	Regosol, Leptosol, Arenosols (R, L, Ar)	S	2 - 5
	Slope Wetland	flat	stagnic Luvisol, stagnic Cambisol (sL, sC)	E,W	5 - 15
	Valley Bottom Wetland		Gleysol, gleyic plinthosols, planosols (G, sP, P)		> 15
Post-afforestation	Grassland	up-crest	Luvisol, Cambisol, Alisols (L,C,Al)	N	0 - 2
	Pine	down-crest	Regosol, Leptosol, Arenosols (R, L, Ar)	S	2 - 5
	Eucalyptus	flat	stagnic Luvisol, stagnic Cambisol (sL, sC)	E,W	5 - 15
	Plateau Wetland		Gleysol, gleyic plinthosols, planosols (G, sC, P)		> 15
	Slope Wetland				
	Valley Bottom Wetland				

Initially, the HRUs were extracted and reclassified which seemed to be ambiguous in terms of their physiographic characteristic. Since such HRUs were usually small in size and delineated in transition areas, those HRUs were merged to their most similar neighbors. For example, an HRU which was delineated as wetland with a non-hydromorphic *Cambisols* was merged to that nearby HRU representing wetlands with a stagnic *Cambisols*. This results from the assumption, that the wetland distribution was more accurately mapped than the soil distribution. In a second step, all HRUs with a total size smaller then 0.25 ha were merged to that HRU which was assumed to be the most similar HRU in terms of its hydrological response. After the post-processing, two HRU maps with 25 classes (pre-afforestation) and 31 classes (post-afforestation) respectively were generated, and were finally used for the modeling of the Weatherley catchment. As shown in Tables 7.16 and 7.17, each HRU was defined by a number of physiographical parameters, which were used in the model application.

Table 7.16: Summary of HRU characteristics for the HRU data set describing the pre-afforestation stage for the Weatherley catchment (25 HRUs).

No.	Land use	Terrain Unit	Soil-Type	Slope [%]	Aspect	MSlope [%]	Elevation [m asl.]	Area [ha]	Area [%]
1	Grassland	up-crest	R, L, Ar	> 15	N	17.52	1334	1.15	0.83
2	Grassland	up-crest	L,C,Al	5-15	N	8.96	1334	4.11	2.97
3	Grassland	up-crest	L,C,Al	2-5	E,W	3.66	1333	0.56	0.40
4	Grassland	up-crest	L,C,Al	5-15	E,W	10.67	1330	8.64	6.23
5	Grassland	up-crest	L,C,Al	2-5	N	3.45	1329	1.89	1.36
6	Grassland	up-crest	R, L, Ar	> 15	E,W	18.86	1327	3.43	2.47
7	Grassland	down-crest	L,C,Al	> 15	N	21.48	1322	12.94	9.33
8	Plateau Wetland	up-crest	sL, sC	5-15	E,W	9.79	1319	0.38	0.27
9	Grassland	down-crest	L,C,Al	0-2	E,W	1.24	1318	0.88	0.63
10	Grassland	down-crest	L,C,Al	5-15	N	10.73	1316	11.21	8.09
11	Grassland	down-crest	R, L, Ar	> 15	N	25.59	1311	0.88	0.63
12	Grassland	down-crest	L,C,Al	2-5	E,W	3.38	1310	5.38	3.88
13	Grassland	down-crest	L,C,Al	2-5	N	3.02	1305	0.71	0.51

No.	Land use	Terrain Unit	Soil-Type	Slope [%]	Aspect	MSlope [%]	Elevation [m asl.]	Area [ha]	Area [%]
14	Grassland	down-crest	R, L, Ar	> 15	E,W	23.05	1305	2.87	2.07
15	Grassland	down-crest	L,C,Al	> 15	E,W	19.04	1300	19.75	14.24
16	Grassland	down-crest	L,C,Al	5-15	E,W	10.26	1295	26.83	19.35
17	Slope wetland	down-crest	sL, sC	5-15	N	11.84	1294	4.16	3.00
18	Slope wetland	down-crest	sL, sC	5-15	E,W	13.44	1287	2.60	1.88
19	Valley B. Wetland	flat	G, gP, P	5-15	N	6.83	1286	4.64	3.35
20	Slope Wetland	down-crest	sL, sC	5-15	N	11.72	1285	1.05	0.76
21	Slope Wetland	down-crest	sL, sC	5-15	E,W	10.08	1283	11.85	8.55
22	Valley B. Wetland	flat	G, gP, P	2-5	N	3.82	1277	4.83	3.48
23	Valley B. Wetland	flat	sL, sC	5-15	E,W	7.89	1275	3.88	2.80
24	Valley B. Wetland	flat	G, gP, P	2-5	E,W	3.80	1273	2.63	1.89
25	Slope Wetland	flat	G, gP, P	2-5	E,W	4.37	1273	1.43	1.03
								1.385 km²	**100**

MSlope … mean slope; Valley B. Wetland … Valley Bottom Wetland; G, sP, P … Gleysol, gleyic plinthosols, planosols; sL, sC … stagnic Luvisol, stagnic Cambisol; L,C,A … Luvisol, Cambisol, Alisols; R, L, Ar … Regosol, Leptosol, Arenosols

Table 7.17: Summary of HRU characteristics for the HRU data set describing the post-afforestation stage for the Weatherley catchment (31 HRUs).

No.	Land use	Terrain Unit	Soil-Ttype	Slope [%]	Aspect	MSlope [%]	Elevation [m asl.]	Area [ha]	Area [%]
1	Grassland	up-crest	R, L, Ar	> 15	N	17.89	1337	0.93	0.67
2	Grassland	up-crest	L,C,Al	5-15	N	9.19	1334	3.91	2.82
3	Grassland	up-crest	L,C,Al	5-15	E,W	9.81	1334	4.60	3.32
4	Grassland	up-crest	L,C,Al	2-5	N	3.56	1330	2.20	1.59
5	Grassland	up-crest	R, L, Ar	> 15	E,W	19.47	1329	2.58	1.86
6	Grassland	down-crest	L,C,Al	> 15	N	22.21	1325	9.95	7.19
7	Eucalyptus	down-crest	L,C,Al	2-5	E,W	3.29	1324	0.79	0.57
8	Pine	up-crest	L,C,Al	5-15	E,W	12.69	1323	5.59	4.03
9	Grassland	down-crest	L,C,Al	5-15	N	10.24	1322	4.77	3.44
10	Plateau Wetland	up-crest	sL, sC	5-15	E,W	10.72	1319	0.25	0.18
11	Pine	down-crest	L,C,Al	2-5	E,W	2.92	1318	3.77	2.72
12	Pine	down-crest	L,C,Al	> 15	N	19.18	1313	3.11	2.25
13	Grassland	down-crest	R, L, Ar	> 15	N	25.96	1311	0.84	0.60
14	Pine	down-crest	L,C,Al	5-15	E,W	9.90	1311	4.18	3.02
15	Pine	down-crest	L,C,Al	5-15	N	11.26	1311	6.39	4.62
16	Pine	down-crest	L,C,Al	> 15	E,W	20.03	1305	4.71	3.40
17	Grassland	up-crest	L,C,Al	> 15	E,W	22.31	1301	2.35	1.70
18	Grassland	down-crest	L,C,Al	> 15	E,W	20.25	1301	8.21	5.93
19	Eucalyptus	down-crest	L,C,Al	> 15	E,W	17.04	1297	7.00	5.06
20	Eucalyptus	down-crest	L,C,Al	5-15	E,W	11.61	1295	9.43	6.81
21	Grassland	down-crest	L,C,Al	2-5	E,W	3.66	1294	1.93	1.39
22	Slope Wetland	down-crest	sL, sC	5-15	N	11.73	1293	4.46	3.22
23	Grassland	down-crest	L,C,Al	5-15	E,W	9.44	1290	13.61	9.83
24	Slope Wetland	down-crest	sL, sC	5-15	E,W	13.53	1288	2.87	2.07
25	Valley B. Wetland	flat	G, gP, P	5-15	N	6.75	1286	4.45	3.21

No.	Land use	Terrain Unit	Soil-Ttype	Slope [%]	Aspect	MSlope [%]	Elevation [m asl.]	Area [ha]	Area [%]
26	Slope Wetland	down-crest	sL, sC	5-15	N	10.48	1283	0.85	0.61
27	Slope Wetland	flat	sL, sC	5-15	E,W	9.90	1282	11.71	8.46
28	Valley B. Wetland	flat	G, gP, P	2-5	N	3.83	1277	4.90	3.54
29	Valley B. Wetland	flat	sL, sC	5-15	E,W	8.04	1275	4.25	3.07
30	Valley B. Wetland	flat	G, gP, P	2-5	E,W	3.81	1273	2.62	1.89
31	Slope Wetland	flat	G, gP, P	2-5	E,W	4.36	1273	1.27	0.92
								1.385 km²	**100**

MSlope … mean slope; Valley B. Wetland … Valley Bottom Wetland; G, gP, P … Gleysol, gleyic plinthosols, planosols; gL, gC … stagnic Luvisol, stagnic Cambisol; L,C,A … Luvisol, Cambisol, Alisols; R, L, Ar … Regosol, Leptosol, Arenosols

7.2.4.2 Mooi Catchment

The HRUs for the Mooi basin were delineated using the similar procedure and class description which was explained for the HRU delineation for the Weatherley catchment. Nevertheless, a few scale-related differences were taken into account, since the input data varied compared to that used for the Weatherley catchment. The changes can be drawn as follows:

- ***Land use*** information which has been derived from field maps and remote sensing analysis was used to differentiate 8 land use classes (Grassland, Forest, Plateau wetland, Slope wetland, Valley Bottom wetland, Bare soil/Bedrock, and Agriculture). Those areas which were planted by eucalyptus and pine were extracted from the forest data base to analyze their distribution and land use changes. The analysis has shown that only 2.21 % of the forest area is planted with eucalyptus. As a consequence, the eucalyptus and pine were grouped to commercial forest for generalization purposes. Additionally, it was found that agricultural fields and existing forests (mainly wattle stands) are widely replaced by commercial forestry. As a consequence, it is assumed that forest prior to afforestation (1989) is indigenous forest, while forest after afforestation is considered as being commercial forest. This information was also used for the later parameterization of the model.

- The ***geology*** was digitized from the geological map (1:250 000), while *terrain unit* and *aspect* were treated in a similar manner as it was done for the Weatherley catchment. The *Slope* was differentiated into 3 groups (0-5%; 5-15%; >15%) to reduce the number of resulting HRUs.

Table 7.18 summarizes the input data layer and its associated classes which were used for the HRU delineation within the Weatherley catchment representing the pre- and post-afforestation condition.

Table 7.18: Summary of used input data layers and associated classes for the Mooi catchment.

	Landuse	Terrain Unit	Soil	Aspect	Slope [%]
Pre-afforestation	Grassland	up-crest	Dolerite	N	0 - 5
	Indigenous Forest	down-crest	Drakensberg	S	5 - 15
	Plateau Wetland	flat	Clarens	E,W	> 15
	Slope Wetland		Molteno		
	Valley Bottom Wet-land		Elliot		
	Bare soil/bedrock		Alluvium		
	Agriculture				
Post-afforestation	Grassland	up-crest	Dolerite	N	0 - 5
	Commercial Forest	down-crest	Drakensberg	S	5 - 15
	Plateau Wetland	flat	Clarens	E,W	> 15
	Slope Wetland		Molteno		
	Valley Bottom Wet-land		Elliot		
	Bare soil/bedrock		Alluvium		

As a result of the overlay analysis, two HRU maps with 161 classes (pre-afforestation) and 163 classes (post-afforestation) respectively were generated for the Mooi catchment. To reduce the total number of HRUs, the HRUs were regrouped and reclassified by considering the following rules:

- Since open water bodies covered only 0.014% of the catchment, those areas were merged with valley bottom wetlands which also tend to form open water bodies such as lakes and oxbow lakes.
- Combinations of topography and geology were related to soil characteristics of their corresponding soil catenas. It was found that *Regosols*, *Leptosols* and *Arenosols* are mainly developed on steep slopes and at higher altitudes, while *Cambisols*, *Luvisols* and *Alisols* are developed on gentler slopes with underlying sandstone and mudstone. Stagnic *Cambisols* and *Luvisols* are mainly developed in depressional situations on slopes and in transitional areas between bottomslopes and floodplains. *Gleysol*, gleyic *Plinthosols* and *Planosols* are widely restricted to the valley bottom floors.
- HRUs with sizes smaller then 0.2 km² were merged to those HRUs which seemed to be most similar from a hydrological perspective.

Tables 7.19 and 7.20 summarize the HRUs which were finally used for the modeling of the prior to afforestation (70 HRUs) and post-afforestation (66 HRUs) water budget for the Mooi basin.

Table 7.19: Summary of HRU characteristics for the HRU data set describing the pre-afforestation stage for the Mooi catchment (70 HRUs).

No.	Land use	Terrain Unit	Geology	Ass. Soil-Type	Slope [%]	Aspect	MSlope [%]	Elevation [m asl.]	Area [km²]	Area [%]
1	BSB	up-crest	Drakensbg.	R, L, Ar	> 15	E,W	60.18	2259	0.52	0.17
2	Grassland	up-crest	Drakensbg.	R, L, Ar	> 15	E,W	48.15	2145	11.51	3.76

No.	Land use	Terrain Unit	Geology	Ass. Soil-Type	Slope [%]	Aspect	MSlope [%]	Elevation [m asl.]	Area [km²]	Area [%]
3	Grassland	down-crest	Drakensbg.	L,C,Al	5-15	E,W	10.30	2142	0.87	0.28
4	Grassland	up-crest	Drakensbg.	R, L, Ar	> 15	S	55.63	2120	9.30	3.03
5	Grassland	up-crest	Drakensbg.	R, L, Ar	> 15	N	46.12	2101	3.99	1.30
6	Grassland	down-crest	Drakensbg.	L,C,Al	> 15	S	22.16	2060	0.77	0.25
7	Grassland	down-crest	Drakensbg.	L,C,Al	> 15	E,W	21.96	2014	0.78	0.26
8	Sl. Wetl.	down-crest	Drakensbg.	gL, gC	5-15	E,W	10.70	1862	0.20	0.06
9	BSB	down-crest	Cl,Ell,Mol	R, L, Ar	> 15	N	44.59	1770	2.03	0.66
10	BSB	down-crest	Cl,Ell,Mol	R, L, Ar	> 15	E,W	42.02	1675	3.60	1.17
11	BSB	up-crest	Cl,Ell,Mol	R, L, Ar	> 15	S	22.83	1650	0.45	0.15
12	BSB	down-crest	Cl,Ell,Mol	R, L, Ar	> 15	S	40.12	1643	1.03	0.34
13	Grassland	down-crest	Cl,Ell,Mol	L,C,Al	> 15	N	36.61	1613	31.58	10.30
14	Sl. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	> 15	N	48.62	1608	0.14	0.05
15	Grassland	up-crest	Cl,Ell,Mol	R, L, Ar	> 15	S	21.29	1590	6.09	1.99
16	Grassland	down-crest	Cl,Ell,Mol	L,C,Al	> 15	S	36.97	1588	40.38	13.17
17	Indig. Forest	down-crest	Cl,Ell,Mol	L,C,Al	> 15	N	37.25	1586	0.21	0.07
18	Grassland	up-crest	Cl,Ell,Mol	R, L, Ar	> 15	N	21.48	1585	8.17	2.66
19	Grassland	up-crest	Cl,Ell,Mol	R, L, Ar	> 15	E,W	21.42	1573	11.96	3.90
20	Agriculture	down-crest	Cl,Ell,Mol	L,C,Al	> 15	N	30.48	1563	0.44	0.14
21	Grassland	down-crest	Cl,Ell,Mol	L,C,Al	> 15	E,W	32.83	1563	61.54	20.07
22	Grassland	up-crest	Cl,Ell,Mol	L,C,Al	5-15	S	9.80	1550	4.79	1.56
23	Indig. Forest	down-crest	Cl,Ell,Mol	L,C,Al	> 15	S	42.45	1542	1.84	0.60
24	Indig. Forest	down-crest	Cl,Ell,Mol	L,C,Al	> 15	E,W	36.46	1500	0.74	0.24
25	Agriculture	down-crest	Cl,Ell,Mol	L,C,Al	> 15	E,W	29.04	1495	0.38	0.12
26	Sl. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	> 15	S	30.27	1484	0.46	0.15
27	Grassland	up-crest	Cl,Ell,Mol	L,C,Al	5-15	N	9.56	1476	9.51	3.10
28	Grassland	up-crest	Cl,Ell,Mol	L,C,Al	5-15	E,W	9.53	1465	13.66	4.46
29	Sl. Wetl.	up-crest	Cl,Ell,Mol	sL, sC	5-15	E,W	11.13	1462	0.42	0.14
30	Grassland	up-crest	Cl,Ell,Mol	L,C,Al	0-5	E,W	3.53	1442	2.17	0.71
31	Sl. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	5-15	S	10.64	1430	1.00	0.33
32	Val. B. Wetland	flat	Cl,Ell,Mol	L,C,Al	5-15	S	10.46	1425	0.70	0.23
33	BSB	up-crest	Cl,Ell,Mol	R, L, Ar	5-15	E,W	10.54	1413	0.33	0.11
34	Sl. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	5-15	E,W	9.61	1411	2.98	0.97
35	Sl. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	5-15	N	9.72	1409	1.64	0.54
36	Sl. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	> 15	E,W	26.84	1398	0.33	0.11
37	Indig. Forest	up-crest	Cl,Ell,Mol	L,C,Al	5-15	E,W	8.97	1390	0.97	0.32
38	Grassland	down-crest	Cl,Ell,Mol	L,C,Al	5-15	N	9.23	1386	12.67	4.13
39	Grassland	down-crest	Cl,Ell,Mol	L,C,Al	5-15	S	9.64	1379	2.84	0.93
40	Grassland	down-crest	Cl,Ell,Mol	L,C,Al	5-15	E,W	9.29	1374	22.49	7.34
41	Indig. Forest	down-crest	Cl,Ell,Mol	L,C,Al	5-15	N	7.67	1357	0.47	0.15
42	Grassland	up-crest	Dolerit	R, L, Ar	> 15	E,W	20.35	1355	0.56	0.18
43	Grassland	down-crest	Dolerit	R, L, Ar	> 15	E,W	26.52	1355	0.68	0.22
44	Agriculture	up-crest	Cl,Ell,Mol	L,C,Al	5-15	N	7.55	1353	0.62	0.20
45	Agriculture	flat	Cl,Ell,Mol	L,C,Al	5-15	N	7.16	1351	1.09	0.36
46	Indig. Forest	down-crest	Cl,Ell,Mol	L,C,Al	5-15	E,W	9.04	1350	0.74	0.24
47	Grassland	up-crest	Dolerit	L,C,Al	5-15	E,W	10.14	1347	1.23	0.40
48	Val. B. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	5-15	S	18.18	1346	0.77	0.25
49	Grassland	flat	Cl,Ell,Mol	L,C,Al	0-5	E,W	3.55	1346	3.26	1.06
50	BSB	down-crest	Cl,Ell,Mol	R, L, Ar	5-15	E,W	8.90	1345	0.47	0.15

No.	Land use	Terrain Unit	Geology	Ass. Soil-Type	Slope [%]	Aspect	MSlope [%]	Elevation [m asl.]	Area [km²]	Area [%]
51	Grassland	down-crest	Dolerit	R, L, Ar	> 15	S	29.12	1345	0.52	0.17
52	Grassland	up-crest	Dolerit	R, L, Ar	> 15	N	20.89	1342	0.35	0.11
53	Agriculture	flat	Cl,Ell,Mol	L,C,Al	0-5	N	3.82	1342	0.71	0.23
54	Val. B. Wetl.	flat	Cl,Ell,Mol	sL, sC	5-15	E,W	10.25	1342	1.06	0.35
55	Agriculture	up-crest	Cl,Ell,Mol	L,C,Al	5-15	E,W	7.56	1340	1.37	0.45
56	Agriculture	flat	Cl,Ell,Mol	L,C,Al	0-5	E,W	3.62	1339	1.01	0.33
57	Agriculture	down-crest	Cl,Ell,Mol	L,C,Al	5-15	E,W	7.95	1338	2.61	0.85
58	Val. B. Wetl.	down-crest	Alluv.	G, gP, P	0-5	N	3.50	1333	0.37	0.12
59	Agriculture	up-crest	Cl,Ell,Mol	L,C,Al	0-5	E,W	3.59	1332	0.82	0.27
60	BSB	down-crest	Cl,Ell,Mol	R, L, Ar	5-15	N	7.75	1331	0.45	0.15
61	Val. B. Wetl.	flat	Cl,Ell,Mol	G, gP, P	0-5	N	3.25	1328	1.57	0.51
62	Agriculture	down-crest	Cl,Ell,Mol	L,C,Al	5-15	S	6.60	1327	0.20	0.06
63	BSB	flat	Cl,Ell,Mol	R, L, Ar	0-5	E,W	4.70	1325	0.25	0.08
64	Val. B. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	5-15	N	11.77	1325	0.29	0.09
65	Val. B. Wetl.	flat	Cl,Ell,Mol	G, gP, P	0-5	E,W	4.01	1324	4.71	1.54
66	Grassland	up-crest	Dolerit	L,C,Al	5-15	N	10.16	1323	0.69	0.23
67	Val. B. Wetl.	flat	Alluv.	G, gP, P	0-5	E,W	3.58	1321	2.08	0.68
68	Val. B. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	5-15	E,W	15.18	1319	1.52	0.50
69	Val. B. Wetl.	flat	Alluv.	G, gP, P	0-5	N	2.95	1313	0.30	0.10
70	Val. B. Wetl.	flat	Cl,Ell,Mol	G, gP, P	0-5	S	3.32	1305	0.28	0.09
									306.53	**100**

MSlope … mean slope; Indig. Forest … Indigenous Forest; BSB … bare soil/bedrock; Sl. Wetl. … Slope Wetland; Val. B. Wetl. … Valley Bottom Wetland; Drakensbg. … Drakensberg formation; Cl … Clarens Fomration; Ell … Elliot Formation; Mol … Molteno formation; G, gP, P … Gleysol, gleyic plinthosols, planosols; gL, gC … stagnic Luvisol, stagnic Cambisol; L,C,A … Luvisol, Cambisol, Alisols; R, L, Ar … Regosol, Leptosol, Arenosols

Table 7.20: Summary of HRU characteristics for the HRU data set describing the post-afforestation stage for the Mooi catchment (66 HRUs).

No.	Land use	Terrain Unit	Geology	Ass. Soil-Type	Slope [%]	Aspect	MSlope [%]	Elevation [m asl.]	Area [km²]	Area [%]
1	BSB	up-crest	Drakensbg.	R, L, Ar	> 15	E,W	58.77	2263	0.73	0.24
2	BSB	up-crest	Drakensbg.	R, L, Ar	> 15	N	59.99	2192	0.36	0.12
3	Grassland	down-crest	Drakensbg.	L,C,Al	> 15	E,W	47.74	2151	11.21	3.65
4	Grassland	down-crest	Drakensbg.	L,C,Al	> 15	S	53.63	2116	9.78	3.19
5	Grassland	down-crest	Drakensbg.	R, L, Ar	> 15	N	42.27	2076	4.04	1.32
6	BSB	down-crest	Drakensbg.	R, L, Ar	> 15	S	51.38	2076	0.28	0.09
7	Grassland	up-crest	Drakensbg.	L,C,Al	5-15	E,W	10.17	2016	1.25	0.41
8	Grassland	up-crest	Drakensbg.	R, L, Ar	> 15	E,W	20.48	2014	0.75	0.24
9	BSB	up-crest	Drakensbg.	R, L, Ar	> 15	S	21.38	2014	0.25	0.08
10	BSB	down-crest	Cl,Ell,Mol	R, L, Ar	> 15	N	42.38	1727	1.94	0.63
11	BSB	down-crest	Cl,Ell,Mol	R, L, Ar	> 15	E,W	43.45	1663	3.61	1.17
12	Grassland	up-crest	Cl,Ell,Mol	L,C,Al	> 15	S	23.04	1628	5.02	1.64
13	Grassland	down-crest	Cl,Ell,Mol	L,C,Al	> 15	N	37.78	1627	30.03	9.80
14	BSB	down-crest	Cl,Ell,Mol	R, L, Ar	> 15	S	39.98	1619	1.10	0.36
15	BSB	up-crest	Cl,Ell,Mol	R, L, Ar	> 15	N	21.97	1613	0.25	0.08
16	Grassland	down-crest	Cl,Ell,Mol	L,C,Al	> 15	S	36.92	1597	39.35	12.84
17	Grassland	up-crest	Cl,Ell,Mol	R, L, Ar	> 15	N	21.97	1593	6.99	2.28
18	Grassland	up-crest	Cl,Ell,Mol	L,C,Al	> 15	E,W	21.49	1590	10.94	3.57
19	Grassland	down-cres	Cl,Ell,Mol	L,C,Al	> 15	E,W	33.94	1585	56.52	18.45

No.	Land use	Terrain Unit	Geology	Ass. Soil-Type	Slope [%]	Aspect	MSlope [%]	Elevation [m asl.]	Area [km²]	Area [%]
20	Grassland	up-crest	Cl,Ell,Mol	L,C,Al	5-15	S	10.22	1566	3.15	1.03
21	BSB	up-crest	Cl,Ell,Mol	R, L, Ar	> 15	E,W	24.10	1539	0.41	0.13
22	Sl. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	> 15	E,W	27.81	1535	0.46	0.15
23	Sl. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	> 15	N	35.51	1535	0.31	0.10
24	Grassland	up-crest	Cl,Ell,Mol	L,C,Al	5-15	N	10.08	1524	6.52	2.13
25	Grassland	up-crest	Cl,Ell,Mol	L,C,Al	5-15	E,W	10.44	1522	8.12	2.65
26	Grassland	up-crest	Cl,Ell,Mol	R, L, Ar	0-5	E,W	4.00	1519	1.09	0.36
27	Val. B. Wetl.	flat	Cl,Ell,Mol	G, gP, P	5-15	N	11.87	1470	0.47	0.15
28	Sl. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	5-15	E,W	9.66	1446	2.68	0.87
29	Sl. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	5-15	S	10.45	1445	0.51	0.17
30	Grassland	down-crest	Cl,Ell,Mol	L,C,Al	5-15	S	9.90	1442	1.73	0.56
31	Grassland	down-crest	Cl,Ell,Mol	L,C,Al	5-15	N	10.06	1437	4.94	1.61
32	Sl. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	5-15	N	9.74	1423	2.18	0.71
33	Val. B. Wetl.	flat	Cl,Ell,Mol	G, gP, P	5-15	S	11.75	1410	0.24	0.08
34	com. Forest	down-crest	Cl,Ell,Mol	L,C,Al	> 15	N	22.69	1406	1.33	0.43
35	com. Forest	down-crest	Cl,Ell,Mol	L,C,Al	> 15	S	29.76	1406	4.88	1.57
36	Grassland	down-crest	Cl,Ell,Mol	L,C,Al	5-15	E,W	10.13	1406	8.66	2.83
37	com. Forest	up-crest	Cl,Ell,Mol	R, L, Ar	> 15	N	18.75	1404	0.87	0.29
38	com. Forest	up-crest	Cl,Ell,Mol	L,C,Al	> 15	E,W	19.03	1392	1.33	0.43
39	com. Forest	up-crest	Cl,Ell,Mol	L,C,Al	5-15	S	10.56	1388	2.11	0.69
40	com. Forest	up-crest	Cl,Ell,Mol	L,C,Al	> 15	S	20.37	1381	1.14	0.37
41	com. Forest	down-crest	Cl,Ell,Mol	L,C,Al	> 15	E,W	21.05	1372	7.76	2.53
42	com. Forest	up-crest	Cl,Ell,Mol	L,C,Al	5-15	N	9.37	1370	4.13	1.35
43	com. Forest	up-crest	Cl,Ell,Mol	L,C,Al	5-15	E,W	9.04	1367	7.65	2.50
44	Val. B. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	5-15	S	18.66	1367	0.41	0.13
45	com. Forest	down-crest	Cl,Ell,Mol	L,C,Al	5-15	N	8.69	1357	8.80	2.87
46	com. Forest	flat	Cl,Ell,Mol	G, gP, P	5-15	E,W	6.16	1356	0.24	0.08
47	com. Forest	up-crest	Cl,Ell,Mol	L,C,Al	0-5	N	3.84	1351	0.66	0.22
48	com. Forest	down-crest	Cl,Ell,Mol	L,C,Al	0-5	N	4.06	1350	2.07	0.68
49	com. Forest	down-crest	Cl,Ell,Mol	L,C,Al	5-15	E,W	8.96	1350	17.25	5.63
50	com. Forest	up-crest	Cl,Ell,Mol	L,C,Al	0-5	E,W	3.79	1349	1.68	0.55
51	com. Forest	flat	Cl,Ell,Mol	L,C,Al	0-5	E,W	3.58	1348	0.40	0.13
52	com. Forest	down-crest	Cl,Ell,Mol	L,C,Al	0-5	E,W	3.67	1345	2.59	0.85
53	BSB	down-crest	Cl,Ell,Mol	L,C,Al	5-15	N	9.26	1341	0.44	0.14
54	com. Forest	down-crest	Cl,Ell,Mol	L,C,Al	5-15	S	9.62	1335	1.97	0.64
55	Val. B. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	> 15	S	7.20	1332	0.27	0.09
56	BSB	down-crest	Cl,Ell,Mol	L,C,Al	5-15	E,W	9.11	1331	0.44	0.14
57	Val. B. Wetl.	flat	Cl,Ell,Mol	G, gP, P	0-5	N	3.61	1331	1.89	0.62
58	Val. B. Wetl.	flat	Alluv.	G, gP, P	0-5	S	3.40	1328	0.40	0.13
59	Val. B. Wetl.	flat	Cl,Ell,Mol	G, gP, P	5-15	E,W	8.61	1324	0.95	0.31
60	BSB	down-crest	Cl,Ell,Mol	R, L, Ar	0-5	E,W	5.23	1324	0.21	0.07
61	Val. B. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	5-15	N	12.68	1322	0.44	0.14
62	Val. B. Wetl.	flat	Alluv.	G, gP, P	0-5	E,W	3.94	1321	2.13	0.70
63	Val. B. Wetl.	flat	Cl,Ell,Mol	G, gP, P	0-5	E,W	4.08	1317	4.16	1.36
64	Val. B. Wetl.	flat	Alluv.	G, gP, P	0-5	N	3.22	1314	0.41	0.13
65	Val. B. Wetl.	down-crest	Cl,Ell,Mol	sL, sC	5-15	E,W	14.95	1306	1.38	0.45
66	Val. B. Wetl.	flat	Cl,Ell,Mol	G, gP, P	0-5	S	3.92	1306	0.32	0.10
									306.53	**100**

MSlope … mean slope; Com. Forest … Commercial Forest; BSB … bare soil/bedrock; Sl. Wetl. … Slope Wetland; Val. B. Wetl. … Valley Bottom Wetland; Drakensbg. … Drakensberg formation; Cl … Clarens Fomration; Ell … Elliot Formation; Mol … Molteno formation; G, gP, P … Gleysol, gleyic plinthosols, planosols; gL, gC … stagnic Luvisol, stagnic Cambisol; L,C,A … Luvisol, Cambisol, Alisols; R, L, Ar … Regosol, Leptosol, Arenosols

7.2.5 Conclusions and Implications for System Modeling

An integrated system analysis was conducted in order to provide an improved generalized understanding of the multi-faceted processes controlling wetland and catchment functioning. Summarizing the integrated system analysis, the following main conclusions are drawn forming the base for hydrological modeling and the landscape model.

- The analysis of climate parameters has shown that in particular rainfall shows a high spatial and temporal variability that needs to be taken into account for the modeling applications.
- The soil survey indicated a complex soil distribution pattern characterized by the occurrence of 15 different soil types. Based on the analysis of individual soil profiles, several soil types were grouped with respect to similar soil-physical properties in order to reduce input layers for the HRU delineation.
- The geophysical and sedimentological survey provided information on wetland characteristics. While thickness and structural properties of wetland sediments were derived by refraction seismic measurements, ^{14}C dating and pollen analysis provided background information on conditions and timing of wetland formation processes.
- Based on vegetation analysis it was found that differences regarding vegetation composition and bio-physical parameters exist between wetland and grassland areas. Using this information, wetlands were characterized by higher biodiversity; higher cover densities and increased rooting depths compared with grassland, and thereby can be separately parameterized in the model application.
- Investigating species-related characteristics of commercial forest plantations, it was found that forest plantations can be differentiated based on bio-physical properties such as tree heights, tree density, LAI, DBH and cover density. In addition, the most dominant species (*Pinus patula*) planted showed variations of these parameters within age-specific classes which will be taken into account for the modeling of plant growth and hydrological dynamics.
- Land use analysis proved that forest area increased by 17 %, while grassland (-11 %) agricultural fields (-2 %) and wetland area (-2 %) decreased since 1989 in the Mooi basin. About 35 % of the experimental Weatherley catchment was planted in 2002.
- Based on the integrated analysis of hydrometric monitoring and soil data recorded, a hillslope model describing major runoff generating processes on hillslopes was developed for the Weatherley catchment. Three dominant runoff generation mechanisms (overland flow, near-surface macro-pore flow and groundwater flow) were identified controlling streamflow dynamics and thereby need to be considered in the hydrological model applications. In addition, water storage capacity and antecedent soil moisture content were recognized as important variables controlling baseflow dynamics (in particular during the dry season) and flood generation.
- The wetland ecosystem analysis provided information on different types of wetlands as well as their characteristics and functioning. Three main wetland types could be identified, namely Plateau Wetland (PWL), Slope Wetland (SWL) and Val-

ley Bottom Wetland (VWL), being different in terms of landscape position, extent and size of the tributary catchment, soils, vegetation composition and hydrological dynamics. Wetland soils were differentiated regarding differences in particle size distribution, organic matter content, bulk densities and hydraulic conductivities. The variety in vegetation composition results in different vegetation heights, cover density and rooting depths and are strongly related to the temporal hydrological dynamics (periods of saturation). Process dynamics of PWL and SWL are mainly controlled by recharge mechanisms, while larger VWLs are driven by interlinked ground-/surface water dynamics, discharge/recharge processes and direct rainfall input. With respect to their size, their temporary nature and hydrological process dynamics, plateau wetlands are assumed to have minor influence on the basin water budget. Addressing their potential to store water (water storage capacity), wetlands play an important role for the catchment water cycle in terms of flood attenuation and the continuous release of water during the dry season.

- Aggregating the information and data obtained from the previous studies, it was found that land use, soils, geology and topographic features are key parameters influencing streamflow generation, evapotranspiration and storage dynamics in the Weatherley and Mooi catchments. Thus, the HRUs were delineated by GIS overlays for each basin utilizing data layers of land use including different wetland types and forests, slope, aspect, soils and geology as well as a topographic unit. Since land use information was available for different time periods (pre- and post afforestation), scenarios of landscape dynamics were considered in the HRU delineation process.

7.3 Integrated Modeling Approach

The integrated model approach applied in this study concerns on the combined use of two process-based models in order to assess the impact of afforestation on wetland and catchment hydrology in the study area. Thus, this section describes the parameterization, calibration and application of the **P**hysiological **P**rocesses in **P**redicting **G**rowth model (3-PG) and the **P**recipitation-**R**unoff-**M**odeling **S**ystem (PRMS). The 3-PG model was applied to simulate forest growth dynamics in forest stands in the North Eastern Cape. From this effort, parameters were derived that were used to calibrate and validate the catchment model to simulate forest scenarios (prior to and after afforestation) and their effect on hydrological processes at different scales.

7.3.1 Plant Growth Modeling

This section discusses the parameterization and calibration process carried out to model forest growth of pine and eucalyptus stands within the study area. Since 3-PG was especially developed to simulate forest production and biomass accumulation of primarily forest stands, only those model predictions are presented and discussed which are of importance for further application in the hydrological model.

7.3.1.1 Parameterization of 3-PG Model

Initially, the user needs to define the species and the number of years applied to the model. For this study, species-related numbers of years were chosen to satisfy species-related differences in rotation cycles. A 15 years period (1983-1998) was chosen to simulate *Eucalyptus nitens* stands and 20 years were considered for *Pinus patula* (1978-1998) and *Pinus radiata* (1978-1998) stands. Once the species and periods are defined, climate input data and parameters are manually edited using the spreadsheet editor given by 3-PG, V. 2.0.

7.3.1.1.1 Climate Data Adjustment

Climate data are typed in a spreadsheet mask for each month of each year manually. Since the model operates on a monthly base, it requires monthly averages of daily total solar radiation, and daytime atmospheric VPD, monthly rainfall, frost days per month, and mean air temperature (SANDS, 2004). These data records can be either actual monthly weather data or long-term monthly averages. These input data were derived as described below.

- ***Radiation***

Monthly radiation data were determined applying an approach introduced by CLEMENCE (1992). The author analyzed a large number of daily radiation observations from Southern Africa and provided an equation to estimate solar radiation by

$$Rs = 0.04184 \cdot (1.233 \cdot R_a \cdot t_{range} + 10.593 \cdot t_{\max} - 0.713 \cdot t_{\max} \cdot t_{range} + 16.548) \qquad [7.1]$$

where Rs is the estimated daily solar radiation on a horizontal surface [MJ m^{-2} day^{-1}],
R_a is the extraterrestrial solar radiation [MJ m^{-2} day^{-1}],
$t_{\max}$ is the daily maximum air temperature [°C],
t_{range} is daily temperature range $t_{max} - t_{min}$ [°C).

CLEMENCE (1992) found good correlations between simulated values and data from independent sources particularly for inland summer rainfall conditions with r^2 varying from 0.49 to 0.84. In order to map monthly means of daily solar radiation, the extraterrestrial radiation variable was applied to the 15th day of each month. Monthly temperature averages were computed from the available data base.

- ***Vapour Pressure Deficit (VPD)***

Since only a few data records are available to describe VPD variations corresponding to a complete pine rotation, daily mean air VPD was determined using a relationship given by DYE (2000, pers. comm.)

$$VPD = \frac{(SVP \cdot t_{\max} - SVP \cdot t_{\min})}{2} \qquad [7.2]$$

where VPD is the mean vapour pressure deficit [kPa],
SVP is the saturated vapour pressure [kPa],
$t_{\min}, t_{\max}$ are maximum and minimum daily temperatures [°C].

SVP was determined using the formula presented by Snyder & Paw (2002)

$$SVP = \left(\frac{17.27 \cdot t_{mean}}{t_{mean} + 237.3} \right) \qquad [7.3]$$

where t_{mean} is daily temperature [°C].

- ***Rainfall***

Monthly rainfall was extracted from daily rainfall records from the station in Maclear for the selected periods.

- ***Days of frost***

Since days of frost have not been explicitly recorded by the climate station in Maclear, the number of days has been extracted from the hourly temperature data of the station. Hereby, daily means were computed and only days with values smaller than 0 °C were considered as frost days.

- ***Temperature***

Temperature data were extracted from the station data in Maclear. Since temperature tends to show significant regional variabilities, temperature data of a six year record were compared to data of the same period from a station in Weatherley. It was shown, that data varied in particular in winter within a range of ± 1.32 °C, and thereby were considered as reliable.

7.3.1.1.2 Parameter Estimation and Model Calibration

To serve the processes implemented in 3-PG, a variety of parameters were defined to calibrate the model.

- ***Stand age***

Parameter *MaxAge* represents the tree age for rate of physiological decline and was set to 28 for the pine species and 20 for eucalyptus. 3-PG only simulates forests with closed canopies. Thus, the *stand age* parameter which characterize the tree age at the start of the model run was set to 3 for all species with respect to the field measurements.

- ***Soil water***

The availability of soil water to the trees at different soil water contents is expressed by the parameters soil water constant (*Swconst*), modifier for soil water prediction (*SwPwr*) and available soil water (*AvailSw*). *Swconst* and *SwPwr* are assigned to four soil texture classes discussed by LANDSBERG & WARING (1997). With respect to the soil studies the predominant soil texture class was defined as clayey loam, and so both constants were set to 0.5 and 5, respectively with respect to the model-internal coding. *AvailSw* is difficult to estimate, but usually range between 50 and 250 mm (LANDSBERG & WARING, 1997). According to the field observation, it was predicted to be 200 mm. Given the conceptual nature of the sub-surface representation within the 3-PG model, it is unlikely that the overall model performance is particularly sensitive to these parameters.

- ***Tree canopy***

The specific leaf area (*SLA* in m² kg^{-1}) is used to relate foliage dry mass to a LAI and requires weighed leaf mass and measured LAI. From previous studies reported by HELMSCHROT (1999) and LANDSBERG *et al.* (2003), estimates of SLA are given for pines (5.3 m² kg^{-1}) and eucalyptus (4.1 m² kg^{-1}). The litter fall rate per month (*MaxLitterFall* in t ha^{-1} $month^{-1}$) affects gross primary production and transpiration, since it constrains the foliage biomass and LAI. As summarized by JACOBS (1999), several estimates of annual litter production in pine stands of different ages are given in the literature. After the comparison of own estimates of annual litter production with literature values, values were set for pines (*P. rad.* = 0.014 t ha^{-1} $month^{-1}$, *P. pat* = 0.026 t ha^{-1} $month^{-1}$) and eucalyptus (0.005 t ha^{-1} $month^{-1}$). Monthly variations in litter production as reported by JACOBS (1999) have not been considered for the estimates, nor have annual variations were taken into account. According to recommendations given by DYE (2000, pers. comm.), a value of 0.5 was used as an extinction coefficient (*ExtCoeff*) which is required to estimate canopy light interception from solar radiation and LAI (LANDSBERG & WARING, 1997). The fraction of rainfall intercepted by vegetation was set for pine (0.12) and eucalyptus (0.04) stands as given by DYE *et al.* (2004).

- ***Tree transpiration***

As discussed in LANDSBERG & WARING (1997), 3-PG requires a set of four parameters aiming to simulate monthly transpiration. Since little information was available for species in the study area, these values were set as defaults given by SANDS (2004). Thus, mean monthly canopy conductance (*MaxCond* in m s^{-1}) was set to 0.02, while the stomatal conductance *StomCond* and the boundary layer conductance *BLCond*, both in m s^{-1}, were set to 0.005 and 0.2, respectively. A coefficient which defines stomatal response (*CoeffCond*) to *VPD* was set to 0.05.

- ***Tree growth***

A variety of parameters need to be defined for the simulation of tree growth. Latitude is required to calculate day length and was set to 31°50'S.

With respect to own biomass studies (HELMSCHROT, 1999) and complementing data found in MORRIS (1992, 1995) and DYE *et al.* (2004), initial biomasses (T ha^{-1}) were defined for foliage (*WF*), root (*WR*) and stem (*WS*). Herein, values were set for pine (2 T ha^{-1}, 5 T ha^{-1}, 8 T ha^{-1}) and eucalyptus (1 T ha^{-1}, 6 T ha^{-1}, 8 T ha^{-1}).

Maximum (t_{min}), minimum (t_{max}) and optimum (t_{opt}) temperatures (°C) define the range of mean monthly temperatures at which growth is zero or optimum. Values have been set for all species to 25 °C, 3 °C and 19 °C with regard to discussions with local foresters.

Fertility rating (*FR*) is a measure for the growth conditions ranging from 0 (poor) to 1 (good). Since the sites were assumed as being in good condition for commercial forestry, the value has been set to 0.8 for all simulations.

Two parameters are required for the allometric equation describing the relation between foliage dry mass and DBH. According to literature values (DYE, 2000, pers. comm.; DYE *et al.*, 2004, the constant *FolPra* and coefficient *FolPrn* were set for *P. rad.*

(0.00156; 1.17), *P. pat.* (0.088; 0.530) and *E. nit.* (0.00005; 2.484). The allometric equation describing the relation between stems (and branch) dry mass and DBH is determined by the constant *StemPra* (Eq. 6.22 and 6.23) and coefficient *StemPrn*. With respect to biomass studies in the study area (HELMSCHROT, 1999) and from other studies (DYE, 2000, pers. comm.; SANDS, 2004), these values (a_s, n_s) were set for *P.rad.* (0.000004; 3.17), *P. pat.* (0.00000769; 3.112) and *E. nit.* (0.095; 2.4). The canopy quantum efficiency constant a_c (eq. 6.8) which was only required for pine stands was set to 0.05 (DYE, 2000, pers. comm.).

The root turnover rate per month (*RttOver*) is required to compute the accumulation of root biomass. In the absence of any data describing root turnover, the default of 0.015 has been used for all species.

The parameter *WoodDens1* and *WoodDens2* characterize the wood density at the start and the end of rotation, respectively. These parameters have been set as defaults (0.5) given by the model itself. Stem density is expressed as an initial stem number per hectare (*StemNo*). As shown by own studies (HELMSCHROT, 1999), pine stands show a notable loss of stems within the first three years, while eucalyptus stay very dense. Consequently, *StemNo* was set for averaged number found in the plantations in the third year after planting (*P. rad.* = 984, *P. pat.* = 836, *E.nit* = 864) (HELMSCHROT, 1999).

- ***Thinning regime***

The used Version of 3-PG, V2.0 was modified by a module developed by Dye (2000, pers. comm.) to improve the representation of thinning treatments. This function requires five parameters and was only used for pine stands. The coefficient *kStem* is used to the -3/2 power law to determine the onset of tree mortality. This value was set to a default (6,000,000). The row thinning was adopted defining thinning of every fifth row in four years intervals. First thinning of smallest trees was set to thin 120 stems in the fourth year.

7.3.1.2 Model Results and Discussion

The 3-PG model has been primarily applied to provide knowledge on the growth dynamics of eucalyptus and pine stands in the study region. In addition, model predictions were provided to improve the representation of forest dynamics in PRMS. Thus, variables predicted by 3-PG were used to estimate cover density (from LAI, basal area, and stocking), interception volumes (from leaf mass, monthly and annual transpiration a percentage of rainfall) and stand water use (from water use efficiency) in forest stands.

The model was run with the parameter sets described above for *Eucalyptus nit., Pinus pat.* and *Pinus rad.* Figure 7.48 illustrates annual averages of the received parameters (stocking, DBH, LAI, leaf mass and basal area) as curves fitted to measured and plotted against empiric data.

Analyzing model results shown in Figure 7.48 it is concluded that model performance generally provided reliable outputs for the variables of interest. Compared to data given from the forest data base and field survey, fitted stocking shows a good agreement with data given for *E. nitens* (r=0.84) and *P. radiata* (r=0.87) stands. It also reveals a general overprediction for *P. patula* (r=0.78) stands, in particular for stands older than 12 years which were planted by farmers before forest industry started afforestation. Hence, the overprediction of stocking is explained as a cumulative effect resulting from higher distances between plants during planting (i.e. lower tree densities), non-optimal growth conditions and self thinning (DYE, 1997).

From the comparison of fitted DBH curves with empiric data it is indicated that the model is able to represent DBH dynamics for all three species (*E. nit.*: r=0.92, *P .pat.*: r=0.95, *P. rad.*: r=0.97).

When examining predicted LAI and measured LAI it is shown that the trend was basically matched by the model (*E. nit.*: r=0.62, *P .pat.*: r=0.83, *P. rad.*: r=0.84), but it also reveals that LAI is slightly overpredicted for very young and older stands, while the most dynamic growth phases are slightly underpredicted. As reported in the literature (LANDSBERG *et al.*, 2003) a similar behavior was found for *E. grandis* stands in a different region in South Africa. Here the authors argued that the model results seemed to be more accurate than the observed data which were calculated from a relationship between stem size and leaf mass. On the other hand, DYE *et al.* (1997) have shown that LAI for *E. grandis* never exceeded a value of 3, not even under optimal growth conditions. Thus, more studies are needed to evaluate variations resulting from differences of species and growth environments.

Only a small number of data were available from former studies (HELMSCHROT, 1999) for evaluating the accuracy of green biomass (leaf mass) modeling. Nevertheless, the model results indicate a good agreement for the first years with an excellent coincidence with *P. radiata*, but slight divergencies for *E. nitens* and *P. patula*. These findings are in contrast to LAI measurements which usually show the same dynamic like green leaf biomass (LANDSBERG *et al.*, 2003). Consequently, simulated and observed data were compared to literature values (DYE *et al.* 1997; LANDSBERG *et al.*, 2003; SUMMERTON, 1995). From this effort it is concluded that the model seems to provide reliable results, while the recorded values for leaf biomass seemed to be too high.

The basal area was computed from the relation between DBH and stocking. *E. nitens* and *P. radiata* were slightly underestimated, while *P. patula* showed a contrary trend. Such variations are related to environmental conditions affecting tree growth (for example water and nutrient availability) or thinning treatments including self thinning effects (LANDSBERG & WARING, 1997).

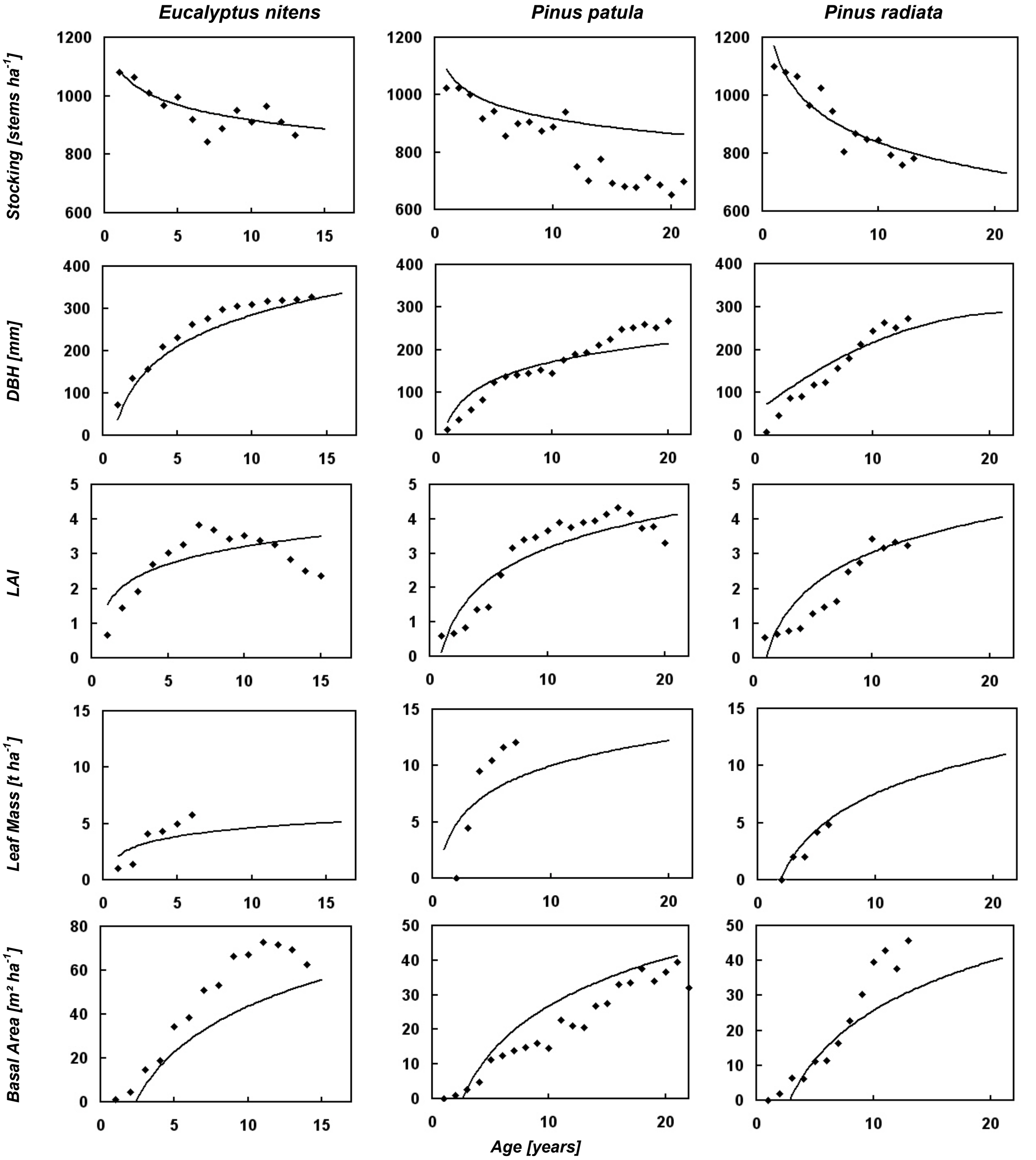


Figure 7.48: Calibration of 3-PG predictions (without thinning) of age-based tree density (stems ha^{-1}), DBH (mm), LAI, green leaf biomass (t ha^{-1}) and basal area (m^2 ha^{-1}) against data given by field survey and from forest data base. The points are empiric values (whereas basal area was computed from measured DBH and stocking) and the curves are the best fit obtained simultaneously for all variables by adjusting parameter values in the model to empiric data by non-linear regression. The evaluation of best match did not involve statistical analysis.

Since thinning treatments affect forest growth significantly (JUODVALKIS *et al.*, 2005; PRETZSCH, 2001), thinning was simulated for pine stands implementing a routine developed by DYE (2000, pers. comm.). Figure 7.49 reflects the effect of thinning on LAI in comparison with simulated, measured and literature (SUMMERTON, 1995) LAI values. Even though no verification was performed it is concluded that the model respond very sensitive regarding thinning practice which results in significantly higher growths rates for leaf biomass after the treatment.

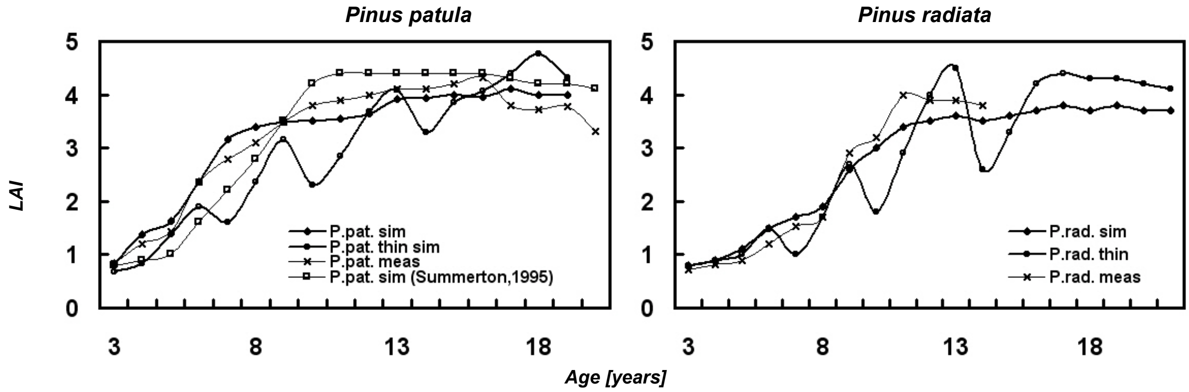


Figure 7.49: Comparison of age-related LAI values derived from 3-PG modeling (simulation with and without thinning treatment), field survey and literature values for P. pat (left). and P. rad.(right).

Water use of forest stands was of primary interest for this study, Figure 7.50 shows the simulated water use efficiency (WUE) of pine species and simulated annual transpiration against rainfall. WUE is expressed as tonnes of stem per tonnes of water transpired. Water use derived for the two species varies between 833 m^3 water per tonne wood (i.e. 0.83 m^3 kg^{-1} or 0.0012 t m^{-3}) and 420 m^3 water per tonne wood (i.e. 0.42 m^3 kg^{-1} or 0.0024 t m^{-3}). These values are in the range of WUE values provided by DYE (2000, pers. comm.) from studies in *P.pat.* stands. Assuming a wood density of 320 kg dry mass per m^3, DYE (2000, pers. comm.) derived a mean WUE of 522 m^3 t^{-1}, or 0.0019 t m^{-3} for *P.pat.* As shown in Figure 7.50, WUE is generally decreasing for the two species over the rotation. This is addressed to the slowdown in stem growth and a relatively stable LAI after the closing of the canopy, which in turns causes a decrease of transpiration rates. In contrast to findings by DYE *et al.* (1997), little evidence is given that annual WUE significantly decreases in years of low rainfall. The comparison of simulated annual transpiration (Figure 7.50, right) and observed annual rainfall led to the assumption that *P.pat.* transpires a slightly higher proportion of rainfall (89 %) than *P.rad.* (87 %).

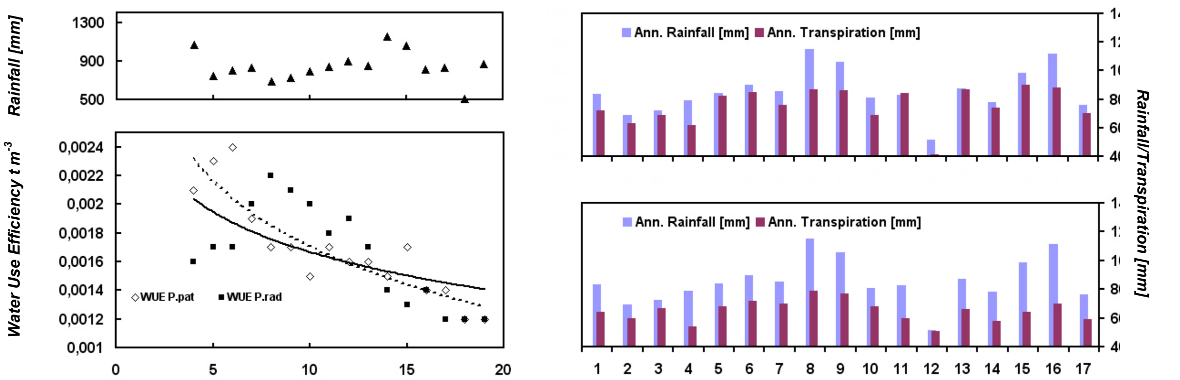


Figure 7.50: Left: Simulated Water Use Efficiency (WUE) values for P. pat. and P. rad and their respective fitting curve based on non-linear regression (P.pat.: dotted line, P.rad.: solid line). Right: Comparison of observed annual rainfall [mm] and simulated transpiration for P. pat.(above) and P. rad (below).

The simulation of thinning treatments did not show significant changes in annual WUE and transpiration. This indicates that either the module is not adequately linked to the processes accounting stand water use or the model is not sensitive enough or thinning treatments do not affect water use noticeably.

7.3.1.3 Conclusion of the Plant Growth Modeling and Implications

Summarizing the plant growth model application described above, the following conclusions can be drawn.

- 3-PG is a powerful predictive tool for simulating growth and water use in forest plantations. It is process-based in nature, but simple to use.
- 3-PG provides, with suitable parameterization, a number of variables on monthly and annual time scale which can be further used in a variety of environmental model applications, but also for management purposes.
- Applying the model, reliable times series of LAI, DBH, basal area, stocking, leaf mass, transpiration and WUE were derived reflecting growth and water use dynamics of forest stands of different species (*E. nitens., P. patula* and *P. radiata*).
- 3-PG usually works with the assumption of optimal growth conditions. Thus, further studies are needed to evaluate the impact of environmental conditions (e.g. site conditions, local climate) and management treatments (e.g. plant techniques, pruning) on growth dynamics.
- Little information is given regarding the sensitivity of parameters used in the model, since parameter sensitivity analysis was excluded from this study. However, as shown by ESPREY *et al.* (2004), a thorough sensitivity analysis provides sound parameterization in order to improve model performance, and thereby need to be taken into account for further studies.

7.3.2 Hydrological Modeling

The Weatherley and Mooi catchments were simulated prior to and after afforestation using PRMS to model the impact of afforestation on wetland and catchment scale. The following section describes the parameterization, calibration and model application for the two catchments. Summarizing the model outputs, the discussion mainly focuses on alterations of the total runoff and changes in volumes of selected flow components in different wetland types in the two catchments.

7.3.2.1 Model Parameterization and Optimization

Addressing the process-oriented nature of PRMS, the model needs to be parameterized by a variety of parameters which are either defined from the system analysis or literature values. This section concerns on the development of a parameter set which was used for all model applications.

7.3.2.1.1 Climate Data Adjustment

As discussed in Section 6.5.2, PRMS requires an adjustment of input data aiming to satisfy spatial and temporal variations of rainfall, temperature and solar radiation.

Previous analysis (Section 7.2.1.1) has shown how rainfall varies spatially depending on the geographic position and local climatic phenomena. This is of particular importance in the Mooi basin. Thus, the regionalized rainfall distribution was explored to identify an HRU-specific adjustment factor for each HRU reflecting the spatial variability of rainfall. The rainfall analysis further revealed rainfall dynamics alterations during the rain season. While the rainfall is orographic at the beginning of the rain season, thunderstorm frequency increases during the season resulting in more intense rainfall events. In addition, measurement errors resulting from the applied technique are in the range of 5 to 30 %, with higher errors during intense events (BEVEN, 2001). Addressing these aspects, the monthly correction factors for rainfall ($rain_{adj}$) were adjusted (Table 7.21) with respect to estimates given by SCHULZE (1997) and SEUFFERT *et al.* (1999). Adjustments for snowfall have not been performed, since snow is assumed to be less effective to the overall water budget.

Table 7.21: Monthly correction factors for rainfall ($rain_{adj}$ in percent) used in all model runs.

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
***rain**$_{adj,}$*	10	12	14	15	15	14	12	10	8	8	8	10

Temperature data were spatially adjusted with the regionalized temperature gradient (0.42 °C per 100 m) given by HERBERT (1997). The mean altitude of each HRU was related to the station altitude. Since little knowledge was available about monthly variations of the temperature gradient, this approach was applied to the entire data set. In addition, the exposition class of each HRU was considered, since HERBERT (1997) found significantly lower temperatures on south-facing slopes compared to north-facing slopes. Temperatures measured on slopes with different aspects in Weatherley were compared to temperature data given from the Glen Cullen estate office. Temperature correction factors ($tmax_{adj}$, $tmin_{adj}$) were used for HRUs representing north-facing slopes (1.2) and south-facing (-1.5), while measured temperatures were derived and used for east- and west-facing slopes. Moreover, the monthly air temperature coefficient used in JENSEN & HAISE (1963) evapotranspiration computations was calculated as described in LEAVESLEY *et al.* (1983).

The system analysis indicates that solar radiation varies with respect to the time of the year, aspect and slope. The model considers such variations by the computation of the daily short wave radiation received on the slope-aspect combination of each HRU (Eq. 6.52). The daily potential solar radiation (pot_{sw}) of an HRU is expressed as a determinant of slope and aspect and requires an exposition parameter (rad_{asp}), a slope parameter (rad_{slope}) and latitude. Applying this formula to each HRU combination using mean slopes (%) and expositions (°), it was found (Table 7.22) that clear differences exist between north- and south oriented slopes in the Mooi basin, in particular regarding seasonal variations. Daily solar radiation pot_{SW} (Mean: 18.71 MJ m^{-2}) shows highest values (Max: 23.31 MJ m^{-2}) on moderate (5-15 %), north-facing slopes in summer months (Oct-Mar) and lowest (Min: 8.3 MJ m^{-2}) on steep (>15 %), south-facing slopes in winter (Apr-Sep). This is also reflected by annual variations showing highest values on moderate, north-facing slopes (18.25 MJ m^{-2}) and lowest on steep, south-facing slopes (13.43 1 MJ m^{-2}). These results confirm model results derived from measurements in

Weatherley showing a similar seasonal variability (Section 7.1.1.1) and assumptions by HERBERT (1997).

Table 7.22: Annual and seasonal variations of daily solar radiation (pot_{SW}) depending on aspect (°) and slope (%) classes used in all model runs. (Bold values indicate highest and lowest pot SW).

		N (0-45; 315-360)			E (45-135)			S (135-225)			W (225-315)		
		0-5	5-15	>15	0-5	5-15	>15	0-5	5-15	>15	0-5	5-15	>15
pot_{sw} [MJ m^{-2}]	Year	17.8	**18.2**	18.0	16.0	17.2	15.1	13. 6	14.3	**13.4**	15.8	16.6	152
	Oct-Mar	23.0	**23.3**	22.1	21.1	20.7	18.9	20.2	22.8	22.1	19.2	21.1	21,5
	Apr-Sep	13.6	14.0	14.2	13.2	14.8	11.2	9.80	10.5	**8.30**	10.8	14.3	12.1

7.3.2.1.2 Land Use Parameter Adjustment

As discussed in Sections 7.1 and 7.2, land use is a crucial parameter affecting interception storage. Interception is simulated as the proportion of rain that is stored in the vegetation canopy and litter, and thereby available for evapotranspiration. Thus, PRMS considers interception as a function of cover density which is seasonal ($covden_{sum}$ and $covden_{win}$) and the maximum interception storage depth on vegetation ($srain_{intcp}$, $wrain_{intcp}$ and $snow_{intcp}$) (Eq. 6.54 – 6.56). These values are set as half-year averages, whereas growth specific differences between vegetation and non-vegetation periods are defined. The maximum possible area contributing to surface runoff was estimated based on field observations and cover density estimations. In this study, cover densities and interception capacities for different land use types (Table 7.23) were set using average values derived from empirical observations (Section 7.1) and literature values (SCHULZE, 1997). Agricultural fields are considered as maize with a high cover density during summer and sparse grassland used for stock-farming during winter.

Table 7.23: Land use / land cover-related parameters used in all model runs sort by land use class.

Land use class	$covden_{sum}$	$covden_{win}$	$srain_{intcp}$	$wrain_{intcp}$	$snow_{intcp}$	$carea_{max}$
Agricultural fields	0.8	0.3	1.5	0.5	0.0	0.7
Indigenous forest*	0.9	0.9	5.5	5.5	10	0.5
Forest plantation*	0.7	0.7	4.0	4.0	7.0	0.7
Eucalyptus	0.6	0.6	2.5	2.5	3.0	0.7
Pine (2-5 yrs)	0.5	0.5	1.5	1.5	2.0	0.8
Pine (5-10 yrs)	0.85	0.85	5.0	5.0	8.0	0.4
Pine (5-15 yrs)	0.75	0.75	4.5	4.5	8.0	0.5
Pine (> 15 yrs)	0.7	0.7	3.5	3.5	6.0	0.6
Grassland	0.6	0.5	0.8	0.8	2.0	0.8
dense	0.9	0.8	2.0	2.0	3.0	0.6
medium	0.7	0.6	1.0	1.0	1.5	0.8
sparse	0.3	0.2	0.5	0.5	1.0	1
Plateau Wetland	0.65	0.5	0.5	0.5	1.5	1
Slope Wetland	0.8	0.7	1.5	1.5	2.0	1
Valley B. Wetland	0.9	0.8	2.5	2.5	4.0	1

**Stemflow is not considered as a substantial part of interception processes in PRMS. According to MICHL (1999) and WATSON (1999) who reviewed a number of forest hydrological studies, stemflow is also negligible in pine and eucalyptus forests, since its proportion at the net precipitation is less than 1%. Thus it is not relevant for model applications at this respective scale..*

Transmission coefficient for short-wave radiation through winter canopy (*rad*$_{trnfc}$) affects interception (Eq. 6.60) with *rad*$_{trnfc}$ being reduced with increasing cover density. Since snow accumulation is rarely expected, theses values were set to default 1.0 for all vegetation types.

7.3.2.1.3 Soil Parameters Adjustment

Soil moisture accounting in the active soil profile is determined by field capacities *soil*$_{moistmax}$ (for the average rooting depth of the active soil profile, lower zone) and *soil*$_{rechrmax}$ (for the upper soil layer, i.e. recharge zone). These two layers were averaged for each soil type found in the study area based on field-based profile descriptions. Field capacities for each layer were then provided combining data received by laboratory analysis of soil samples or from other soil studies (ESPREY, 1997; ROBERTS *et al.*, 1996). Table 7.24 summarizes the determined field capacities used for *soil*$_{moistmax}$ and *soil*$_{rechrmax}$.

Table 7.24: Soil-specific averaged values of available soil water used for soil layers (recharge zone, lower zone) in PRMS.

Soil Type	Parameter	Vegetation		
		Grassland/Wetland [mm]	Agricultural Field [mm]	Commercial Forest [mm]
Cambisol	*soil*$_{rechrmax}$	55	65	85
	soil$_{moiststor}$	120	140	160
Luvisol	*soil*$_{rechrmax}$	75	85	90
	soil$_{moiststor}$	160	160	160
Regosol	*soil*$_{rechrmax}$	35	---	45
	soil$_{moiststor}$	75		80
Stagnic Cambisol	*soil*$_{rechrmax}$	145	---	160
	soil$_{moiststor}$	230		230
Stagnic Luvisol	*soil*$_{rechrmax}$	155	---	---
	soil$_{moiststor}$	260		
Gleysol	*soil*$_{rechrmax}$	175	---	---
	soil$_{moiststor}$	375		

Groundwater recharge tends to be lowest on steeper slopes, since soil water exceeding field capacity on steep slopes generates rapid interflow (FLÜGEL, 1979). Hence, the field capacities were adjusted to different slope gradients. Adjustment factors listed in Table 7.25 were defined on a trial-and-error basis, i.e. those values were used which showed best fits between the volume and timing of observed and simulated runoff.

Table 7.25: Adjustment factors for field capacities with respect to slope gradients.

Parameter	Description	Slope [%]			
		0-2	2-5	5-15	> 15
soil$_{moistmax}$	maximum available water holding capacity of soil profile	1.025	1	0.75	0.5
soil$_{moistinit}$	initial value of available water in soil profile				
soil$_{rechrmax}$	maximum value of available water in the soil recharge zone				
soil$_{rechrinit}$	initial value of available water in the soil recharge zone				

7.3.2.1.4 Parameterization of Snow Processes

In areas where snow is accumulated in a certain period of the year, snow processes are considered as very important for evaporation and interception dynamics at catchment scale (LEAVESLEY *et al.*, 1983). Since snow accumulation is rarely observed for more than one or two days in the study area, relatively little attention has been given to the parameterization of snow process modules. Consequently, snow algorithms have been parameterized using default values given by the model.

7.3.2.1.5 Adjustment of Slope-specific Parameters

Many variables controlling flow generation processes are affected by slope gradients. As shown in the system analysis. For example, interflow rates increase proportional with increasing slope, while groundwater recharge decreases. To address the effect of slope on runoff generation processes, parameters and coefficients used in PRMS for runoff generation computation were adjusted with respect to slope classes. Table 7.26 summarizes the parameters and their adjustments sorted by slope classes.

With respect to the values shown in Table 7.26, the following assumptions were made:

- Linear and non-linear routing coefficients controlling subsurface flow ($ssrcoeff_{lin}$, $ssrcoeff_{sq}$) are strongly related to the slope gradient, i.e. subsurface flow increases with increasing slopes.
- Initial storages for each subsurface reservoir ($ssstor_{init}$) and groundwater reservoir ($gwstor_{init}$) was estimated based on field capacities observed for different slope gradients and advises given by LEAVESLEY (2004, pers. comm.).
- Inflow from the subsurface to the groundwater reservoir controlled by parameters $ssr2gw_{max}$ and $ssr2gw_{rate}$ was defined as a function of slope, i.e. inflow is decreasing from flat terrain (0-2 %) to low and moderate slopes (2-15 %). It is also indicated that the subsurface reservoir is not directly linked to the groundwater reservoir on steep slopes, so that no recharge to groundwater reservoir is generated on slopes steeper than 15 %, i.e. only surface flow and interflow is generated on steep slopes. Consequently, the groundwater reservoir on steeper slopes is only assessed by inflow from upslope groundwater reservoirs.
- Groundwater discharge rate ($gwflow_{coef}$) is described as a linear function following the hydraulic gradient, i.e. groundwater discharge is higher on steep slopes than in flat areas.
- Groundwater sink ($gwsink_{coeff}$) was defined on flat and moderate terrain taking the fraction of the sandstone into account.
- Surface runoff is strongly controlled by surface properties and infiltration capacities of a specific HRU. It is also expressed as a non-linear function of antecedent soil moisture that itself is variable depending on slope position. Addressing the variability of soil moisture on slopes (e.g. formation of wet zones at the toeslope or saturation in depressions), parameters affecting surface runoff generation ($smidx_{coef}$, $smidx_{exp}$) were defined with respect to slope classes, i.e. values decrease when slope gradient increases. In addition, the $smidx_{coef}$, and $smidx_{exp}$ were multiplied by factor

1.3 in wetland areas, since these areas are assumed to provide surface runoff, once they are saturated.

Table 7.26: Adjustment of parameters affecting runoff generation and groundwater dynamics with respect to slope gradients.

Parameter	Description	Slope [%]			
		0-2	2-5	5-15	> 15
$ssrcoeff_{lin}$	linear subsurface routing coefficient to route subsurface storage to streamflow	0.01	0.1	0.25	0.5
$ssrcoeff_{sq}$	non-linear subsurface routing coefficient to route subsurface storage to streamflow	0	0.025	0.5	0.1
$sstor_{init}$	initial storage for each subsurface reservoir which is estimated based on observed flow	0.3	0.2	0.1	0.01
$ssr2gw_{exp}$	coefficient to route water from subsurface to groundwater	1	1	1	1
$ssr2gw_{rare}$	coefficient to route water from subsurface to groundwater	0.03	0.01	0.005	0.0
$\mathrm{ssr2gw_{max}}$	maximum value for water routed from subsurface to groundwater	1	1	1	1
$gwflow_{coeff}$	groundwater routing coefficient to obtain groundwater flow contribution to streamflow	0.0015	0.005	0.01	0.02
$gwsink_{coeff}$	groundwater sink coefficient to compute the seepage from each reservoir to a groundwater sink	0.001	0.001	0	0
$gwstor_{init}$	storage in each groundwater reservoir at beginning of run	0.3	0.2	0.1	0.01
$smidx_{coef}$	coefficient in non-linear contributing area algorithm	0.8	0.2	0.1	0.1
$smidx_{exp}$	exponent in non-linear contributing area algorithm	0.8	0.4	0.2	0.1

7.3.2.1.6 Model Optimization

After initial calibration of each model scenario, internal optimization tools based on the approach introduced by ROSENBROCK (1960) were examined in order to improve model performance. The approach allows the user to set minimum and maximum thresholds for selected parameters. Comparing daily differences between simulated and observed runoff volumes, the algorithm computes the optimized parameter value iteratively. A detailed description of the algorithm is given by LEAVESLEY *et al.* (1983).

In this study, the majority of parameter was derived from empirical observations or the literature. Hence, little focus was on optimizing measured parameters, because particular processing has been performed as described in the previous sections. In contrast, little knowledge was available on the model coefficients used to compute potential evaporation. Thus, monthly air temperature coefficient (jh_{month_coef}) and HRU-related coefficient (jh_{coef}) were explored within the optimization procedure. From this effort, the initial monthly air temperature coefficient (jh_{month_coef}) reflecting the monthly variation in the JENSEN & HAISE formula (1963) was optimized using an adjustment factor of 1.6 for the summer months (December – February) and 1.3 for the transition time (October – November and March – April). The coefficient jh_{coef} was optimized with respect to land use of each HRU. Dense vegetated areas (forests, dense grassland, wetlands) received higher values in the range of 17 and 18 than sparse vegetated areas varying between 13 and 15.

7.3.2.2 Modeling of the Mooi River Basin

For modeling the Mooi catchment (307 km²), climate input data were available for the period between 1980 and 2002. With respect to the beginning of afforestation, two scenarios were defined in order to simulate the hydrological dynamics prior to and after afforestation by splitting the period in 1993, i.e. before the canopy of the forest plantations was closed. The two scenarios were calibrated and validated by individual time series as described below.

7.3.2.2.1 Modeling of Pre-Afforestation Conditions

Initially, the model was calibrated to evaluate initial conditions of key parameters such as soil moisture and storage in the subsurface and groundwater reservoirs using the basic parameter set described above. Although data were available from 1980, the period 1988 - 1990 was chosen for calibration for two reasons:

- Regarding long-term rainfall dynamics identified in the system analysis (Section 7.2.1.1), notable forest growth affecting hydrology started at the beginning of a rather wet period in 1994. To compare model performance and to reduce effects caused by climatic trends, it was decided to choose a wet period for the calibration as well. While the period from 1980 – 1987 was relatively dry, only the period from 1988-1990 fulfilled required conditions.
- Little knowledge was available about farm and land management in the early 80s. The calibration period was chosen as closely as possible to the first field survey in 1997 which provided reliable information on land management (by farmer interviews) at least for the past 10 years.

The model results for the calibration period after optimization are shown in Figure 7.51 resulting from an input data set of 70 HRUs. The graph shows the mean precipitation of the catchment, simulated (red) and observed (blue) runoff and the differences between simulated and observed runoff. The model was able to capture the overall hydrological runoff dynamics of the basin and simulated the time and the volume reasonably well. It predicts both high flow conditions usually resulting from stormflows during the rain season and low flow conditions during winter time resulting from the wetland drainage accurately. Stormflow peaks above the baseflow were generally predicted at correct times and with correct magnitudes for the rain season in 1990, with the exception of extreme runoff peaks occurring when heavy rains generate rapid surface flow and interflow after a longer dry period. The obvious underprediction of runoff for the wet season of 1990 is assumed to be a result of insufficient recharge to fill the groundwater and subsurface reservoirs and to sustain baseflow.

The visual interpretation of the difference plot indicates that the proportion of overpredicted and underpredicted and runoff volumes is relatively balanced. The daily average difference (AvgDiff) is - 0.45 $m^3 s^{-1}$ for the entire period.

As shown in Table 7.27 statistical measures of the accuracy of simulated streamflow confirm satisfying model results for the calibration period. For accuracy assessment, relative volume error in percent (RVE) was selected as the measure of prediction error. The coefficient of efficiency Eff [Q] introduced by NASH & SUTCLIFFE (1970) was examined as a measure of the overall quality of model fit, with a value of 1 representing a perfect fit. The coefficient of efficiency is a widely used measure, which is analogous to the coefficient of multiple determination, r^2, used in regression analysis (LEAVESLEY *et al.*, 1983). When evaluating statistical measures given in Table 7.27 it is shown that runoff in dry seasons, i.e. low flow conditions, is significantly better simulated than in wet seasons or for the entire period. This is caused by the very low runoff values at this time of the year which were reasonably predicted by the model. The RVE values confirm that the model slightly underestimates runoff in 1989, but is still satisfying over the entire period.

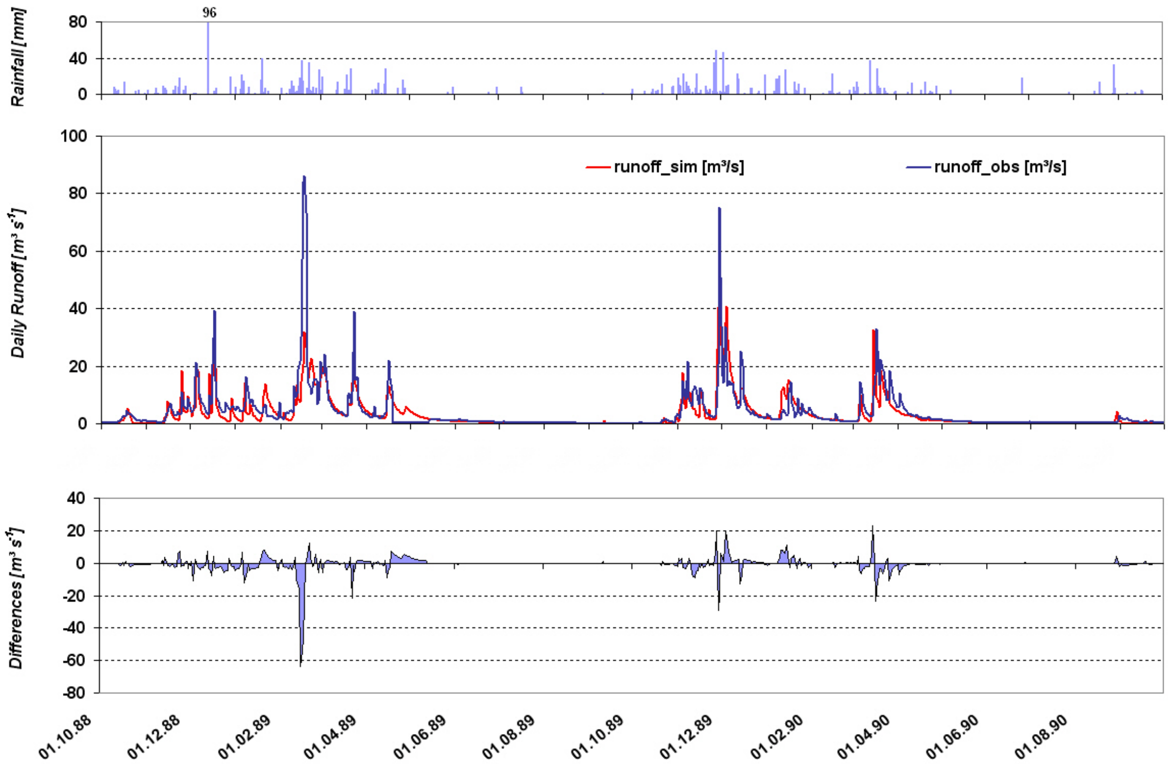


Figure 7.51: Model results for the calibration period (Hydrological Years: 1989 and 1990) obtained from the Mooi River watershed with grassland as dominant land use. The upper graph shows daily precipitation, the middle graph the observed (blue) and simulated (red) runoff, and the lower plot shows the differences between observed and simulated runoff.

Table 7.27: Errors in simulated daily streamflow for the calibration period (Hydrological Years: 1989 and 1990) obtained from the Mooi River watershed with grassland as dominant land use.

Year	Hydrological Year (Oct-Sep)		Dry season (Apr-Sep)		Rain season (Oct-Mar)	
	RVE [%]	Eff [Q]	RVE [%]	Eff [Q]	RVE [%]	Eff [Q]
1989	-11.3	0.81	-1.7	0.92	-14.1	0.74
1990	-4.3	0.84	-1.9	0.95	-3.7	0.84
Total	**-2.0**	**0.82**	**-1.8**	**0.93**	**-8.9**	**0.79**

RVE … relative volume error [%]; Eff [Q] … Coefficient of efficiency (NASH & SUTCLIFFE, 1970)

While the model was calibrated to obtain the best fit to the calibration period data, the validation results represent an independent assessment of model performance. Hence, the model was validated for the periods 1980 - 1988 and from 1990 – 1993. Figure 7.52 illustrates model results for the validation period 1990 – 1993, while Table 7.28 lists error measures for the entire validation period.

Comparing observed and simulated hydrographs visually, the model performance was basically satisfying and thereby similar to the model run for calibration (AvgDiff: -0.28 $m^3 s^{-1}$) with similar pattern of uncertainty. However, the model runoff seemed somewhat less accurate concerning predicted runoff volumes and peak flow timing. This is mainly related to the relatively low rainfall volumes and intensities over the entire period, in particular for 1991 and 1993. These under- and overestimation for the peaks are not entirely caused to the modeling errors. They also may be a result of data errors and the neglecting spatial distribution of rainfall. Similar results were found for the validation period from 1980 – 1988 as shown in table 7.28.

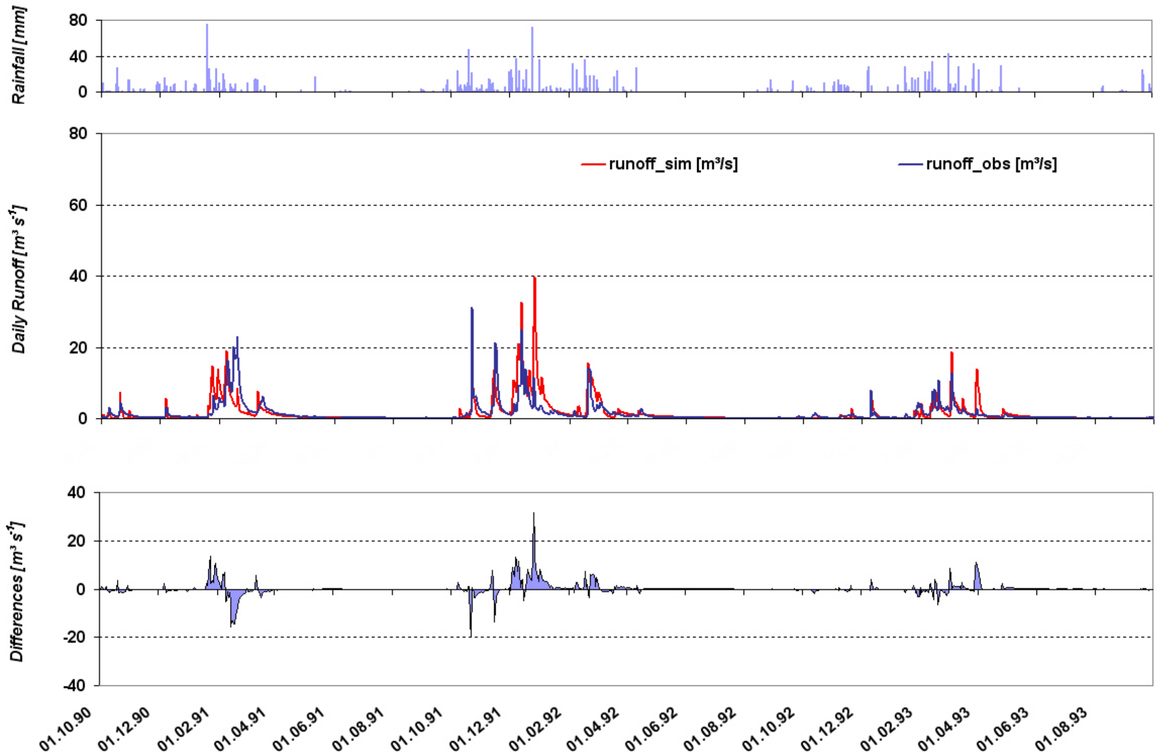


Figure 7.52: Model results for the validation period (Hydrological Years: 1991 - 1993) obtained from the Mooi River watershed with grassland as dominant land use. The upper graph shows daily precipitation, the middle graph the observed (blue) and simulated (red) runoff, and the lower plot shows the differences between observed and simulated runoff.

Simulation errors (Table 7.28) for the period 1991 – 1993 were greater than for the calibration model run that was mainly caused by the overprediction of the runoff during the wet season. This is also shown by the higher volume errors. Nevertheless, it was confirmed that better results were obtained for dry seasons simulations.

Table 7.28: Errors in simulated daily streamflow for all validation periods (Hydrological Years: 1980 – 1988; 1991- 1993) obtained from the Mooi River watershed with grassland as dominant land use.

Year	Hydrological Year (Oct-Sep)		Dry season (Apr-Sep)		Rain season (Oct-Mar)	
	RVE [%]	Eff [Q]	RVE [%]	Eff [Q]	RVE [%]	Eff [Q]
1980	1.4	0.90	0.2	0.92	1.2	0.84
1981	0.4	0.91	-1.2	0.94	1.8	0.89
1982	2.8	0.89	-0.3	0.97	4.1	0.82
1983	-3.2	0.84	-1.2	0.90	-4.0	0.78
1984	-11.2	0.68	-0.7	0.86	-15.9	0.62
1985	-12.1	0.51	-4.5	0.78	-16.6	0.46
1986	-6.0	0.77	-1.0	0.89	-8.4	0.73
1987	-4.7	0.82	2.3	0.92	-9.0	0.80
1988	-9.4	0.81	1.9	0.89	-8.5	0.78
1991	-5.3	0.76	-2.1	0.95	-8.1	0.74
1992	13,2	0.71	1,2	0.90	21,6	0.69
1993	3.3	0.79	1,1	0.87	5.7	0.79
Total	**-2.6**	**0.78**	**-0.4**	**0.90**	**-4.6**	**0.74**

RVE … relative volume error [%]; Eff [Q] … Coefficient of efficiency (NASH & SUTCLIFFE, 1970)

7.3.2.2.2 Modeling of Afforestation Conditions

PRMS is not able to simulate forest growth over rotation. For the present study, forest stands are considered as being 10 to 15 years old. Assuming best growth conditions and closed canopies for the individual species, the model was calibrated with the highest values for parameters cover density (*covden*) and rain interception ($srain_{intcp}$, $wrain_{intcp}$) and lowest for the maximum area contributing to surface runoff generation (c*areamac*).

To model the forest scenario, calibration was performed for the hydrological years 1996 and 1997 in order to make sure that canopies are closed in most forest plantations. The HRU data set derived comprised 66 HRUs. As shown in Figure 7.53, the model simulated timing and volumes of runoff reasonably well (AvgDiff: - 0.17 $m^3 s^{-1}$). The visual interpretation of the difference plot indicates that runoff was generally underpredicted. This is confirmed by the statistical measures summarized in Table 7.29. This underprediction over the entire period is caused by the underestimation of most stormpeaks.

The recession of the curve drops down earlier than at the observed hydrograph, in particular after heavy rains. This may be caused by surface and subsurface flow that is generated at the slopes and passes the wetland too fast. Alternatively, the incomplete closing of forest canopy in some of the forest areas could explain this phenomenon.

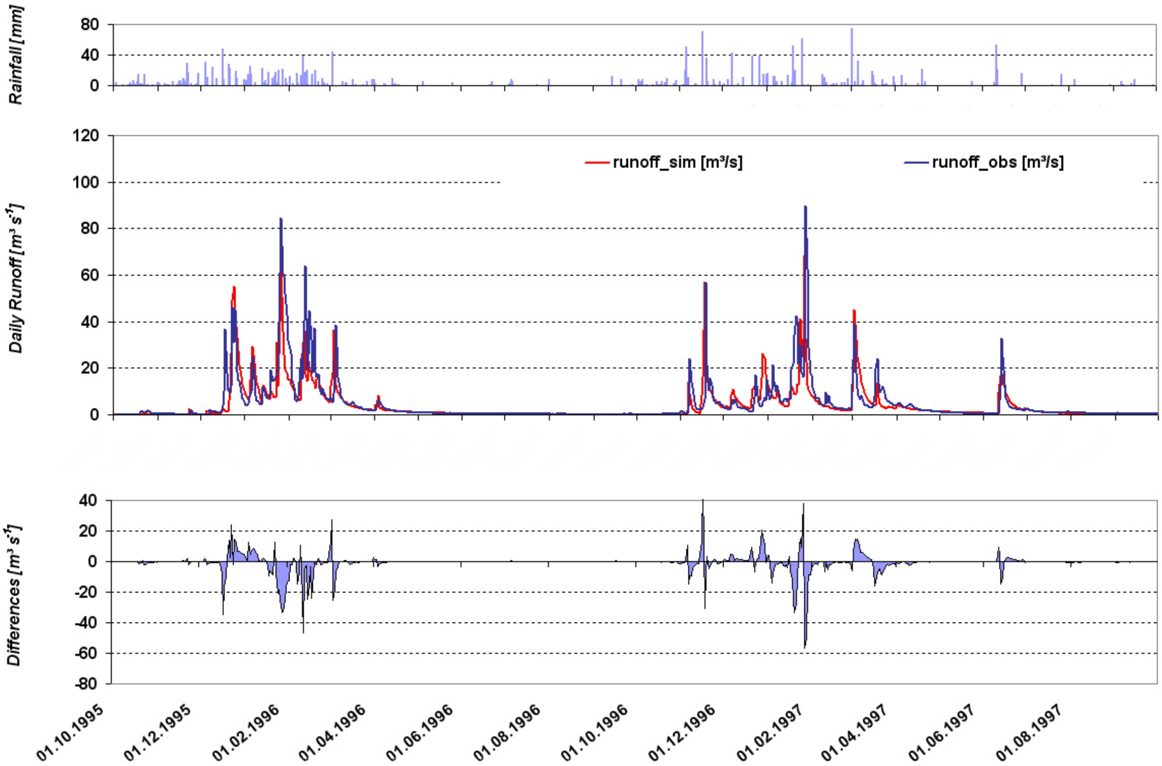


Figure 7.53: Model results for the calibration period (Hydrological Years: 1996 and 1997) obtained from the Mooi River watershed with grassland and forest plantations as dominant land use. The upper graph shows daily precipitation, the middle graph the observed (blue) and simulated (red) runoff, and the lower plot shows the differences between observed and simulated runoff.

Table 7.29: Errors in simulated daily streamflow for the calibration period (Hydrological Years: 1996 and 1997) obtained from the Mooi River watershed with grassland and forest plantations as dominant land uses.

	Hydrological Year (Oct-Sep)		Dry season (Apr-Sep)		Rain season (Oct-Mar)	
Year	**RVE [%]**	**Eff [Q]**	**RVE [%]**	**Eff [Q]**	**RVE [%]**	**Eff [Q]**
1994	-3.1	0.83	-0.4	0.89	-3.1	0.78
1995	-1.2	0.88	0.3	0.95	-2.1	0.86
1996	-13,8	0.83	0.4	0.94	-13.1	0.79
1997	-3.3	0.81	-0.9	0.91	-2.2	0.80
Total	**-5.3**	**0.84**	**-0.2**	**0.92**	**-5.1**	**0.81**

RVE … relative volume error[%]; Eff [Q] … Coefficient of efficiency (NASH & SUTCLIFFE, 1970)

Validation was performed with the time series of the remaining years, i.e. the hydrological years 1998-2001. The model results of the validation period (Figure 7.54) and accuracy measures (Table 7.30) confirm the reliability of the model, since both intra- and inter-annual variations in flow were accurately predicted (AvgDiff: -0.44 $m^3 s^{-1}$). The overall accuracy is in the same range as assessed for the calibration period.

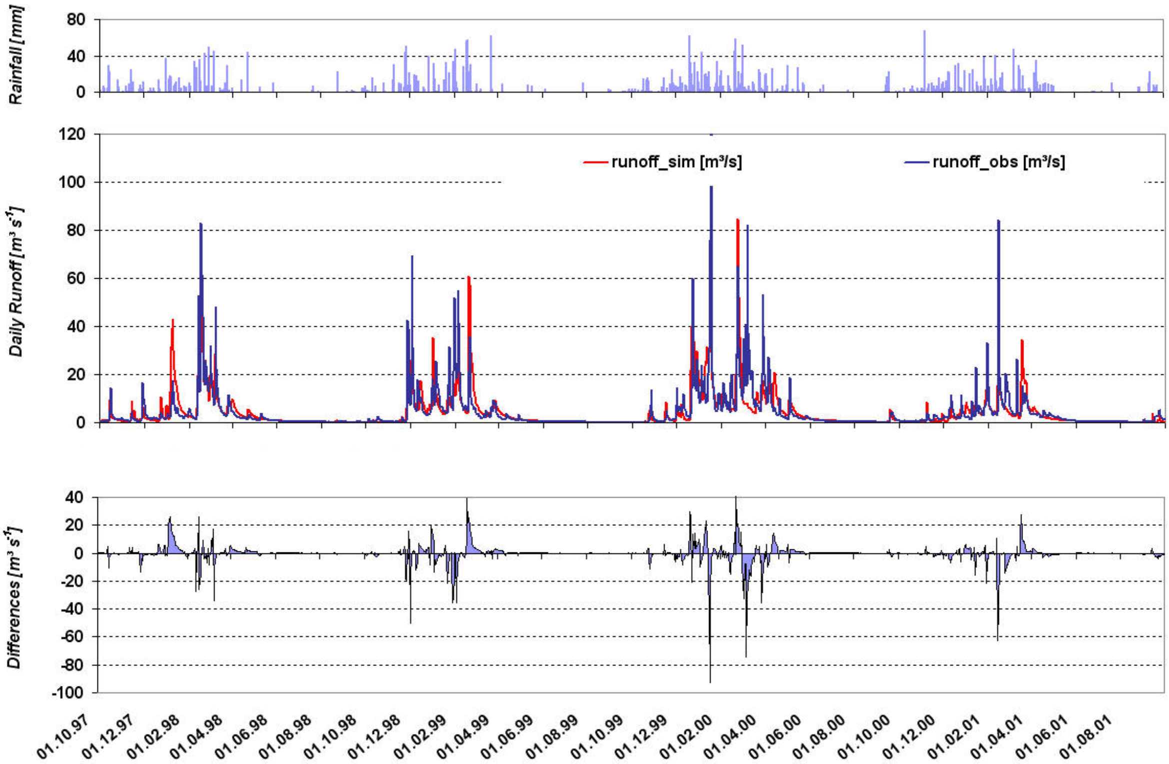


Figure 7.54: Model results for the validation period (Hydrological Years: 1998, 1999, 2000 and 2001) obtained from the Mooi River watershed with grassland and forest plantations as dominant land use. The upper graph shows daily precipitation, the middle graph the observed (blue) and simulated (red) runoff, and the lower plot shows the differences between observed and simulated runoff.

Table 7.30: Errors in simulated daily streamflow for the validation period (Hydrological Years: 1998, 1999, 2000 and 2001) obtained from the Mooi River watershed with grassland and forest plantations as dominant land uses.

Year	Hydrological Year (Oct-Sep)		Dry season (Apr-Sep)		Rain season (Oct-Mar)	
	RVE [%]	Eff [Q]	RVE [%]	Eff [Q]	RVE [%]	Eff [Q]
1998	-6.3	0.73	-1.2	0.88	-4.1	0.72
1999	-3.2	0.89	-1.7	0.91	-4.8	0.84
2000	-6.0	0.87	-0.3	0.96	-4.3	0.86
2001	2.4	0.82	-0.6	0.87	2.7	0.81
Total	**-3.3**	**0.83**	**-1.0**	**0.90**	**-2.6**	**0.81**

RVE … relative volume error [%]; Eff [Q] … Coefficient of efficiency (NASH & SUTCLIFFE, 1970)

Finally, both models were applied to simulate hydrological dynamics for the entire period. The pre-afforestation phase was simulated using data from 1980 – 1993, while afforestation was simulated with data from 1994 – 2001. The combined model results are illustrated in Figure 7.55 showing observed rainfall with predicted evapotranspiration, storage and observed and predicted runoff. The total volumes and some basic statistic measures are given in Table 7.31.

In general, evapotranspiration follows the rainfall tendency, i.e. the more rain is observed the more water transpires with the evapotranspiration never exceeding 636 mm. With the exception of 1980, 1987, 1988 and 2000, storage is always in the range of 30 and 50 mm. While the highest increase of rainfall within the non-afforestation time caused an increase of water storage in the basin, a similar effect was not predicted for the time after planting.

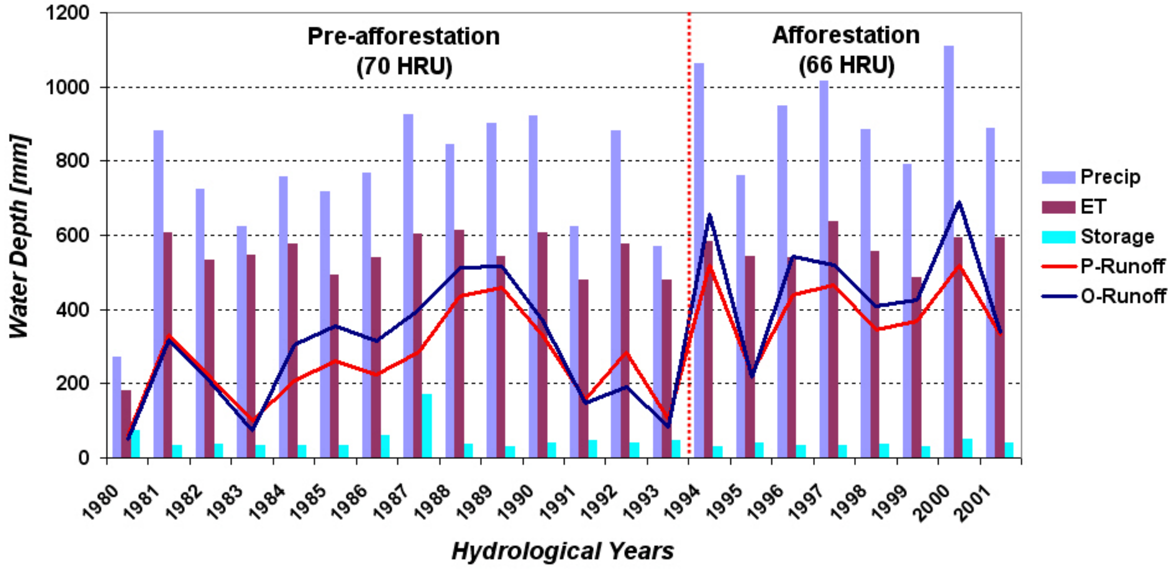


Figure 7.55: Model results of major hydrological water budget components (in mm) for the entire period from 1980 – 2001(hydrological years) obtained from the Mooi River watershed. The graph combines the results received for the entire periods before and after afforestation using the calibrated models separately.

Precip … annual precipitation; ET … annual evapotranspiration; P-Runoff … predicted runoff; O-Runoff … observed runoff

Table 7.31: Model results of major hydrological water budget components and statistical measures for the entire period from 1980 – 2001(hydrological years) obtained from the Mooi River watershed.

Year	P [mm]	ET [mm]	Stor [mm]	Q_{sim} [mm]	O_{obs} [mm]	Year	P [mm]	ET [mm]	Stor [mm]	Q_{sim} [mm]	O_{obs} [mm]
1980	271	181	73	61	52	**1991**	623	480	46	157	147
1981	881	608	34	333	318	**1992**	881	575	40	285	193
1982	726	534	36	213	202	**1993**	570	481	47	103	85
1983	622	546	35	99	73	**1994**	1064	582	30	519	655
1984	758	576	33	207	306	**1995**	761	543	40	229	218
1985	717	493	34	263	355	**1996**	949	538	34	437	542
1986	768	540	59	224	314	**1997**	1017	636	33	466	521
1987	925	604	172	284	399	**1998**	884	557	36	345	408
1988	844	614	38	436	513	**1999**	791	487	30	369	426
1989	903	542	31	458	518	**2000**	1110	592	52	520	692
1990	921	607	39	329	368	**2001**	887	593	40	331	338
						Mean	812	541	46	303	347
						Min	271	181	30	61	52
						Max	1110	636	172	520	692
						Med	862	551	37	307	346
						Std	184	92	30	135	181

P … Precipitation ; ET … Evapotranspiration ; Stor … Storage ; Q_{sim} … Predicted runoff ; Q_{obs} … Observed runoff; Mean … Average; Min … Minimum, Max … Maximum; Med … Median; Std … Standard deviation

Since highest rainfall and runoff volumes of the entire period were observed after afforestation started, it is assumed that the forest prevents recharge of the basin reservoirs up to their maximum storage capacity (which is at least 172 mm as predicted for 1987). Further, it is demonstrated that runoff generally shows the same tendency as rainfall, i.e. increasing rainfall causes runoff increase, with the exception of 1986, 1997 and 1999. Comparing the annual runoff it is indicate that the model generally represents the inter-annual trend, but slightly underpredicts runoff with the exception of 1980 – 1984 and 1991 – 1993, when runoff is slightly overpredicted. This seems to be more related to dry years when the year before was significantly wetter.

To evaluate the overall performance of the model, annual volumes of observed runoff were plotted against predicted annual volumes (Figure 7.56). It is shown that both variables show a significant correlation (r^2=0.92), confirming the reliability of the model applications. Compared to the 1:1 line, it is shown that predicted annual runoff tends to be more underpredicted when observed runoff volumes increase. However, the slope of the regression line of 0.71 quantifies the overall drift for underestimating predicted runoff volumes.

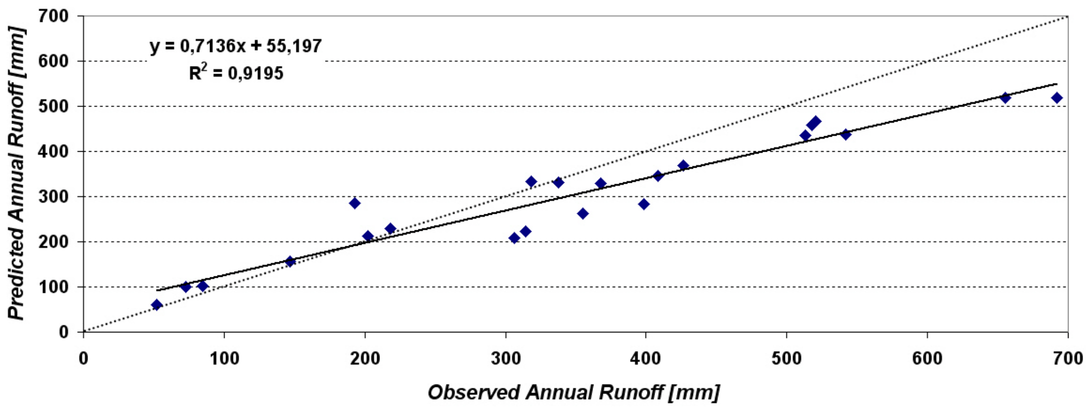


Figure 7.56: Annual volumes of observed runoff against annual volumes of predicted runoff for the entire simulation period. (All volumes are in mm)

Summarizing modeling efforts that were conducted for the Mooi basin, the following conclusions can be made:

- The model applications have shown that both pre-afforestation and afforestation conditions were sufficiently simulated showing Nash– Sutcliffe coefficients of efficiency in the range of 0.77 and 0.84. Intra- and inter-annual dynamics are well reflected in the model performance.
- Comparing relative volume errors of each model run based on daily data it is shown that the model generally tends to underpredict runoff. This was confirmed through the comparison of annual total runoffs. As emphasized by Beven (2001), models tend to underestimate runoff continuously when either rainfall data are continuously too low or the evapotranspiration processes are overpredicted. Since underpredictions were identified for all model runs, they seemed to be independently from land use conditions. Such underpredictions are obviously more significant during the rain season. Thus, measured rainfall

values maybe subject to systematic measurement errors, in particular during heavy rainfall events.

- Both models representing conditions prior and after afforestation were able to simulate the timing of the stormpeaks during the rain season accurately with a mismatch for the volume for several events. This also can be attributed to rainfall data inconsistencies.
- For many events it was found that simulated stormpeaks receive faster recession than the observations. As discussed above, rapid pipeflows and lateral subsurface flow occur on slopes during heavy rainfalls, but access the river with a delay of 1-2 days. It is assumed that these dynamics were not accurately matched by the model. Rapid surface runoff is simulated instead of pipeflow causing the steep recession of the hydrograph.
- In general, the prediction of low flow during the dry season was accurately performed in all model runs. This, of course, is related to the low rainfall inputs during this time. Nevertheless, it also reveals that the storage dynamics of the subsurface reservoirs which generated the baseflow were well parameterized.

7.3.2.3 Modeling of the Weatherley Creek Basin

Only a limited hydro-meteorological data set ranging from 1998-2001 (hydrological years) was available from observations in the experimental catchment Weatherley (1.4 km^2). Because the afforestation started in 2002, the entire data set was initially used for modeling the hydrological system for grassland representing pre-afforestation conditions. To evaluate forest impact on wetland and basin water budgets, those areas which were planted in 2002 were extracted from the forest data base to be considered for the HRU delineation.

7.3.2.3.1 Modeling of Pre-Afforestation Conditions

Because of sparse climate input data, only the hydrological year 1999 was chosen for model calibration using an HRU data set with 25 HRUs. The model results shown in Figure 7.57 and statistic accuracy measures (Table 7.32) indicate that the discharge of the Weatherley Creek is reproduced with sufficient accuracy and a NASH-SUTCLIFFE model efficiency of 0.80.

Stormflows were widely predicted at the correct times. During extreme rainfall events the simulated volume of runoff is generally lower than the observed, except after drier periods when predicted volumes are higher than observed ones. This is caused by the generation of surface and subsurface runoff instead of filling the wetland storage. Similar to the results of Mooi catchment modeling, hydrographs tend to show a steeper recession after heavy rainfall events. This is related to the insufficient simulation of subsurface flow dynamics. Runoff data exhibit more or less constant base flows during the dry season. The difference plot indicates that the relation of simulated and observed runoffs is well-balanced on an annual base.

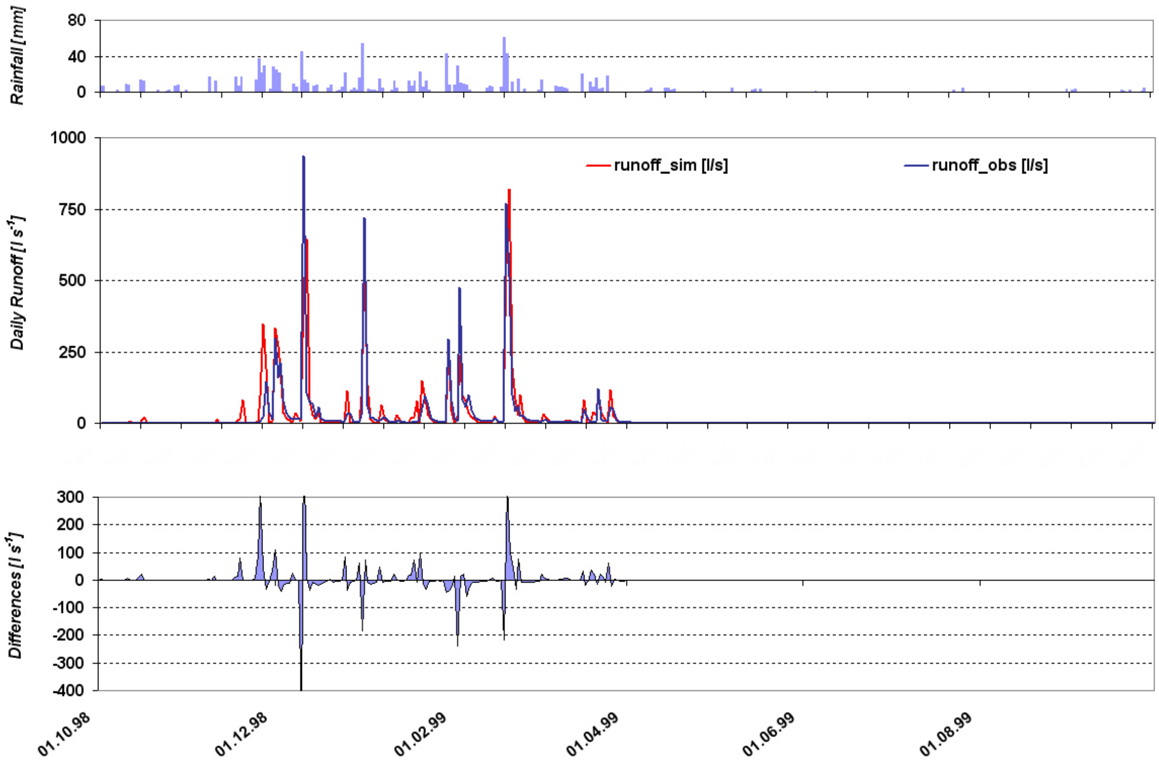


Figure 7.57: Model results for the calibration period (Hydrological Year: 1999) obtained from the Weatherley Creek watershed with grassland as dominant land use. The upper graph shows daily precipitation, the middle graph the observed (blue) and simulated (red) runoff, and the lower plot shows the differences between observed and simulated runoff.

Table 7.32: Errors in simulated daily streamflow for the calibration period (Hydrological Year: 1999) obtained from the Weatherley Creek watershed with grassland as dominant land use.

	Hydrological Year (Oct-Sep)		Dry season (Apr-Sep)		Rain season (Oct-Mar)	
Year	**RVE [%]**	**Eff [Q]**	**RVE [%]**	**Eff [Q]**	**RVE [%]**	**Eff [Q]**
1999	**-2.2**	**0.80**	**-0.2**	**0.98**	**-1.7**	**0.79**

RVE … relative volume error [%]; Eff [Q] … Coefficient of efficiency (NASH & SUTCLIFFE, 1970)

The model was validated using the data for the hydrological years 2000 and 2001. Evaluating the graphs (Figure 7.56) and error measures (Table 7.33) it is shown, that the validation period is slightly better simulated than the calibration period. The timing of most peaks is simulated with reasonable accuracy and the base flow is quite accurately reproduced. A number of runoff events in January and March 2000 are overpredicted. This is because the wetland storage is filled and the model simulates surface runoff generated on the slopes crossing the wetland rapidly towards to contribute to the streamflow. Significant discrepancies were found in December 2000 and January 2001. Low runoff volumes were recorded at these times. Examining the observed data, runoff volumes are notably lower compared to others during similar events. Thus, runoff data from the upper weir in Weatherley were used for evaluation. Since significant differences were found regarding the measured runoff volumes, it is concluded that runoff measurement equipment failed at the lower weir during this period and thereby provided unreliable values. Hence, these records were excluded from error computation and assessment.

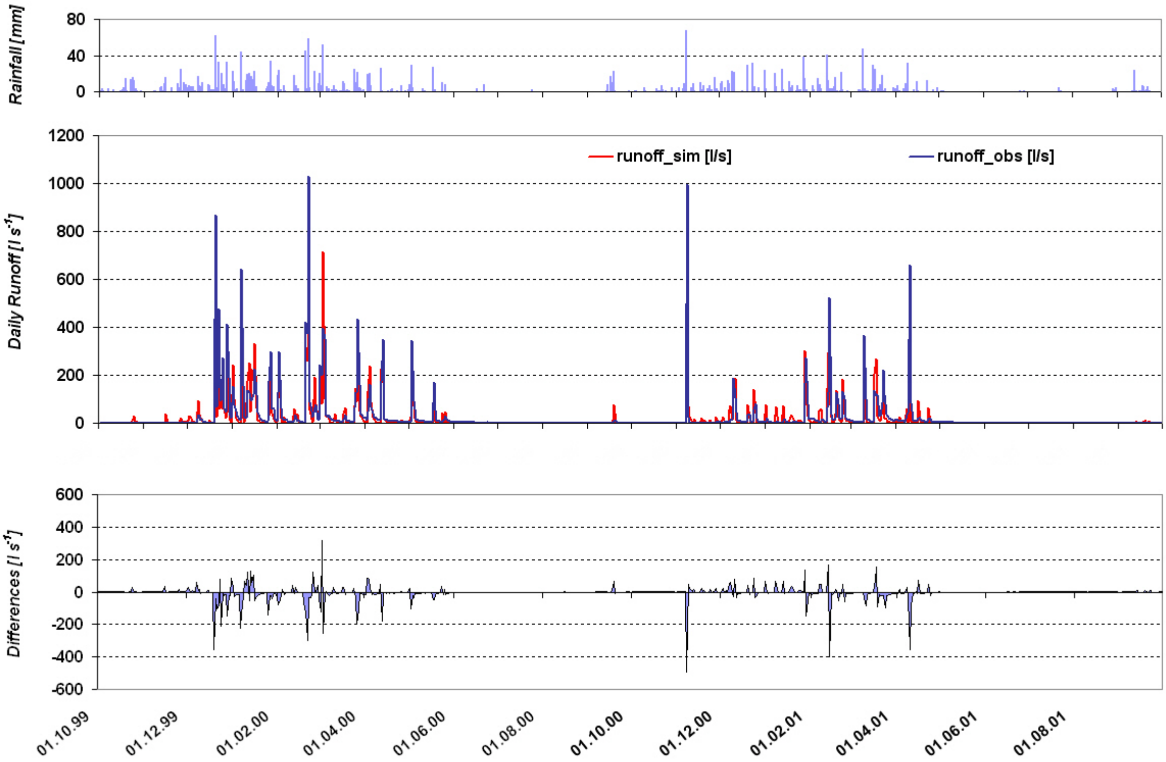


Figure 7.58: Model results for the validation period (Hydrological Year: 2000 and 2001) obtained from the Weatherley Creek watershed with grassland as dominant land use. The upper graph shows daily precipitation, the middle graph the observed (blue) and simulated (red) runoff, and the lower plot shows the differences between observed and simulated runoff.

Table 7.33: Errors in simulated daily streamflow for the validation period (Hydrological Year: 2000 and 2001) obtained from the Weatherley Creek watershed with grassland as dominant land uses.

	Hydrological Year (Oct-Sep)		Dry season (Apr-Sep)		Rain season (Oct-Mar)	
Year	**RVE [%]**	**Eff [Q]**	**RVE [%]**	**Eff [Q]**	**RVE [%]**	**Eff [Q]**
2000	-9.1	0.86	-3.9	0.91	-12.1	0.88
2001	2.7	0.82	1,3	0.94	5.7	0.78
Total	**-3.2**	**0.84**	**-1.3**	**0.92**	**-3.2**	**0.83**

RVE … relative volume error [%]; Eff [Q] … Coefficient of efficiency (NASH & SUTCLIFFE, 1970)

7.3.2.3.2 Impact of Afforestation on Catchment and Wetland Dynamics

An afforestation scenario was performed for Weatherley to simulate the impact of forest plantations on water balance and wetland dynamics. Modeling parameters characterizing 15 years old forest stands in best condition were taken from the Mooi model and transposed to the Weatherley model to parameterize those HRUs which were assumed to be planted. The number of HRU classes increased to 31 when planted areas

(35 % of the catchment) were considered. The model was applied to the entire period 1998 – 2001. Figure 7.59 shows the hydrograph of observed runoff against predicted runoff under afforestation with the parameter set applied to the Mooi model. Since a hypothetical land use was simulated with runoff data measured under grassland conditions, efficiencies statistics were not performed.

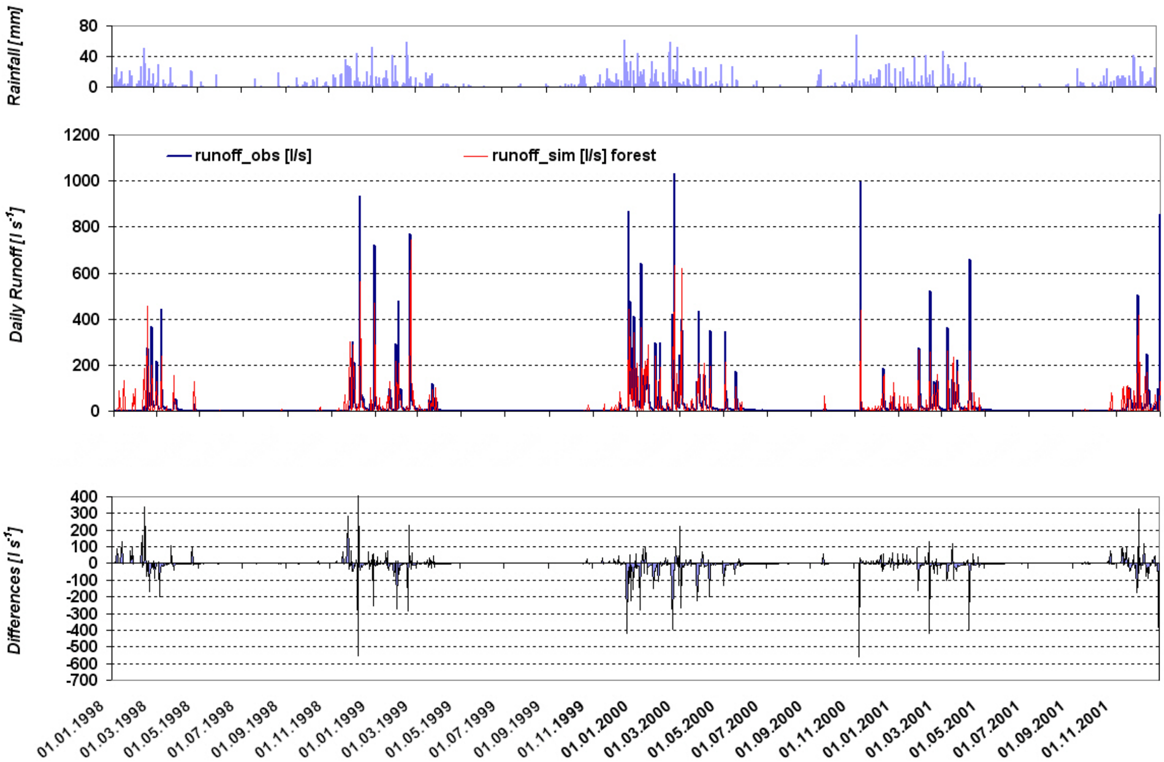


Figure 7.59: Model results received from the modeling of Weatherley with forest plantations (1998-2001). The upper graph shows daily precipitation, the middle graph the observed (blue) and simulated (red) runoff, and the lower plot shows the differences between observed and simulated runoff.

The hydrograph and the difference plot demonstrate that the intra- and inter-annual dynamic of the runoff was predicted accurately. As expected, the runoff peaks are significantly underpredicted indicating a clear reduction of stormflow peaks by the forest plantations. The difference also indicates lower runoff volumes than measured.

Table 7.34 summarizes annual observed runoff (Q_{obs}) compared to simulated runoff (Q_{sim}) under afforestation for the period from 1998-2001. The ΔQ value describes the percentage of annual total water loss as the difference between Q_{obs} and Q_{sim}. As a result it was found that lower runoffs were simulated for all years. Excluding values for 1998, when the weir was installed and calibrated, the results indicate that available water will be significantly reduced by forest plantations by amounts ranging from 13.5 % to 21.5 %. Although this loss seems to be very high, the comparison with findings from other forested catchments in South Africa showed, that this reduction is clearly lower than a decrease of 300-380 mm (VAN LILL *et al.*, 1980) up to 440 mm (BOSCH, 1979). As shown for the period from 1999 to 2001 (Table 7.34), this reduction will be in the range of 8.1 to 9.5 % of the total precipitation (ΔQ_{Prec}). As it was found by water use simulations for optimal growths of pine stands using 3-PG, about 90 % of the annual rainfall in pine stands (23 % of the basin) is transpired by pine trees. Thus, it is hypothesized, that enough water is available for tree growth, but it also reveals that optimal tree growth will reduce runoff significantly, i.e. about 25 % of the annual rainfall will only be used by the pine plantations. As shown by SCOTT & LESCH (1997), eucalyptus trees (12 % of the basin) will intensify this effect.

When examining the flow reduction seasonally, it was found that the percentage decline in low flow during dry season (48 %) was actually greater than in annual flow (17.5 %). This confirms results from other studies (SMAKHTIN *et al.*, 1997; SCOTT & SMITH, 1997) who identified a similar behavior in other catchments. Further this runoff decrease during dry seasons will lead to sporadic dry-outs of the creek, which was already observed during field survey in 2005.

However, flow components were analyzed separately to evaluate afforestation impacts on water flow dynamics. Table 7.34 shows the percentage of annual water loss for each flow component. These results indicate that subsurface flow (*SSF*) will be more affected then surface (*ΔSF*) and groundwater flow (*ΔGWF*). Taking into account, that the model generally tends to underpredict runoff, only subsurface flow is considered to face significant changes of runoff volumes varying in the range of 11.1 to 18.3 % compared to the measured ones. Therefore, less water is available for infiltration due to higher evapotranspiration and interception rates of forest stands that are mainly situated on hillslopes. Additionally, the rapid vertical water movement observed on hillslopes after heavy rainfalls will be reduced as a result of higher cover densities. As a consequence, interflow and rapid macro-pore flow will decrease. In addition, soil water inflowing from non-planted upslope areas will be taken up by the trees instead of supporting interflow. With the exception of perched groundwater on the up-crest slopes, the groundwater component is less influenced, since the groundwater aquifer is connected to the creek. Since surface runoff is mainly generated on bare soil/rock areas and on grassland during intense rainfalls, it is less affected than on afforested grasslands.

Table 7.34: Annual rainfall (P), observed (OR) and simulated (SR) runoff and predicted changes of major flow components at basin scale, Weatherley.

Year	P [mm]	Q_{obs} [mm]	Q_{sim} [mm]	ΔQ [%]	ΔSF [%]	ΔSSF [%]	ΔGWF [%]	$ΔQ_{Prec}$ [%]
1998	678	168	150	-10,6	-4,1	-18,1	-3,1	-2,7
1999	1029	483	399	-17,4	-7,0	-18,3	-4,4	-8,2
2000	1397	846	732	-13,5	-6,3	-15,9	-1,0	-8,2
2001	988	437	343	-21,5	-8,9	-11,1	-1,7	-9,5

P *… Precipitation;* Q_{obs} *… observed runoff (grassland);* Q_{sim} *… simulated runoff (afforestation);* ***ΔQ*** *…* Q_{obs} - Q_{sim}*;* ***ΔSF*** *… change in surface runoff,* ***ΔSSF*** *… change in subsurface runoff (interflow);* ***ΔGWF*** *… change of groundwater flow;* $ΔQ_{Prec}$ *… ΔQ related to precipitation*

With respect to the integrated system analysis it was assumed that afforestation will also have significant impact on wetland hydrology. Since PRMS provides flow volumes for each individual HRU, the impact of afforestation on wetland dynamics has been analyzed separating flow components for each wetland type specifically for the Weatherley catchment. Comparing model results with results for grassland conditions, changes of annual runoff are summarized as percentages in Table 7.35.

Table 7.35: Predicted annual changes of flow dynamics for different wetland types in Weatherley compared to model results received for grassland conditions (in %), 10/1998-09/2001.

Year	Wetland Type	ΔSF [%]	ΔSSF [%]	ΔGWF [%]	ΔSum [%]	ΔTotal [%]
1998	PWL	- 64.3	- 27.1	-11.6	**-36.0**	**- 14.8**
	SWL	- 33.8	- 23.0	- 4.8	**-17.4**	
	VWL	- 7.8	- 16.4	- 4.2	**- 4.3**	
1999	PWL	- 77.7	- 59.8	- 8.9	**- 27.4**	**- 21.3**
	SWL	- 23.1	- 23.4	- 3.1	**- 13.6**	
	VWL	- 8.7	- 10.3	- 3.0	**- 8.1**	
2000	PWL	- 83.0	- 64.0	- 4.4	**- 26.6**	**- 17.0**
	SWL	- 4.0	- 13.0	- 2.0	**- 11.1**	
	VWL	- 6.2	- 2.9	+ 1.2	**- 3.9**	
2001	PWL	- 90.1	- 43.6	- 17.4	**- 47.8**	**- 13.6**
	SWL	- 16.4	- 22.1	- 3.8	**- 19.9**	
	VWL	- 1.4	-8.4	+ 1.7	**- 8.7**	

PWL *… Plateau Wetland;* ***SWL*** *… Slope Wetland;* ***VWL*** *…Valley Bottom Wetland;* ***ΔSF*** *…Change in surface runoff;* ***ΔSSF*** *… change in subsurface runoff (interflow);* ***ΔGWF*** *… change in groundwater discharge;* ***ΔSum*** *… change of total runoff per wetland type;* ***ΔTotal*** *… change of the areal weighted runoff from all wetlands*

Model results showed that wetlands total runoff losses (ΔTotal) vary between 13.6 % and 21.3 %, but it needs to be noted that these results are based on the modeling of optimal plant growths. Nevertheless, it is indicated that wetland dynamics will be influenced by afforestation in terms of altered recharge/discharge mechanisms as well as reduced base flows and subsurface inflows from contributing areas which have been addressed to increased interception losses. It also reveals that these effects are strongly dependent on the type of wetland, its temporal dynamic and its specific size. Summarizing the impacts simulated, it is concluded that:

- The total runoff loss of ***plateau wetlands (PWL)*** range from 26.6 % to 47.8 %. In these wetlands, water input will be widely limited to the direct rainfall input, since the water of the planted surroundings is assumed to be taken up for plant growth. SF generated in plateau wetlands is rarely observed, so that the clear reduction of surface flow is addressed to the absence of surface inflows from upslope areas. Little indication is given regarding to the dynamic of the perched GW in sub-morphological structures, but it is assumed that a proportion will be reduced as a result of the afforestation. Although these changes seem to be very high, it needs to be taken into account that PWL are very small in size, i.e. 0.43 % of the basin. With respect to their size, their temporary nature and hydrological process dynamics, plateau wetlands are assumed to have minor influence on the basin water budget.
- Medium-sized ***slope wetlands (SWL)*** runoff loss varies between 11.1 % and 19.9 % and is mainly caused by reduced surface and subsurface inflows from upslope areas. This is addressed to the decreased volume of exfiltrating water usually supplied by the PWL as SF and the higher water demand of upslope plantations reducing SSF. Alterations within the soil moisture patterns are expected along the slope gradient with impacts on the vegetation composition. Due to the lower inflows from upslope areas, upper parts of the SWL will dry out more frequently allowing

invasive plants to settle in the SWL. Since SWL show a seasonal occurrence, the period of saturation will be shortened resulting from the reduced inflows.

- ***Valley bottom wetlands (VWL)*** are less affected (3.9 - 8.7 % water loss), since those wetlands are mainly driven by interlinked ground-/surface water dynamics, discharge/recharge processes and direct rainfall input. These wetlands were modeled as saturated areas connected to the stream. It is further indicated that the runoff dynamic of these wetlands is related to the time of the year. Reduced runoffs were simulated at the beginning of the rainy season until the wetland storage is filled. Afterwards, the runoff does not show significant flow alterations anymore.

7.3.2.4 Conclusions and Implications for the Landscape Model

All model applications have shown that PRMS is able to simulate the hydrological dynamics of the Weatherley and Mooi catchments prior and after afforestation with sufficient accuracies. Summarizing the model results, the following main conclusions can be drawn with respect to the landscape model introduced in Chapter 8:

- All model runs indicated that the model simulated timing and volumes of daily runoff accurately, but it generally tends to underpredict annual runoff slightly; but independently from the land use. It was also shown that runoff in dry seasons is generally more accurate predicted than for wet periods. The analysis of the difference plots illustrated a well-balanced dynamic of the runoff. Hence, the model results are considered as being plausible.
- As found by the system analysis, the wetlands require between 10 and 20 % of the annual rainfall at the beginning of the wet season to fill their storages. When the forest plantations reduce the water availability notably, the time to achieve storage capacity, if achieved, will take longer than before afforestation. Moreover, it is assumed that low flow contribution will be reduced by this effect, which was confirmed by the model.
- In order to ascertain the model's ability to simulate changes, the runoff components of specific wetland types were evaluated by comparing runoff volumes simulated for grassland and afforestation conditions for Weatherley. Based on the analysis of afforestation scenarios, it is concluded that the hydrological dynamic of wetlands is generally subject to alterations when the catchment will be planted, but also that these changes are dependent on the specific type of the wetland and its size.

Chapter 8

Synthesis: The Landscape Model

Addressing the objectives of this study, Chapter 8 focuses on the development of a landscape model to characterize the formation and recent dynamics of wetlands in the semiarid region of the Eastern Cape Province, South Africa. Addressing the controversial discussion on landscape dynamics during the Holocene, Section 8.1 provides a model of wetland formation which indicates that the wetlands were formed as a result of Holocene climate dynamics and human activities affecting the entire landscape. With respect to the results from the hydrological modeling of afforestation impacts on landscape dynamics, it was found that the afforestation will affect wetland and basin hydrology. Thus, Section 8.2 concerns on human influences on recent landscape dynamics and discusses implications for a sustainable landscape and water resources management.

8.1 Model of Wetland Formation

As discussed in the literature review (Section 2.4), little attention has been given to the formation of wetlands in the study area. Many South African scientists emphasize that the present landscape of the Eastern Cape was basically formed by climatic and geologic processes and remained stable during the entire Holocene. Thus, wetlands are assumed to be relics of the late Pleistocene and thereby older than 10 000 years. MEADOWS & LINDER (1993) argued that the montane grassland was established during the late Pleistocene, but also with phases of expansion of the montane forest during the Holocene. Nevertheless, it is assumed that the forests never dominated the escarpment (MEADOWS & MEADOWS, 1988), because the environmental conditions prevented the establishment of vegetation different to the unpretending grassland vegetation.

On the other hand, there is some indication that the area was covered by higher vegetation than grassland (ACOCKS, 1988, FEBRUARY, 1994) over several periods during the Holocene, whereas relics of indigenous *Podocarpus* forest can still be found in kloofs. These patches of indigenous vegetation as well as the successful establishment of commercial forestry indicate the potential of the landscape to support the growth of higher vegetation. In addition, land management such as annual burning, which has been applied for hundreds or even thousands of years in this region, have led to a reduction of biodiversity and the growth potential for other vegetation than fast growing grass species (EVERSON *et al.*, 1989; EVERSON & TAINTON, 1984; MENTIS & BIGALKE, 1981; SHORT *et al.*, 2003; TROLLOPE, 1974; SMITH & TAINTON 1985). Thus, the human-induced disturbance of the natural vegetation during the Holocene needs to be taken into account when developing a model characterizing the formation of the present landscape and wetlands. Assuming that the formation of wetlands is strongly linked to sediment transport (deposition of wetland sediments) and hydrological dynamics, changes in vegetation pattern may have supported, if not even caused, the existence of recent wetland systems.

In this study, geophysical methods and sediment analyses have been combined with palaeoclimatological and historic land use studies (ACOCKS, 1988; SCOTT & LEE-THORP, 2004; HUFFMANN, 1996; TYSON & LINDESAY, 1992) in order to evaluate whether the evolution of wetlands was predominantly climatically driven or influenced (if not even caused) by human impact. From this effort, a methodological and theoretical framework was provided resulting in an integrated landscape model, which describes the formation and evolution of the wetlands within the study area. As illustrated in Figure 8.1, the developed landscape model comprises six main phases of wetland formation, which differ in terms of morphodynamic processes, vegetation characteristics, and anthropogenic influences on landscape development.

Stage I:

According to the model the sedimentary basis for wetland evolution is represented by deep incised valleys in the basement that is formed by Triassic sandstones (c) and its overlaying weathering layer (b). The valley floors, which were identified by several drillings and retraced by refraction seismic profiles, provide the initial relief of the present floodplains. These deep valleys have been partly filled up with grayish sands (a) and were partially eroded again later. The sandy sediments outcrop slightly above the present sediment level in terms of terraces fringing the valleys. A layer of coarse gravels (e) has accumulated on the remaining sandy sediments in the valley bottoms. The transport and deposition of gravel are assumed to be a result of climatically driven dynamics during the late Holocene. With respect to TYSON (1987), a cooling phase began 4 700 yrs. BP reaching a minimum temperature at 4 300 yrs. BP. Since this cooling phase is associated to wetter conditions than at present (TYSON, 1987), it is assumed that fluvial dynamics increased and thereby lead to an increase of sedimentation and erosion dynamics. Colder conditions also indicate reduced vegetation cover densities which also may have caused higher surface runoffs associated with intensified erosion processes. These sedimentation and erosion processes during the late Holocene altogether provide the morphological basis for the further formation of wetlands.

Stage II:

By 3 500 yrs. BP a relatively stable phase with higher temperatures and drier conditions compared to *Stage I* had become established resulting from an intermediary warming phase which started about 4 300 yrs. BP. (SCOTT & LEE-THORP, 2004; TYSON, 1987). As reported by SCOTT & LEE-THORP (2004) who reviewed studies regarding demographic responses on climate dynamics, migration by hunter-gatherers into the interior landscape increased significantly related to this warming phase. Since people tend to migrate only to places where food (animals and plants) and water is sufficiently available, it is indicated that this climatic trend also led to the formation of dense and species rich vegetation which reduced erosion dynamics on slopes and sediment transport in the rivers notably. Nevertheless, there is no evidence whether what type of vegetation was predominant nor to what extent at this time.

Stage III:

Along with the late Holocene cooling phase which set in 3 400 yrs. BP (SCOTT & LEE-THORP, 2004) and may be related to the Neoglacial Advance, intensified erosion and thus sedimentation of fine material in the floodplains increased. This led to a complete infilling of the valley bottoms up to the present level. Since the cooling phase is related to drier conditions in association with reduced runoff, it is assumed that relatively low transport capacities of the rivers supported sediment deposition of fine grain sizes.

As discussed by HALL (2000) hunter gatherers activities regarding intensive resource exploitation (deforestation of riverine vegetation, hunting by burning) achieved a peak at 3 100 yrs. BP. It is hypothesized that the reason for the higher demand on resources about 3 100 yrs. BP is related to the cooling phase, since decreasing temperatures may affect the availability of wood and game in the landscape. This intensified resource exploitation is assumed to be influential to the density of the vegetation cover and thereby to sediment mobilization on slopes at this time. The corresponding sediments deposited in the valley floors are interpreted as the initial substrate for the formation of wetlands within the study area. Consequently, climate conditions and human activities are assumed to be main drivers for sediment deposition and thereby wetland formation. Results from radiocarbon dating at the base of these sediments at a depth of 220 cm reveal a maximum age of 3 370±51 ^{14}C yrs. BP for wetland formation. The sample was taken at the bottom of the profile, and thereby the given dating is supposed to approximate nearly the initial phase of the deposition of fine sediments found at the base. Assuming that relatively steady conditions occurred during the past 2 000 years (FEBRUARY, 1994) with similar vegetation patterns (ELLERY & MENTIS, 1992) associated with equilibrium conditions for erosion and deposition rates, it can be concluded furthermore that about 2 m of sediment have been deposited within a relatively short time span of about 1 500 years (3 500 – 2 000 yrs. BP).

Stage IV:

Within these sediments showing depths up to 4 m an initial soil formation is identified in terms of a clayey-silty layer with crusted Fe- and Mn-concretions at its base. This is attributed to a steady phase during or after deposition with neither remarkable erosion nor sedimentation. As a consequence, clay mineralization processes and the development of cemented Fe- and Mn crusts led to the development of an impervious layer in a depth of about 0.5 to 1 m that affects the seasonal hydrological dynamics and therefore enables recent wetland conditions. As emphasized by FEY (2004, pers. comm.), soil-chemical considerations indicate that these features developed under constant conditions regarding sediment dynamics and permanent water fluctuations for at least 600 years. Since less evidence is given in terms of significant climate changes compared to recent conditions over the last 2 000 years (FEBRUARY, 1994; TYSON, 1987; SCOTT & LEE-THORP, 2004), it is assumed that soil development took place during the last

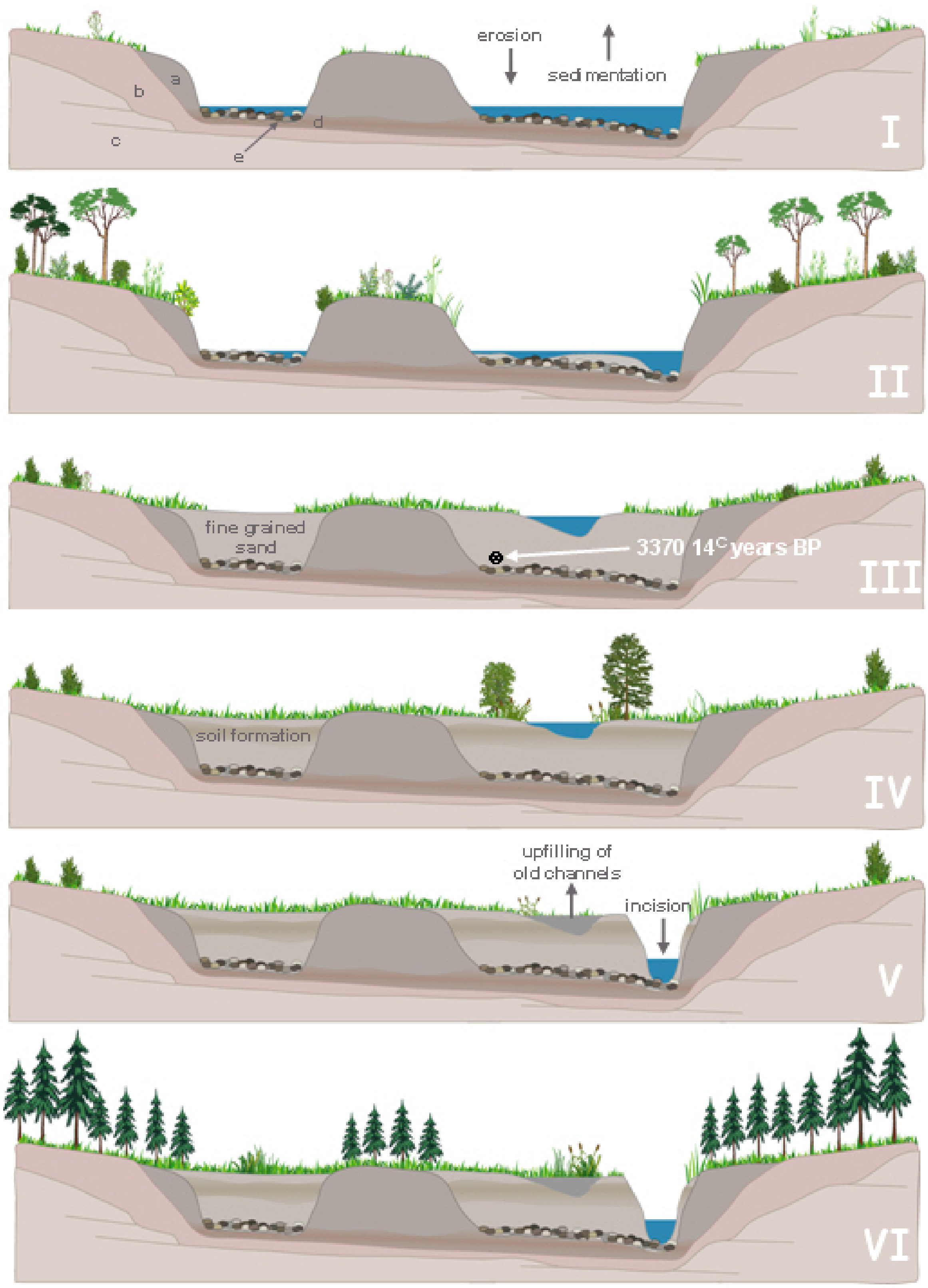
2000 years. Because of the steady climate conditions, sedimentation dynamics were relatively low, i.e. about the same volume of material which eroded from the slopes was removed by the meandering rivers. Latter indicate a low gradient in the valley bottoms and are still evident in the landscape (oxbow lakes). As discussed by FEELY (1987), relatively low flow conditions motivated people to settle close to the rivers and supported the development of pronounced riverine vegetation during this steady stage. Land use dynamics were primarily characterized by the transition of the hunter-gatherer culture into early farming activities, and thereby reveal a persistence of grassy vegetation type (FEELY, 1987).

Stage V:

In recent to sub-recent time scales, a new incision into the valley fills was identified. The incision was much more restricted to narrow channel beds than in *Stage I*, but nevertheless 2 to 3 m deep, down to the basement or at least to the gravel layer. This incision is assumed to be the result of anthropogenic influences due to drainage of the wetlands in order to use the land for pasture management. Drainage lowered the erosion level up to several meters, which is furthermore associated with the onset of deep gully erosion. These dynamics are enforced by rapid subsurface flow as a consequence of land management. Since at least 600 years, the land management is characterized by extensive stock-farming which in some parts led to notable land degradation caused by (over)grazing and fire management on an annual base. Little information is available about the overall sediment balance, but field survey indicates that the balance is still well-balanced.

Stage VI:

In addition to or by replacing the existing farm management established at least 600 years ago, intensive afforestation with pine and eucalypt started in 1989 within the Umzimvubu catchment. To some extent the plantations cover the slopes of the tributary catchments of the wetlands or even reach into the wetlands. Thus, it is assumed that afforestation will significantly influence wetland hydrology, sedimentation dynamics and biodiversity. With respect to environmental laws, wetlands are being restored recently by the replacement of drainage facilities and rehabilitation activities. The impacts of these activities on wetland and basin dynamics need to be subjected to further research.



a … grayish sands; b … weathering layer of the Triassic sandstone, c … Triassic sandstone; d … palaeosoil; e … gravel

Figure 8.1: Illustration of the landscape model, which describes the reconstructed evolution of wetlands within the study area in terms of geomorphodynamic processes, vegetation characteristics and anthropogenic influence by land use in 6 consecutive stages.

Summarizing the wetland formation, it is concluded that both climate dynamics and human activities during the Holocene are the main drivers that formed the wetlands, in particular in the valley bottoms. The basic idea of the model is that climate conditions during the Holocene provided a landscape potential motivating people to migrate to this area. With variations of climate and an increasing population, people were forced to an increased resource exploitation resulting in an alteration of vegetation composition and density in the landscape. A sparser vegetation cover, however, led to the mobilization of unconsolidated materials on hillslopes which was transferred to the valley bottoms. With the assumption, that these dynamics occurred during the Holocene, the present model is in contrast to the common assumption that the landscape in general and the wetlands in particular are relics of the Pleistocene. As a consequence, further studies are needed to verify the given assumptions. For example, isotope analysis will provide further data for climate reconstruction and further pollen analysis will improve the knowledge on vegetation dynamics during the Holocene.

8.2 Wetlands and Afforestation: A Landscape Perspective

Many studies conceptualize wetlands as isolated landscape features, and ignore the interactions of wetlands with their surrounding landscape. Although there are wetlands sites which are identified as hydrologically disconnected to their surrounding landscape (BROOKS, 2005; LEIBOWITZ, 2003), the majority of wetlands is interacting with components of the landscape along several spatial and temporal scales. Thus, the thorough study and improved theoretical understanding of wetland functioning and dynamics has to consider a broad landscape and catchment context, rather than being restricted solely to features of the particular site.

When scaling up the results of this study to the landscape scale, it is hypothesized that wetlands in the semi-arid landscape of the upper Umzimvubu catchment fulfill a variety of functions, and thereby play a significant role in the landscape of this semiarid region, i.e. hydrological functions, biological functions and socio-economic functions. In this study, hydrological functions of wetlands were identified in terms of runoff interception, flood attenuation, groundwater recharge, discharge and storage. The biological functions are addressed to biodiversity and habitat functions for flora and fauna adapted to wetland conditions. Socio-economic functions were recognized twofold. Wetlands are used for stock-farming during the dry season. In addition, the storage capability of wetlands reduces the probability of damage to man-made structures such as dams by decreasing the probability of damages by floods and the risk of becoming sediment laden.

Regarding the complex nature of wetland ecosystems, integrated and landscape-based approaches are required to assess wetland dynamics and functioning. This is much more important when the tributary areas of wetlands face a fundamental change of land use. Such changes may affect the eco-hydrological dynamics of the wetlands in general or of an individual wetland site.

This study has shown that the transition from range land to commercial forestry in the semi-arid Umzimvubu-River basin will influence the hydrological dynamics at catchment and wetland scales. A variety of implications for the hydrological and ecological functioning of these wetland systems within a landscape perspective and their sustainable use can be highlighted once the total water balance is changed by higher interception and evapotranspiration rates of commercial forest stands:

- Decreasing subsurface inflow from the upslope areas may result in a progressive desiccation, in particular of temporal and seasonal wetlands. This reduction of water input to the wetland will alter plant community structure and allow the encroachment of alien and invasive species.
- As a consequence of reduced water inputs, the storage dynamics of the valley bottom wetlands will be altered, i.e. the period of the filling of wetlands will take longer causing the extension of the period when water is released. This may affect the behavior of migrating birds, vertebrates and invertebrates as well as plant species.
- The study results indicate a decline of runoff peaks caused by the afforestation of the upslope areas. This will result in the reduction of sediment transport towards the deposition areas, i.e. the wetlands, with possible impacts on the wetland sediment balance. Since wetlands are recently subject to notable erosion processes due to management practices like (over)grazing and annual burning over hundreds or even thousands of years, a decreasing sediment volume may support wetland destabilization.

Besides those hydro-ecological aspects, afforestation also provides direct and indirect benefits to the landscape and the human environment. Since the planted areas reduce the generation of rapid stormflow on hillslopes, afforestation supports flood control, in particular at the end of the rainy season when wetlands achieved their storage capacity. In addition, the establishment of plantation forestry and secondary industries such as furniture factories and transportation companies provide job benefits to an area which is characterized as one of the poorest in South Africa, afforestation also have a remarkable socio-economic effect.

Depending on the perspective, the impact of afforestation can be positive or negative for current human utilization of the landscape. However, the study also highlighted that the formation of the wetlands themselves are likely to be linked to human activities in the past. As a consequence, any protection of the current wetland status needs to consider maintaining a quasi-natural environment. Afforestation and its impacts affect a variety of elements and actors in the landscape and require a multi-faceted assessment and management strategy.

Without a doubt, studies like this one are key to gain understanding and support discussions made here although the overall impact of afforestation is depending on the perspective. Negative environmental impacts require compensation and this process has started in the study region. Forest industries have taken steps for wetland restoration to minimize negative impacts. However, restoration efforts do require thorough understanding of the landscape functioning to be effective. Possible avenues include direct restoration of wetlands by planting stabilizing wetland vegetation and adjusted forestry management in terms of successive rotation length in the planted areas.

Because further areas will be owned by the forest industry in near future, the increase of forest activities will intensify the discussion on the afforestation impacts on regional and local environment. In particular, the expected increase of population and the associated increasing water demand will lead to a critical debate on a sustainable water resources management satisfying all potential water users. Given the recent provision for integrated catchment management principles in South African policy and law that require catchment manager to recognize and consider the needs of all users of catchment water resources. As a consequence, land use management that interfere with hydrological and ecological balances that sustain wetland and catchment functioning and dynamics need to be understood if water resource management and environmental conservation is concerned. Thus, this research also provides information and knowledge fundamental to both the forestry impact assessment and for environmental restoration and rehabilitation towards a sustainable landscape management in the semiarid region of the Eastern Cape Province.

Chapter 9

Conclusion and Future Needs

9.1 Conclusion

Wetlands are key landscape elements in almost every environment. Addressing the continuous loss of wetland area worldwide, they are recognized as highly vulnerable regarding natural and anthropogenic system changes. Because of their wide range of natural and socio-economical functions, their importance for the water and nutrient cycles as well as their role as wildlife habitat, the analysis of human impacts on wetland dynamics is of particular interest to water and environmental authorities for an efficient and sustainable landscape and water resources management.

The landscape of the semi-arid Eastern Cape Province, South Africa is characterized by the occurrence of different types of palustrine wetlands which vary in extent, topographic position and hydrological functioning. Although these wetlands have been recognized as important ecosystems fulfilling essential eco-hydrological functions such as flood flow attenuation, groundwater recharge, baseflow control, and sediment and nutrient trapping, little knowledge is available regarding their distribution and functioning, nor the impact of human activities on past and recent wetland dynamics.

Intensive afforestation in the headwaters of the Umzimvubu catchment since 1989 induce changes in wetland characteristics, however, little attention has been given to evaluate and quantify related impacts. Addressing this research deficit, the main objectives of this dissertation were ***i) the development of an integrated, landscape-based research approach to improve the understanding of formation, functioning and dynamics of palustrine wetlands*** and ***ii) the prognostic modeling and assessment of afforestation impacts on these wetland systems***.

The conceptual and methodological approach of this dissertation was based on three individual aspects: *i) observation and data mining*; *ii) integrated system analysis*; and *iii) system modeling and assessment* combining empirical field studies, laboratory analysis, GIS and remote sensing techniques, and process-oriented, plant growth and hydrological modeling.

A comprehensive data pool was developed for the two headwater catchments Mooi (307 km²) and the experimental catchment Weatherley (1.4 km²) incorporating hydro-meteorological time series at different scales, data of soil properties and distribution, vegetation data, multi-temporal- and multi-scale satellite-based land use and cover classifications and field-based wetland distribution maps. Additional observations were derived from pollen analysis and geophysical and sedimentological investigations (refraction seismics, ^{14}C datings) in selected test sites.

An integrated system analysis was performed at several scales (hillslope, ecosystem, catchment and landscape) in order to identify and characterize the driving environmental variables controlling eco-hydrological processes at wetland and catchment scale by the integration and aggregation of the empirical observations.The study used spatial and temporal rainfall and runoff dynamics and the analysis of vegetation and soil to describe soil and vegetation pattern. Land use change detection was performed to quantify land use changes resulting from the transformation of range land to commercial forest plantations. In addition, a model was developed by the analysis of hydrometric data recorded at Weatherley in order to characterize the dominant runoff generation processes on hillslopes. These studies led to the identification of different wetland types being different in terms of landscape position, size and extent of the tributary catchment, soils, vegetation composition and hydrological dynamics. This confluence of information resulted in a thorough theoretical framework on hydrological system dynamics, their relationships and regionalization by means of the delineation of hydrological response units (HRUs).

Based on this theoretical framework, process-based models were applied to simulate forest growth dynamics (3-PG) and the impact on afforestation on wetland and catchment water budgets (PRMS). The hydrological model was further used to identify the main hydrological processes within wetlands that will be affected by the afforestation.

Integrating the results of observations, system analyses and model applications, a wetland and landscape model was developed in order to characterize the wetland formation and possible impacts of human activities on past and recent wetland and landscape dynamics.

Regarding the integrated and multi-disciplinary nature of this study, a variety of results were provided addressing different research and methodological aspects. The main findings of this thesis, however, can be summarized by answering the research questions highlighted at the beginning of this thesis.

- *What are the different types of wetlands occurring in the headwaters of the Umzimvubu basin and where are they located?*

Three main wetlands types being different in terms of landscape position, soils, vegetation composition and hydrological dynamics were identified. *Plateau wetlands (PWL)* are located in plateau and bench positions. They are small in size (less then 1 ha) and formed in depressions or topographic lows or areas underlain by impermeable material. These wetlands are temporary and disconnected from the fluvial system. *Slope wetlands (SWL)* are found at hillslope section with steep to moderate gradients. They are either isolated or interlinked to both the fluvial system and adjoining slope wetlands, whereas isolated patches are smaller in size (1 – 5 ha) than interlinked wetlands (< 15 ha). SWL are temporary or seasonal, but also permanent SWL were observed. *Valley bottom wetlands (VWL)* are located in floodplains and riparian corridors in association with stream channels at the bottom of valleys with negligible gradients. They are larger than other wetland types (> 10 ha) and are either associated with a stream (channelized) or diffuse with temporally and spatially variable channels which drain the wetland. Because of the flat terrain, streams usually tend to meander.

- *What are the driving environmental variables controlling wetland processes, dynamics and functioning and how are the interactions with the adjacent landscape?*

As a result of this study, two main external drivers controlling wetland dynamics were identified. Besides the spatio-temporal dynamic of rainfall which affects wetland processes directly, the water availability and release in their tributary catchments are recognized as important factors. The water release from up-wetland areas is in turn strongly dependent on the land management of these areas. Thus, it is concluded that changes in land management will affect wetland processes, dynamics and functioning notably.

Internal drivers controlling the hydrological functioning of wetlands are soil properties and slope gradients. With respect to soil analysis, the clayey-silty soils of VWL show high water retention capacities which enable the wetlands to store large volumes of water. Because of this retention capacity, VWL provide several services to the landscape such as flood attenuation during the dry season as well as the control of the low flow dynamics during the dry season. In contrast, PWL and SWL soils are characterized by relatively good drainage properties. Thus, these wetlands are dependent on the subsurface inflow (interflow) and exfiltrating water from the upslope areas, which will in case of afforestation significantly decreased. In addition, such changes will affect environmental functions and biodiversity due to habitat loss and alterations.

- *How can process-oriented models working on different spatial and temporal scales be integrated to simulate and quantify the impact of afforestation on the catchment hydrology in general and on different wetland types in particular?*

The coupling of process-based plant growth and hydrological modeling emphasized, how models working on different spatial and temporal scales can be integrated for such environmental studies. The 3-PG model working on ecosystem (stand) scale was used to simulate forest growth dynamics and water use of the main forest species planted in the study area. As a result, the temporal dynamic of bio-physical parameters such as tree density, DBH, biomass and LAI was determined and, thereby, the timing of canopy closure of each species was estimated. The model application provided further system understanding and parameters which were applied to calibrate the hydrological model. PRMS was able to simulate the hydrological dynamic prior and after afforestation for the Mooi catchment and pre-afforestation conditions for the Weatherley watershed sufficiently. The forest parameters were used to simulate an afforestation scenario for Weatherley. Since PRMS provides total volumes of runoff components for each individual HRU, the impact of afforestation on selected runoff components was then quantified for each wetland type. Because of the reliable results received from the modeling it is concluded that the model results of the plant growth modeling could be successfully used to improve the model performance of PRMS remarkably.

- *How is afforestation affecting the hydrological processes and dynamics on wetland and catchment scale?*

The present study showed that afforestation generally affects the quantity of hydrological dynamics at catchment and wetland scale. For the Weatherley catchment, it was found that the runoff will be significantly reduced by forest plantations by amounts ranging from 13.5 % to 21.5 %. When examining the flow reduction seasonally, it was found that the percentage decline in low flow during dry season (48 %) was actually greater than in annual flow (17.5 %). These findings on total losses confirm results from other studies (SMAKHTIN *et al.*, 1997; SCOTT & SMITH, 1997) who identified a similar behavior in other catchments. The analysis of the individual flow components indicates that subsurface flow (SSF) will be more affected then surface (ΔSF) and groundwater flow (ΔGWF).

Furthermore it was found that afforestation influences wetland dynamics and their landscape functions as a consequence of total runoff losses in the range of 13.6 % to 21.3 %. Depending on the wetland type, these losses are addressed to altered recharge/discharge mechanisms as well as reduced base flows and subsurface inflows from contributing areas which have been addressed to increased interception losses. Even though PWL will be most affected by afforestation (27 - 48 % runoff loss), changes of their hydrological dynamics are assumed to have minor influence on the basin water budget. This is addressed to their size, their temporary nature and hydrological process dynamics. SWL runoff losses vary between 11.1 % and 19.9 % and are mainly caused by reduced surface and subsurface inflows from upslope areas. The decreased volume of exfiltrating water usually supplied by the PWL as SF and the higher water demand of upslope plantations reducing SSF is accounting for this phenomenon. Because of their seasonal occurrence and due to the lower inflows from upslope areas, SWL will dry out more frequently allowing invasive plants to settle in the SWL. VWL are less affected (3.9 - 8.7 %), since those wetlands are mainly driven by interlinked ground-/surface water dynamics, discharge/recharge processes and direct rainfall input.

- *What is the potential of integrated research approaches to identify the human impact on wetland formation and recent dynamics of wetlands?*

Regarding the complex nature of wetland ecosystems, integrated and landscape-based approaches are required to assess wetland formation, dynamics and functioning. As shown by this study, an integrated research approach provides information to characterize human impacts on wetland formation and recent dynamics. Based on the results of the field work and laboratory analysis, it is concluded that both climate dynamics and human activities during the Holocene are the main drivers that formed the wetlands, in particular in the valley bottoms. The model was based on the assumption that anthropogenic influence changed the sediment dynamics on hillslopes as a result of land management, and thereby, contributed to the wetland formation. As shown by the hydrological modeling, the re-establishment of vegetation which reduces sediment transport and net water inflow will again alter the wetland functions. This might be subject to further studies as discussed in the next section.

In summary, this dissertation research contributes to the field of integrated wetland research and provided improved theoretical understanding on formation, distribution and functioning of wetland systems in the South African landscape. The results of the study help to define requirements for sustained landscape management and the maintenance of the hydrological functions of these wetlands. To maintain wetland functioning, the water requirements of wetlands must be balanced with the needs of all water users in a catchment. Thus, the challenge to water authorities, policy makers and industry should be a sustainable use of the limited water resources, in particular in semi-arid South Africa. Addressing the environmental law in South Africa, adequate information is required towards the formulation and operation of sustainable management strategies for wetlands. In this context, this study contributes to an increased understanding of relevant processes and problems which could be associated with such strategies.

9.2 Future Research Needs

Given the integrated nature of this research approach, a variety of research questions arise from the present study addressing various methodological aspects of wetland and landscape research. The following main research needs were identified.

- The hydrological system analysis indicated that the catchments of the investigation area will be affected by the large-scale afforestation. For example, the water supply from the slopes to the wetland areas will be substantially reduced due to increasing water retention by the planted areas. These assumptions were confirmed by the model approach applied to the Weatherley catchment. Since the modeling was restricted to the Weatherley catchment, further work is needed to scale up and verify the assumptions regarding afforestation and land use management impacts. Since PRMS is not able to perform rotation and growth cycles of forest stands, more dynamic models need to be explored to implement growth dynamics in a sophisticated manner. In addition, several management techniques for grassland (grazing, burning etc.) and plantations (pruning, thinning etc.) need to be incorporated into a more flexible modeling system. Such a model might be the process-based J2000 model (KRAUSE, 2001), which was successfully applied to a variety of forest-dominated areas. The advantage of J2000 is related to its flexibility, since the Java - programming environment and its platform-independent framework JAMS (Jena Adaptive Modeling System, KRALISCH & KRAUSE, 2006) allows the user to develop and implement process modules to the user's specific needs. Hereby, the user can focus on the development of process components itself, since the system core takes care on data I/O, visualization and internal error handling by standardized procedures.
- Since it was shown that large volumes of water are transported by macro-pore and piping processes and thereby have major influence of wetland and catchment hydrology, a challenge of further model applications might be the better representation of these processes. In addition, the activity of flora and fauna (including the problem of tussock formation) which is being of major interest for water transport processes in wetland systems could be of interest to further modeling efforts.
- While the hydrological impact on wetlands is evaluated by this study, little information is given regarding recent sediment dynamics and biodiversity alteration resulting from afforestation. However, regressive erosion was observed in almost all wetlands indicating either an increase of fluvial dynamics or a destabilization of the wetland sediment bodies. Even though these findings were not verified yet due to

insufficient sample size and measurement technique, they indicate alterations of wetland dynamics. In addition, field-based survey in different wetlands during the past seven years showed an increase of invasive plant and animal species indicating drier conditions. This is controversial, since rainfall recorded for the past 10 years (with the exception of 2003) was in the range of or higher than the long-term mean. Thus, further studies on vegetation and sediment dynamics are needed to identify whether these changes are caused by afforestation or are an effect of long-term climatic trends. It also reveals on further studies (and measurements) to evaluate the spatio-temporal rainfall patterns more accurately.

- Since many of the fundamental hydrological processes are now better understood, future research linking water quality and carbon dynamics, for example, becomes more feasible and amenable for model applications. Future studies may consider water quality investigations in order to improve the knowledge on wetland functioning on the base of hydro-bio-chemical investigations, i.e. the analysis of the C and N cycles. Such studies could give indications on vegetation composition variations as a consequence of reduced nutrient incomes resulting from a change of land management (i.e. transition from an annual burning management of grassland in upslope areas to commercial forestry). In addition, the questions of whether and how adjacent land use affects wetland buffer function, i.e. for water quality improvement and for provision of plant and animal habitat should be investigated as well.
- The model of wetland formation is based on basic geomorphological and sedimentological studies. Since these investigations were widely restricted to three wetland sites, further studies are needed to verify the model by examples from other wetland sites and hillslope areas. These studies also need to be focused on the retrieval of further climate records to improve the knowledge on palaeo-climatological dynamics. A soil core taken from a wetland site near the Diepfontein farm may be subject to further palaeo-ecological and –climatological studies. Based on ^{14}C dating it was found that the core represent the entire Holocene. Thus, further datings and the consideration other natural isotopes may provide additional information for climate reconstruction. Other geoarchives such as pollen should be analyzed in detail in order to complement data on vegetation dynamics within the entire landscape during the Holocene.

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Selbstständigkeitserklärung

Ich erkläre, dass ich die vorliegende Arbeit selbstständig und unter Verwendung der angegebenen Hilfsmittel, persönlichen Mitteilungen und Quellen angefertigt habe.

Jena, 07. Juli 2006 (Jörg Helmschrot)

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Auszeichnungen / Preise / Stipendien

2006	***Poster Presentation Award*** von der Society of Wetland Scientists (SWS), 27th International Wetlands Conference in Cairns, Australia
2005	***Student Travel Award*** von der Society of Wetland Scientists (SWS), 26th International Wetlands Conference in Charleston, SC, USA
2005	***EU-Stipendium*** zur Teilnahme an der "Conference for Wetlands: Monitoring, Modelling and Management (W3M)", ausgerichtet durch das "Center of Excellence in Wetland Hydrology", 22 -25 September, Wierzba, Poland

Mitgliedschaften

Seit 2006	Mitglied der Thüringer Geographischen Gesellschaft zu Jena e.V.
Seit 2004	Mitgliedschaft der Society of Wetland Scientists (SWS)
Seit 2003	Mitgliedschaft der Association of State Wetland Managers (ASWM)

Jena, Juli 2006 (Jörg Helmschrot)