THE IMPACTS OF DEGRADED VEGETATION ON WATER FLOWS: A CASE STUDY IN THE MZIMVUBU CATCHMENT

by

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Agricultural Engineering, School of Engineering of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, South Africa. The research was financially supported by the Water Research Commission.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

Signed: RR Sutcliffe

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Signed: Dr ML Toucher

Date: 21 January 2019

DECLARATION: PLAGIARISM

I, Roanne Ruth Sutcliffe, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

  a) their words have been re-written, but the general information attributed to them has been referenced;

  b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

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ABSTRACT

The Mzimvubu River is the largest undeveloped river course in South Africa, with the Mzimvubu catchment set to undergo high levels of both social and economic development. A study was undertaken for the catchment with the aim being to determine the impacts of different land use management scenarios on the catchment water flows through the use of the ACRU model.

The verification stage of the study involved the modelling of the baseline scenarios of two preselected catchments, viz. T35C and T32A/B/C, in order to perform statistical comparisons of both simulated and observed streamflow. Whilst a number of the desired statistics were out of the ±15% confidence range, the differences between observed and simulated variances and standard deviations were well within the range and the R^2 and Nash-Sutcliffe Efficiency Index (E_f) factors, though not exceeding 0.7, were deemed acceptable.

The verification of the two Mzimvubu catchments was not ideal, and it was hypothesised that this may have been due, in part, to the parameterisation of degraded areas in the ACRU model configuration Degradation of vegetation can be considered in a number of different ways (from loss of cover through to bush encroachment and poor burning practice), although in ACRU it has only been modelled as a pure loss of vegetative cover. A methodology for determining vegetation parameters was thus determined from Leaf Area Index (LAI) data for 2008-2017 for sites within degraded areas and pristine veld areas within protected sites, and included calculation of crop coefficient, interception and percentage surface cover parameters that were then used within ACRU as the degraded vegetation parameters.

These parameters were then input into the model, with simulations being run for both study catchments using both the Kristensen and FAO dual crop coefficients, as well as a set of simulations using degraded parameters that were calculated by using a percentage change (between 10 and 15 % difference) on the existing Acocks veld parameters within the model. This percentage change yielded very minor changes to the initial verification simulations; however, the two other sets of runs using the different crop coefficients both made significant changes to the verification simulations. The T32A/B/C simulation improved by almost 20 % and was only just outside the range of ±15% for the Kristensen set of runs. The T35C simulation, on the other hand, worsened although a challenge existed insofar as only the natural

and degraded vegetation Hydrological Response Units (HRUs) had updated parameters – the large amount of commercial forestry,a known streamflow reduction activity (SFRA), within the catchment could have played a role in the under simulation of all the catchment's model runs.

Lastly, land use change scenarios were then modelled by changing both vegetative parameters and the area of different HRUs within both the T35C and T32A/B/C catchments. The scenarios modelled considered land degradation in its many forms, from the degradation of natural vegetation and subsequent rehabilitation, the increase in bush encroachment, differing severities and timing of burning, changes in areas under irrigated and dryland agriculture, and the conversion of traditional dryland crops to biofuel crops. These different scenarios proved to have different sensitivities to change, although all scenarios showed a lessening in the sensitivity as the area under change increased.

Given the problems with both rainfall and streamflow records, further research on remote sensing and satellite imagery could provide another source of data for both climatic and land use. Further to this, the methodology used to determine the degraded vegetation parameters using remotely sensed data was shown to be an explicit and repeatable method and can be extended to incorporate the calculation of the parameters of other land uses, such as forestry and agricultural practices. This could be done in conjunction with in situ studies to test whether the methodology works for all types of land use.

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ACRU - Agrohydrologic Catchment Response Unit
ET - Evapotranspiration
FAO - Food and Agriculture Organisation of the United Nations
HRU - Hydrologic Response Unit
LAI - Leaf Area Index
NDVI - Normalised Difference Vegetation Index
NLC - National Land Classification
NWRS - National Water Resources Strategy
SEBS - Surface Energy Balance System
SFRA - Streamflow Reduction Activity
SANS - South African National Standard
WRC - Water Research Commission

1. INTRODUCTION

Once a part of the former Transkei homeland, the Mzimvubu catchment is economically poor and underdeveloped, with the Mzimvubu River being the largest undeveloped river course in South Africa (Schulze *et al.*, 2009; Van Tol *et al.*, 2014). Given the development proposed for this catchment which has large areas of degradation, the catchment hydrology needs to be considered in terms of how changes in both rangeland and agricultural practices will affect the stream-, base- and quickflow of the area. Due to these proposed changes to the area, the Mzimvubu catchment, covering parts of southern KwaZulu-Natal and the northern Eastern Cape, was identified as one of the four study areas to be considered in the WRC-funded "*Modelling Water Flows with Change in Land Management in Selected River Catchments"* (Toucher *et al.*, 2017) project, and subsequently as the catchment of focus in this dissertation.

1.1 Rationale and Motivation for the Research

The NWRS (Republic of South Africa, 2013) highlighted the Mzimvubu-Keiskama region as one of the Water Management Areas (WMA) to undergo high levels of both social and economic development. Part of this development includes the proposed construction of the Ntabelanga and Laleni Dams (Van Tol *et al.*, 2016) which, whilst aiming to increase development in the area, are threatened by heavy siltation owing to the highly erodible soils of the catchment, high levels of degradation, and loss of natural vegetation due to overgrazing and burning practices (Toucher *et al.*, 2017), which threaten the sustainability of the grasslands.

Currently, the main agricultural practices in the area are the rearing of cattle, goats and sheep which are left to graze throughout the predominantly community-owned lands, and the production of crops/vegetables, especially maize, for home consumption and sale at local markets (Van Tol *et al.*, 2014; Van Tol *et al.*, 2016). On the commercial agriculture side, large areas within the catchment are utilised for the growing of wheat and maize crops, as well as the grazing of dairy and beef cattle herds. In the higher rainfall areas of the catchment, extensive forestry plantations have been established, especially along the northern tributaries (DWAF, 2007).

Approximately 400 000 ha of potential rainfed crop land has been identified, much of which is to incorporate rainwater harvesting techniques and conservation tillage in order to negate the substantial impacts of soil erosion (Republic of South Africa, 2013). High levels of degradation

(Figure 1.1) are prevalent throughout the catchment given the types of soils present (Van Zyl and Lorentz, 2003) and the poor management practices throughout much of the non-commercial crop- and rangeland (Gbetibouo and Ringler, 2009).

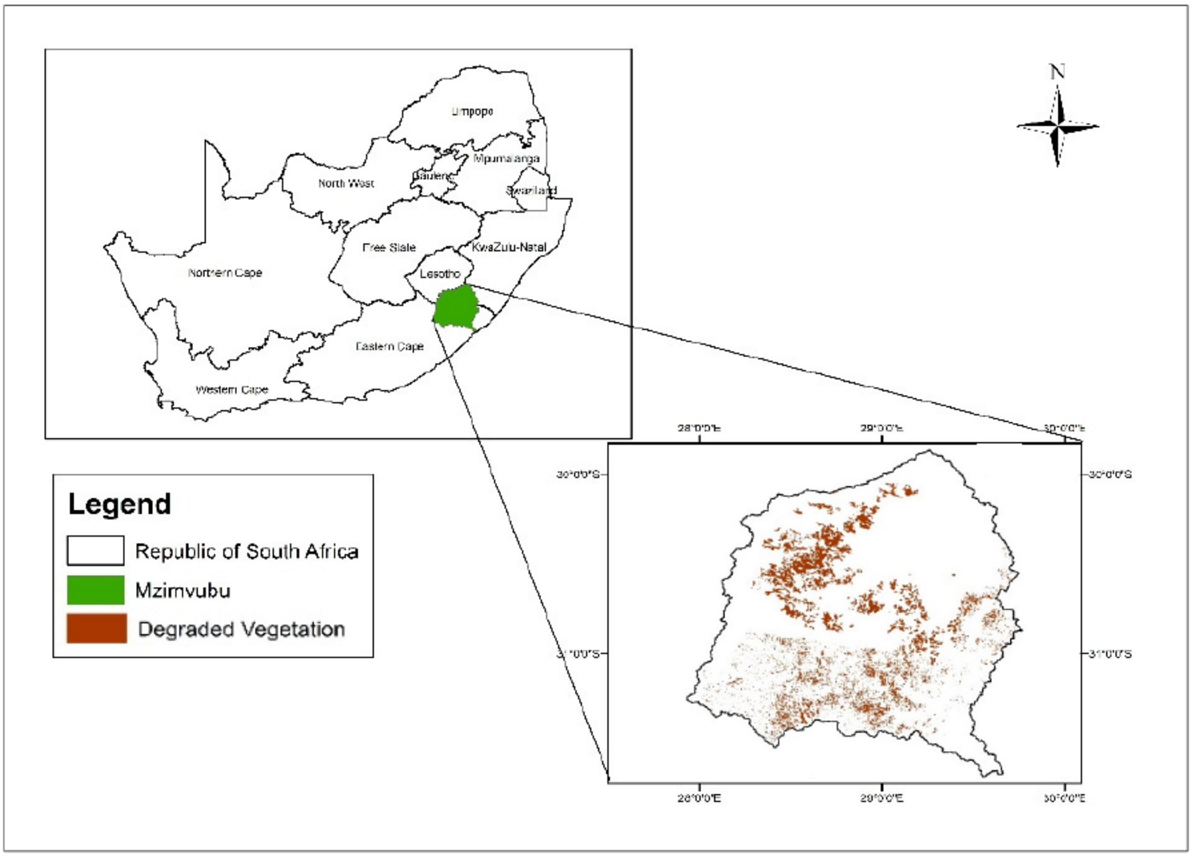

Figure 1.1 Degraded vegetated areas within the Mzimvubu catchment (after Van den Berg *et al.*, 2008)

Degradation of grasslands is a global issue, and one which is prevalent in South Africa. Given the issues surrounding land ownership and the former South African government's policies that led to the creation of the homelands, large parts of the country have become degraded (Hoffman and Todd, 2000). In the 1999 National Review on Degradation (Hoffman and Todd, 1999), the degradation of veld was classified according to six main types:

- loss of veld cover,
- deforestation,
- change in species composition,
- alien species invasion,
- bush encroachment,

- and the expansion of mining, urban, and commercial agricultural areas.

Given the high levels of poverty and the many challenges facing the area, the Mzimvubu catchment has been proposed for largescale development. However, this development needs to be considered in terms of the impact on the hydrology of the area as the numerous proposed land use change scenarios will impact the catchment flows in different ways. Thus the changes in land use within the catchment need to be simulated to allow for the hydrological responses of different water resources management plans to be understood.

It was proposed that a study be done to (i) verify the use of the ACRU model for two sub-catchments within the greater Mzimvubu catchments, (ii) given the level of degradation present within the catchment and the perceived uncertainty in the current degraded parameters, derive revised degraded vegetation parameters that are consistent and based on observations for use within the ACRU model, and (iii) determine the effects of different rangeland and agricultural land use management scenarios on the water flows within the catchment using the ACRU model to inform the land use changes to be taken in the catchment. Owing to the larger WRC study utilising the ACRU model, the study within the Mzimvubu also made use of the model. However, a weakness of the model was identified in the early stages of the project whereby the ACRU parameters used for the modelling of degraded vegetation needed to be revised to make them consistent and based on observation.

The following research questions were posed:

a) Can remotely-sensed LAI data be used in determining the vegetative parameters of degraded areas within the catchment to model the degradation more accurately?
b) How does the use of the revised degraded vegetation parameters affect the model simulations for the Mzimvubu catchment?
c) How will changes in land use within the catchment affect water quantity, including the amount of baseflow, stormflow, and streamflow available?
d) Will rangeland practices have a greater impact on the available water quantity than agricultural practices?
e) How will the hydrological impacts of the already high level of degraded areas within the catchment be impacted by increased subsistence farming and overgrazing?

It is hypothesised that changes in land uses have significant impacts on the hydrological flows of a catchment. Of these changes, degraded vegetation has the most noticeable impact on the stream-, quick- and baseflows of a catchment.

1.2 Aims and Objectives

The aim of this research was to model the changes in water quantity in the Mzimvubu catchment using the ACRU model in order to determine the impacts on water resources under different land use management scenarios related to the degradation of natural vegetation. The effects of degradation throughout the catchment were considered, with proposed improvements to the degradation parameters used within ACRU derived.

The following objectives were determined for this study:

a) To improve the way in which the ACRU model simulates degraded areas through the use of remotely-sensed LAI data to derive vegetative parameters for degraded areas.

b) To assess how different land use management scenarios alter water flows, including stormflow, streamflow and baseflow amounts, by comparing the flows simulated under each change to those of the baseline determined for the catchment. The land use management changes to be modelled were:

   a. increases in degraded areas throughout the catchment, as well as the rehabilitation of already degraded land,
   b. increases in bush encroachment as a result of overgrazing,
   c. increases in the area under burning management regimes,
   d. changes in both subsistence and commercial agricultural management practices, particularly changes in the areas under irrigated and dryland agriculture, and
   e. changes in dryland crops from current to proposed sorghum biofuel crops.

1.3 Outline of Dissertation

A review of relevant literature is given in Chapter 2 on how the main changes in land use identified, both current and proposed, impact on water resources and flows, and how degradation parameters can be determined. This is then followed by conclusions drawn from the available literature. In Chapter 3, background on the study site is given and the methodology used in this research is presented. This methodology includes that of the verification of the ACRU model for the study area, as well as the development of a methodology for the recalculation of degraded vegetation parameters for use in the ACRU model, and lastly a methodology for the modelling of land use changes. Chapters 4 and 5 present the results of the study, along with a comprehensive discussion of the results obtained. Lastly, Chapter 6 provides the conclusions, along with recommendations drawn from the study and the contribution made by the research to better the understanding of parameterizing degraded vegetation and the impacts of changes in land use management practices on water quantity in the Mzimvubu catchment.

2. REVIEW OF LITERATURE

Land use and the hydrologic cycle are inextricably linked as the type of land use and vegetative cover will impact the stream-, base-, and quickflow generated from an area. Agriculture, on both a commercial and subsistence level, has been identified as one of the main economic and developmental drivers in the Mzimvubu catchment. Thus, it is expected that the changes in land use management practices will be dominated by agricultural activities, both in terms of irrigated and dryland agriculture. Given that a portion of the Mzimvubu catchment study area falls within the former Transkei homeland (Figure 2.1), the issue of land degradation poses a problem to the project given that there is no consensus amongst different scientific communities regarding how degradation is defined. The review of literature covers the impacts of different agricultural activities on water resources given that much of the proposed development in the catchment is agriculturally based. It also considers how degradation is defined across a number of disciplines, and how degraded vegetation parameters can be determined for use in hydrological modelling.

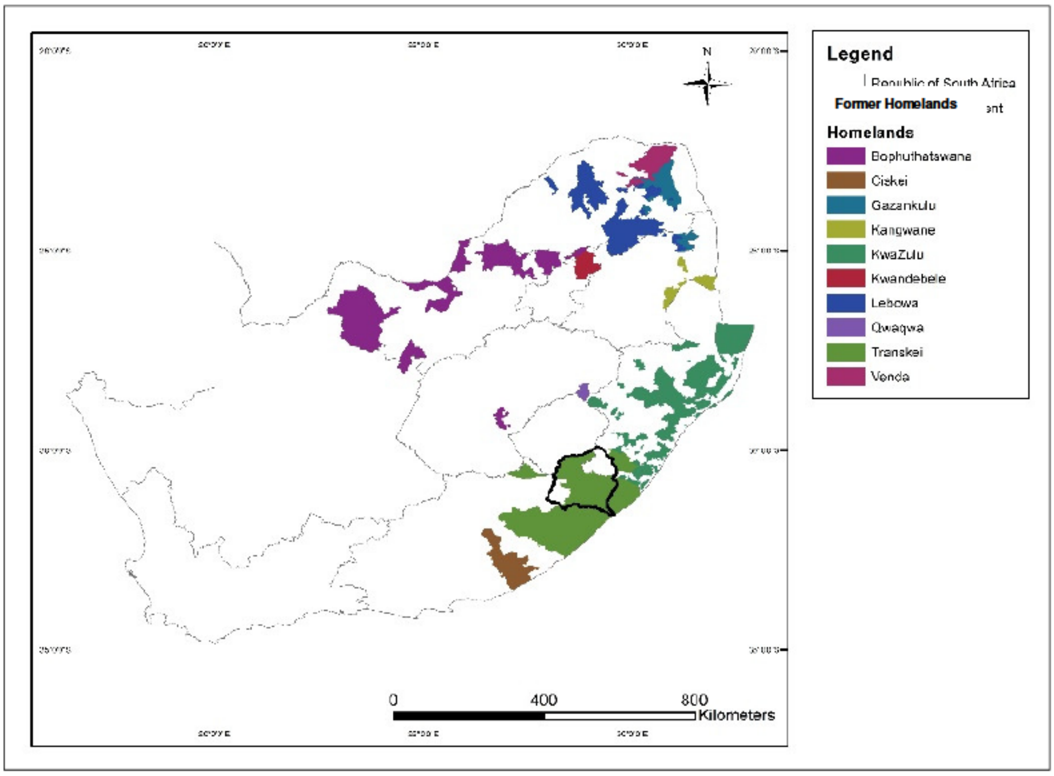

Figure 2.1 Location of former homelands within South Africa[1]

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[1] Homeland shapefile from: https://africaopendata.org/dataset/former-tbvc-states-shape-file

2.1 Impacts of Different Crops on Water Resources

The nature of the impacts of different crop types on water resources stem largely from the different vegetative properties of different crops such as albedo, LAI, rooting patterns and dynamic forces, such as surface wind effects on the canopy (Gordon *et al.*, 2010), which influence the crop evapotranspiration. Not only do these properties differ between crop type but also at different life stages of each crop type. The crop yield is also highly influenced by the agricultural management practices used, irrigation, and climate (Parajuli *et al.*, 2013). Along with the numerous factors affecting yield, the evapotranspiration of different crops is also affected by numerous parameters, viz. climate, soil water availability and quality, method of irrigation system used, and agricultural practices (Doorenbos and Pruitt, 1992). As stated by Doorenbos and Pruitt (1992), the water required by different field and vegetable crops will vary depending on which of the four developmental stages the plant is in, i.e. germination, developmental, early maturity, or late maturity, meaning that the subsequent effects on water resources will vary throughout the season.

The agricultural crop which has the most significant impact on water is commercial afforestation. Given that the afforestation of land, for commercial purposes, reduces the streamflow of a river for all types of flow events (Smith and Scott, 1992; Sorriso-Valvo *et al.*, 1995; Lane *et al.*, 2005; Tewari, 2005; Nordblom *et al.*, 2012), it is imperative that forestry be monitored to ensure that the effects do not become too adverse on downstream ecosystems. The effects of commercial afforestation can be attributed to the fact that the LAI of trees is far greater than grassland vegetation it typically replaces owing to their evergreen nature which allows for significantly higher levels of evapotranspiration to occur from forested lands (Zhang *et al.*, 2001; Tewari, 2005). Whilst studies have been done on the impacts of afforestation on streamflow within South Africa including those by Gush *et al.* (2002), Dye and Versfeld (2007) and Everson *et al.* (2011), many have only taken afforestation into account and have not considered it as part of a greater change in land use practices.

Smidt *et al.* (2016) suggested that crops such as maize tend to be more favoured by farmers despite their water-intensive nature, as they will tend to produce the greatest profit after only a short growth season. This means that in many instances, short-term economic benefits will be chosen by the farmer over the long-term hydrological impacts caused by the irrigation systems used and the impacts caused by the type of crop grown. Therefore, it can be seen that depending on the types of crops grown, the water usage will vary and in many instances, water usage will increase as the more economically viable crops (including maize and forestry) have increased water consumption rates.

2.2 Impacts of Irrigated Agriculture on Water Resources

Due to the reduction in flows in many areas, irrigation is considered a consumptive water use. Poorly managed irrigation schemes result in a dominance of processes that are considered as losses to the natural hydrological system, viz. evaporation and transpiration (Gordon *et al.*, 2010). Should the irrigation amount applied exceed the crop's needs, it will either infiltrate the soil and increase the height of the water table or it will evaporate and increase the level of humidity within the area (Gordon *et al.*, 2010).

In a study in the Pinios river catchment in Greece, it was shown that were the irrigated agriculture to be removed, the annual and monthly flows would increase and the evapotranspiration would decrease as a result of the irrigated crop demand not existing (Stefanidis *et al.*, 2016). There is also the potential for a decrease in the annual groundwater recharge should irrigation be used in areas where groundwater is abstracted for irrigation purposes due to less soil infiltration occurring as irrigation limits the amount of water applied (Ghaffari *et al.*, 2010).

Merchàn *et al.* (2013a) and Gordon *et al.* (2010) showed that monthly and annual flows are changed by irrigation, and the nitrate and salt loads within the basin's watercourses increased after the introduction of irrigation systems in the area. Irrigated agricultural practices have resulted in adverse impacts on water resources, including the salinization of areas that have become waterlogged, nutrient leaching from the use of fertilizers, and salt mobilization (Scanlon *et al.*, 2007). Van Rensburg *et al.* (2011) postulated that the type and level of impact caused depended on the management of the irrigation schemes, saying that increases in salinity and changes to flows tend to be as a result of poor management of the irrigation system, rather than as a result of the system itself.

2.3 Impacts of Conservation Agriculture and Tillage on Water Resources

Conservation tillage, as defined by Van Wie *et al.* (2013), involves the use of reduced- and no-till techniques in order to reduce the levels of soil erosion by leaving a minimum of 30% crop residue on the croplands. During the study conducted by Kongo and Jewitt (2006) in the Potshini area of South Africa, it was seen that conservation tillage methods caused a reduction in cumulative surface runoff that was over 100% greater than that of traditional tillage methods. These findings were confirmed by Kosgei *et al.* (2007) in the same area, where it was found that no-till practices resulted in higher soil moisture contents and generated lower wet season runoff, as well as increases in the maize yields, when compared to conventional tillage practices. In agreement, Ngigi *et al.* (2006) showed that conservation tillage measures not only increased soil moisture storage and plant water use by upwards of 25%, but also reduced the amount of surface runoff (Figure 2.2). This means that whilst water was being retained in the soil for crop use, the catchment's runoff yields and peak flows were reduced.

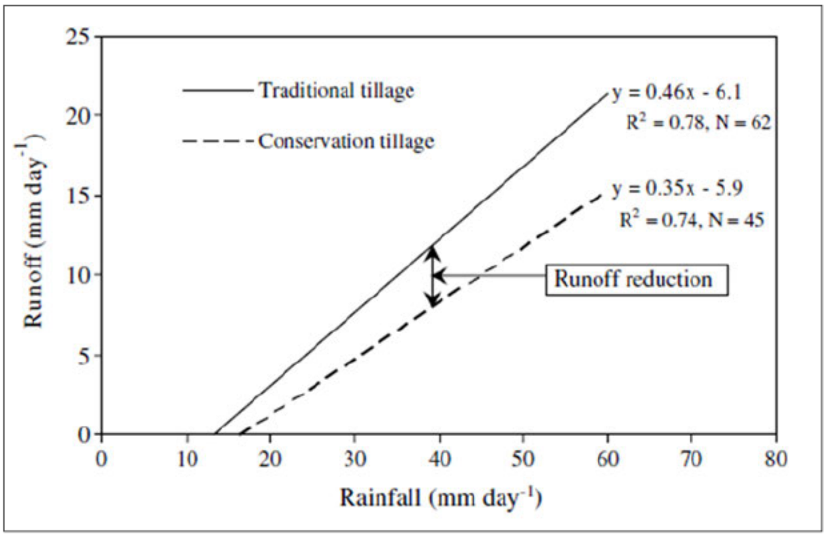


Figure 2.2 Rainfall-runoff relationship for different types of tillage practices in the Ewaso Ngiro basin (after Ngigi *et al.*, 2006)

In the study conducted by Nyamadzawo *et al.* (2012) in Zimbabwe, it was shown that conservation measures decreased the amount of surface runoff and soil eroded from the study sites and caused increased infiltration, thereby causing a change to the ground and surface flow regimes. Similarly, Garg *et al.* (2012) showed that, whilst the runoff losses were smaller and allowed for improved agricultural productivity in a region with highly variable rainfall, the introduction of conservation methods decreased the downstream flows by up to 50%.

2.4 Impacts of Livestock Grazing on Veld Condition and Water Resources

Whilst non-point pollution of water sources from livestock waste is well documented in studies such as those by Goldberg (1989), Hoorman *et al.* (2008) and Gu *et al.* (2008), the main impact on water resources caused by livestock in the Mzimvubu area will be as a result of erosion.

Both the physical action of different livestock hooves and the stocking rate affects the land under grazing due to the constant movement and compaction of the soil (Mwendera and Saleem, 1997a; Stavi *et al.*, 2016).

The nature of pastoral systems is problematic. If riparian areas are within, or bordering, the pasturelands, livestock will tend to graze these areas disproportionately, resulting in eroded streambanks and sedimentation of watercourses (Scrimgeour and Kendall, 2002). Mixed farming systems, on the other hand, affect the water resources both with respect to livestock and crop practices as not only are the effects of grazing on pasturelands observed, but irrigation required by the crops grown will also impact the local water resources (Schlink *et al.*, 2010).

Mwendera and Saleem (1997a) showed, in the Ethiopian Highlands, that both surface runoff and soil erosion increased as stocking rates increased and could be attributed to the combined compaction by the animals' hooves and the removal of vegetative cover by grazing. This effect on soil erosion and surface runoff was further shown by Savadogo *et al.* (2007) in Burkina Faso and Stavi *et al.* (2011) in the USA, whereby it was determined that grazing reduced the soil's infiltration capacity through hoof compaction. The greater the stocking rate on an area, the greater the risk of erosion is and the higher the chance of eroded soil entering nearby waterbodies (Figure 2.3).

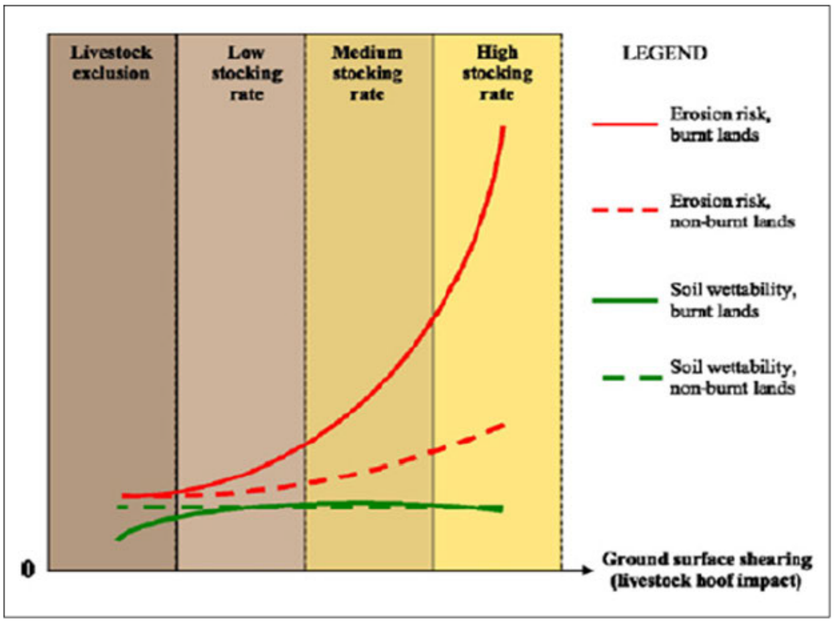


Figure 2.3 Effect of different stocking rates on soil wettability and soil erosion (after Stavi et al., 2016)

The modelling done by Van Zyl and Lorentz (2003) showed that livestock grazing increased the sediment yield of the Weatherly and Kokstad research sites, although the increases were small in comparison to those of veld conversion to arable land (). These findings of increases in sediment yields are supported by the report by Gbetibouo and Ringler (2009) which suggested that in many areas of South Africa, the carrying capacity of grazing lands is exceeded which then leads to increased erosion and land degradation. Further to this, studies such as those by Martindale (2007), Hockey *et al.* (2015) and Dedekind (2016b) describe how the grazing habits of livestock tend to cause changes in vegetation type which further exacerbates the degradation of the grazing land.

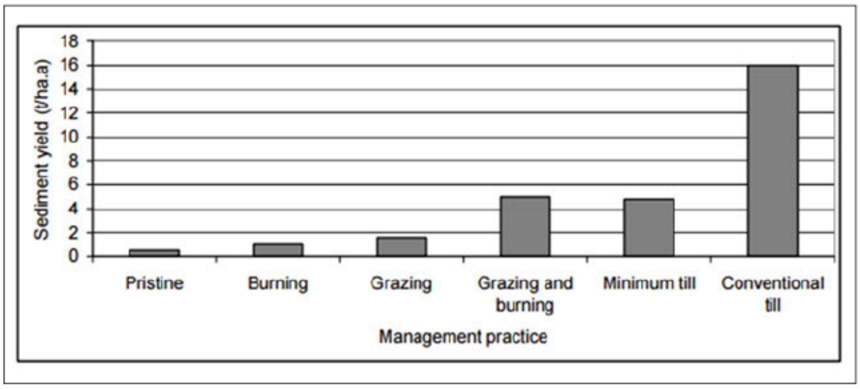


Figure 2.4 Modeled sediment yields for different farming practices in the Weatherly catchment (after Van Zyl and Lorentz, 2003)

It is also noted by Pimentel and Kounang (1998) and Van Tol *et al.* (2016) that soil erosion increases when land is degraded and overgrazed by livestock, as much of the vegetative cover is removed and the soil becomes compacted, causing infiltration to decrease and surface runoff to increase. Given that grazing by livestock removes much of the vegetative cover from the soil surface, continuous grazing can result in increased soil erosion and eventual land degradation (Chartier and Rostagno, 2006). The soil that is eroded can then enter the nearby watercourse, where much of the sediment is deposited causing the natural water resources to degrade. This sedimentation of waterbodies is shown not only to silt up the channels, but also to lead to a water crisis as water resources are degraded by excess sediment (Van Tol *et al.*, 2014; Parwada and Van Tol, 2016).

Pimentel and Kounang (1998) state that as surface runoff increases and the soil infiltration decreases, erosion increases. Not only does this increase the amount of water becoming streamflow, but it also means that nutrients such as nitrogen and phosphorous held in the eroded soil are transported away and enter the watercourses near to where the erosion has occurred. This increase in nutrient-rich sediments within the water resources can then lead to siltation of channels and reservoirs, eutrophication of rivers and waterbodies, soil pollution of aquatic ecosystems and increased risk of flooding as the river channel is altered by sediment deposition.

2.5 Representing Degraded Areas in a Hydrological Model

The degradation of natural vegetation can have significant and sometimes irreparable impacts on a catchment's water resources. Healthy vegetative cover not only acts as a protective layer that intercepts, evaporates, and regulates the precipitation of the area (Figure 2.5), but the rooting system of the vegetation binds the soil and allows for infiltration into the soil, which allows for groundwater recharge whilst also reducing overland flow (Qin, 2016). However, as a catchment becomes degraded, the regulation of these hydrological processes by the natural vegetation is disrupted. As shown during the studies of Mander *et al.* (2008) and Schulze *et al.* (2009), the degradation of natural vegetation leads to an increase in streamflow and decrease in baseflow.

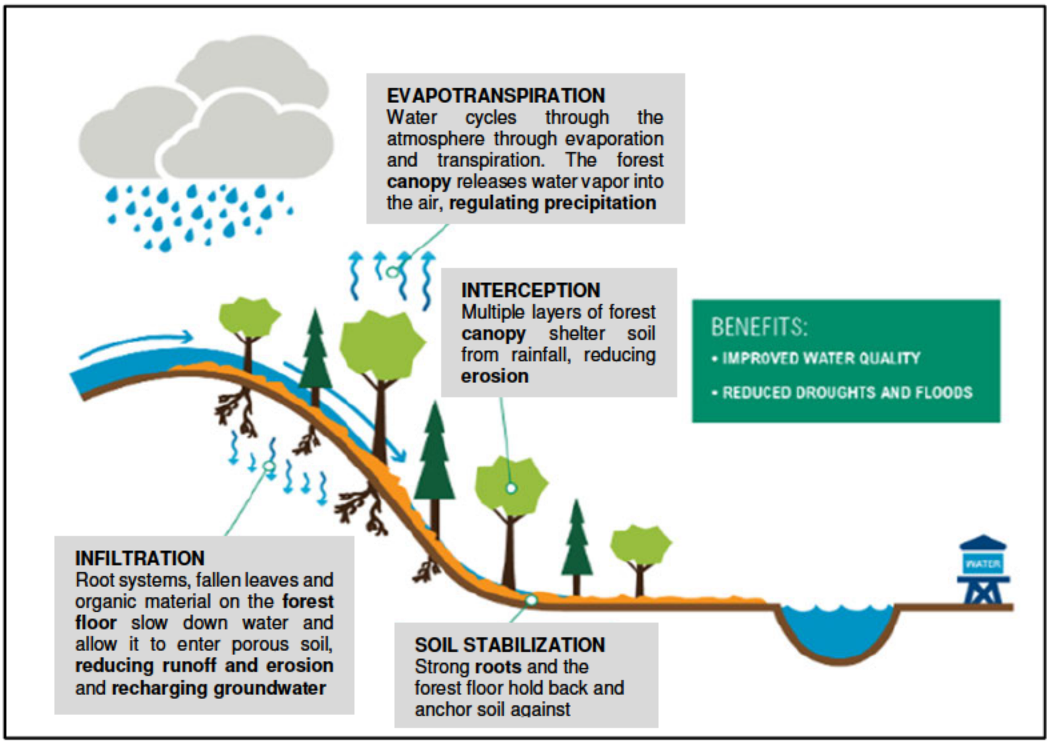


Figure 2.5 Impact of healthy vegetative cover on water resources (after Qin, 2016)

An obstacle in the determination of degraded areas, however, is that of the classification used to define such areas in the NLC 2000 (Van den Berg *et al.*, 2008). According to SANS 1877 (SABS, 2004), degraded areas are classified as those with reduced vegetative cover as a result of human activity, meaning that a level of subjectivity exists in the classifying of whether land is degraded or not. Hoffman and Todd (1999) showed that the definition of veld degradation can encompass a number of different aspects of degradation – from loss of cover and species change to urbanisation and alien invasive species infestations. For this study, the definition of degradation was limited to a loss of vegetative cover as a result of overgrazing and poor rangeland management practices.

2.5.1 Background to the ACRU model

The ACRU model is a physical conceptual model that works at a daily time step and was chosen by the WRC project, and therefore for this study, given its ability to allow for assessments of land use changes to be carried out and subsequent changes to water resources to be determined (Schulze *et al.*, 1995a). Not only has the model been used in projects both locally and internationally, but it has also been used for a range of different purposes, including changes in land use, design hydrology, and crop yield estimations (Nemeth *et al.*, 2012; Gericke and Smithers, 2017; Schütte and Schulze, 2017; Smithers *et al.*, 2017; Aduah *et al.*, 2018; Kusangaya *et al.*, 2018; Smithers *et al.*, 2018).

The model uses a multi-layer soil water budgeting process (), that considers the distribution of soil water throughout the soil. Any precipitation that is not partitioned into vegetation interception or directly to streamflow enters the soil surface and fills up the topsoil horizon until its drained upper limit. Once this limit is reached, water then percolates through to the subsoil horizon where it proceeds to fill to the subsoil's drained upper limit before then further percolating into the groundwater store from where baseflow is generated within the model (Smithers and Schulze, 1995).

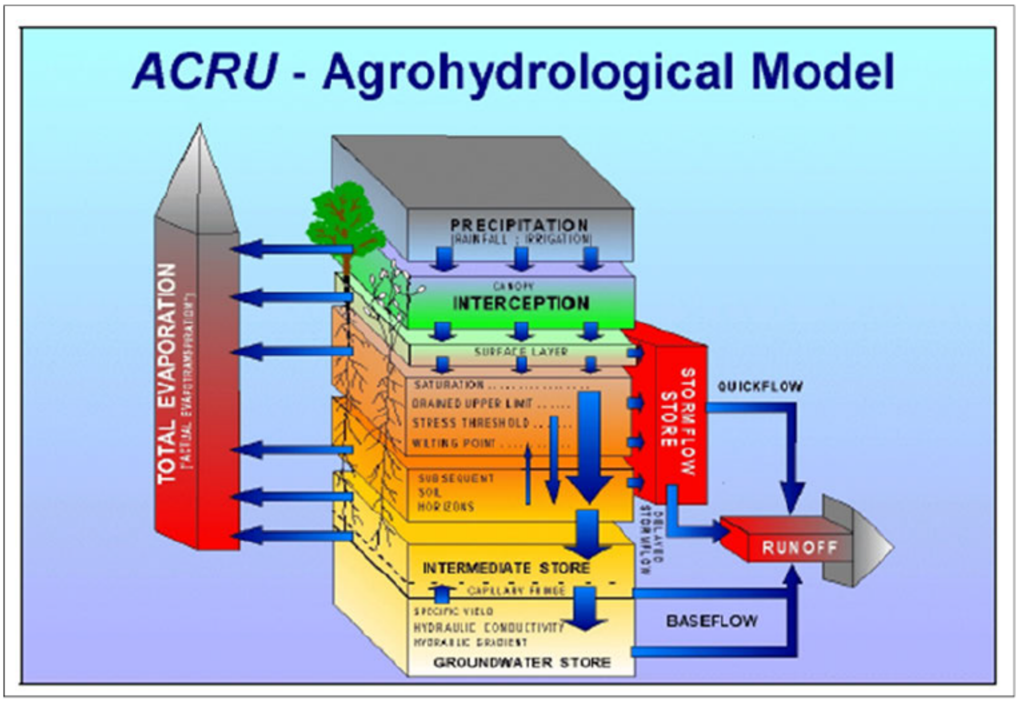


Figure 2.6 The ACRU soil water budgeting process (after Schulze *et al.*, 1995a)

Stormflow is generated within the model by firstly considering all initial abstractions (such as interception, depression storage and infiltration), and then producing runoff based on the amount of rainfall, its intensity, and the critical stormflow-generating soil depth. Whilst stormflow is generated on a daily basis, it does not all exit the catchment on the same day as the model allows for a lag to be created between stormflow generation and its leaving the catchment.

2.5.2 Modelling of vegetation types within the model

In order for the soil water budget to be realistically represented within the model, the vegetation and land cover of an area need to consider the above-ground, surface, and below-ground factors of the particular cover. These factors include canopy interception, water use by the vegetation type, amount of litter on the surface, and rooting distributions (Schulze *et al.*, 1995b). Given the problem with assigning a dominant land type to a particular HRU (in order to give a standardised set of crop parameters), the ACRU model uses the Acocks vegetation types (Acocks *et al.*, 1988) as the baseline natural vegetation cover of a catchment with a number of working rules being used to determine the most suitable crop parameters for the particular veld type based on expert opinion (Schulze, 2008a). It is this natural vegetation that was chosen to be used in the representation of degraded areas by adjusting the natural vegetation cover parameters.

Within the ACRU model, each crop type is represented by a number of crop parameters including the crop coefficient (CAY), interception losses (VEGINT), and percentage surface cover (PCSUCO).

The crop coefficient, K_c (or CAY in the model) (Monteith, 1965), can be calculated using ET from vegetation at a particular growth stage and the reference ET_o from a nearby control site (Equation 2.1).

$$K_c = \frac{ET}{ET_o} \tag{2.1}$$

This relationship between the evapotranspiration of the crop and that of a reference site gives an indication as to the amount of vegetation that is actively undergoing photosynthesis (Schulze, 2008a). Monthly data is typically used to calculate coefficients that reflect the growth and senescence stages of the vegetation, such as those in Figure 2.7.

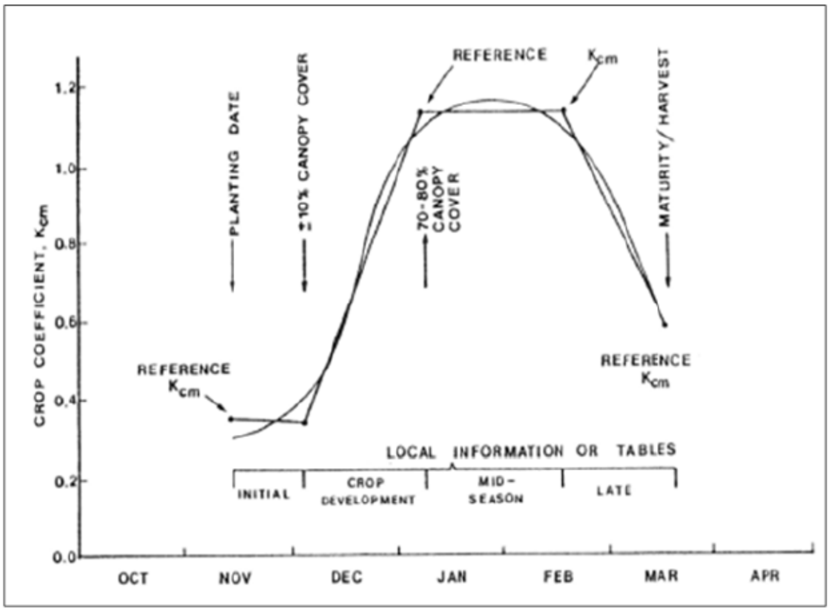


Figure 2.7 The FAO generic method for determining crop coefficients (after Doorenbos and Pruitt, 1977)

The interception values on which the Acocks veld type VEGINT parameters were based were taken from the work done by De Villiers (1975). The maximum interception values calculated in the study were then adjusted according to MAP, frost days, monthly heat units and rainfall concentrations corresponding to the veld types to give the final crop parameters for use within the ACRU model (Schulze, 2008a).

The percentage surface cover caused by vegetative litter (PCSUCO) for each of the Acocks veld types were determined using the crop coefficient, K_c (Schulze, 2008a). However, despite Figure 2.7 showing a dynamic growth cycle for vegetation, the PCSUCO value within each set of crop parameters is determined using the highest monthly K_c value for the vegetation class (Equations 2.2 to 2.4) (Schulze, 2008a), resulting in a constant PCSUCO value.

$$PCSUCO = 100(K_c - 0.2) \qquad \text{for } 0.2 \leq K_c \leq 0.40 \qquad (2.2)$$

$$PCSUCO = 20 + 177.8(K_c - 0.40) \qquad \text{for } 0.4 < K_c \leq 0.85 \qquad (2.3)$$

$$PCSUCO = 100 \qquad \text{for } 0.85 < K_c \qquad (2.4)$$

Within the ACRU model, a generalised set of degraded vegetation parameters (i.e. a loss of vegetative cover) was determined to allow for degraded areas to be modelled within the South African Quaternary Database. However, these values were not determined from any one veld type and were instead assigned based on expert opinion (Schulze *et al.*, 2008). Studies conducted in both the Baviaanskloof and Maloti catchments based degraded vegetation parameters on the Acocks veld type used as each catchment's baseline vegetation type (Mander *et al.*, 2008; Schulze *et al.*, 2009). In both instances, the baseline crop parameters were changed according to the assumptions that overgrazing would lead to a reduction in the amount of plant matter available for transpiration and interception, and a reduction in the amount of litter on the soil surface.

2.5.3 Determination of vegetation parameters from observed data

One of the biggest challenges facing the determination of vegetation parameters for modelling, however, is the fact that, as is the case in many studies (Oluwole and Sikhalazo, 2008; Stronkhorst *et al.*, 2009; Stronkhorst *et al.*, 2010a; Stronkhorst *et al.*, 2010b; Stronkhorst *et al.*, 2010c; Manssour, 2011; Ndandani, 2016), land degradation has been quantified in terms of changes in species composition, with the determination of percentage changes in Increaser and Decreaser species being the primary focus and indicator of land degradation. Whilst this methodology is useful for crop and animal scientists studying grazing habits and changes in veld species (Martindale, 2007a; Hockey *et al.*, 2015b; Dedekind, 2016a), it does not provide for an adequate determination of the hydrological implications of land degradation, as these studies focus on changes to species rather than loss of vegetative cover.

In order to derive a relationship between natural veld and areas where there has been a loss of vegetative cover based on observation, this study considered three methods based on available literature, including (i) the use of remotely-sensed data to determine vegetation properties, (ii) the use of the SEBS model to calculate evapotranspiration from remotely-sensed data, and (iii) the use of LAI to calculate evapotranspiration from remotely-sensed data.

2.5.3.1 Physical data determination

One such method is that of using remotely-sensed data that can then be processed to determine a number of physical and climatic data for large areas. A number of studies (Wessels *et al.*, 2004; Wessels *et al.*, 2006; Mambo and Archer, 2007; Bai *et al.*, 2012; Higginbottom and Symeonakis, 2014; Omuto *et al.*, 2014; Tasumi *et al.*, 2014; Dedekind, 2016a; Pun *et al.*, 2017) have attempted to show relationships between NDVI (normalised differential vegetative index) and levels of degradation. However, whilst much of the work undertaken has shown some correlation between the two, insufficient quantitative results have been obtained to allow for NDVI to be successfully used to quantify degradation.

2.5.3.2 Use of SEBS model to determine the evapotranspiration of vegetation

Another method of determining vegetative parameters through the use of remotely-sensed data is that of the SEBS (surface energy balance system) model developed by Su (2002). The model utilises radiation readings obtained from the processing of satellite datasets to determine the daily evaporative fraction which can then be used to determine daily ET values at particular sites (Gibson, 2013; Ncube *et al.*, 2016; Semmens *et al.*, 2016; Senay *et al.*, 2016; Sharma *et al.*, 2016; Ogunode and Akombelwa, 2017; Pun *et al.*, 2017).

However, whilst much of the work undertaken has shown that SEBS can be used to determine localised evapotranspiration on agricultural crops, insufficient work has been done on natural and degraded natural vegetation in South Africa to show that it may be used as an estimate for actual evapotranspiration.

2.5.3.3 Use of LAI to determine the vegetation parameters

The last method of calculating vegetation parameters is through the use of LAI to determine the crop coefficient and interception amounts. Numerous studies have proven a strong relationship between LAI and crop parameters (Al-Kaisi *et al.*, 1989; Čereković *et al.*, 2010; Shenkut *et al.*, 2013; Borges *et al.*, 2015; Abedinpour, 2016; Corbari *et al.*, 2017b).

Most of these studies use the FAO dual crop coefficient method (Allen *et al.*, 1998a) to determine the crop coefficient, K_c, and then use it as the assumed norm for calculating the crop parameter. This method combines the basal crop coefficient (K_{cb}) and the soil evaporation coefficient (K_e) to calculate the total crop coefficient, K_c, as given by Equation 2.5:

$$K_c = K_{cb} + K_e \tag{2.5}$$

In a South African context, Angus (1987) derived Equation 2.6 from the work done by Kristensen (1974) to allow for the calculating of LAI from K_c

$$LAI = \frac{ln(\frac{K_c - 1.0932}{-0.7947})}{-0.6513} \tag{2.6}$$

Interception loss (I_I) can be calculated according to the Von Hoyningen-Heune equation (Equation 2.7) (von Hoyningen-Huene, 1981) which is used to relate LAI and gross precipitation (P_g) to interception of vegetation.

$$I_I = 0.30 + 0.27P_g + 0.13LAI - \ 0.013P_g^2 + 0.0285P_g.LAI - 0.007LAI^2 \tag{2.7}$$

However, the equation is only stable for P_g values up to 18 mm.day^{-1}, meaning that any values above this limit will produce interception values that are potentially incorrect (Schulze *et al.*, 1995b).

Another method of calculating interception losses using LAI is with the variable storage Gash model. Based on the original Gash model (Gash, 1979; Gash *et al.*, 1995), the variable storage model allows for canopy interception to be determined by classifying storms according to the rainfall intensity, and then modelling the canopy interception (I_c), stemflow (S_f) and throughfall (T). The model has been successfully used in a South African context and, whilst the model itself is relatively complex in its workings, the data required to run it is relatively accessible (Bulcock and Jewitt, 2012).

2.6 Discussion of Literature Reviewed

The review of literature carried out provides for the assessment of impacts on water resources quality, as well as the determination of degraded areas. Not only can different crop types and livestock grazing practices impact on water flows and levels of erosion within a catchment, but different agricultural practices, including irrigated and conservation agriculture, will also impact the normal flows within the catchment. As such, it can be said that, based on available literature, changes in land use, especially from natural land to agricultural or through the degradation of natural veld, can have serious implications for the hydrological cycle within the catchment.

However, as much of the literature showed, many of the impacts on water resources have been determined throughout other parts of the world, with almost no work being carried out in the Mzimvubu area to determine how water flows will be impacted by the high levels of proposed development, much of which is intrinsically linked to agriculture. Of the literature available for the area, much of which has been focused either on grazing practices in Kokstad or else on the research catchment of Weatherly, very little consideration has been given to the modelling of different land use scenarios and impacts on the catchment's watercourses and bodies.

The scarcity of literature providing quantitative changes to the hydrology of an area after it has become degraded has meant that, in many instances, many of the parameter values used in the hydrological modelling of degradation scenarios have been based on educated assumptions, rather than field data. Whilst site-specific field data allows for the most realistic values for model input, the size and location of many catchments makes the acquisition of such data a difficult task, meaning that in situ vegetative assessments are unsuitable for large-scale studies and other data collection methods need to be considered. By creating a set methodology that makes use of observed data, the consistency and repeatability of parameter calculation is ensured, as opposed to the problems that arise when trying to extrapolate values based solely on expert opinion.

Given that the Mzimvubu River is the largest undeveloped watercourse in South Africa, this project was undertaken to determine how changes in land use would affect the water resources within the catchment, as well as look at methods to determine degraded vegetation parameters. This project will also differ from much of the available local literature as it will be forward looking in its consideration of potential scenarios, rather than having a retrospective take on the catchment dynamics.

3. METHODOLOGY

Given the size of the Mzimvubu catchment, the methodology needed to be determined and tested in smaller catchments before expansion to ensure that it would be suitable. In order to test the methodology developed, two smaller catchments – T35C and T32A/B/C – were selected based on them being the two smallest catchments within the Mzimvubu to have streamflow gauges at their outlets. From this, methodologies for the improvement of degraded vegetation parameters and the modelling of various land use changes scenarios were developed.

3.1 The Mzimvubu Catchment and Selected Sub-catchments Description

The Mzimvubu catchment is defined as the T3 secondary catchment within the Mzimvubu-Keiskama Water Management Area. The catchment drainage area is based on the Mzimvubu River, and its tributaries. The Mzimvubu catchment is a trans-province hydrological catchment, with part of the T3 catchment falling within the southwestern corner of the KwaZulu-Natal province and the remainder of the catchment falling within the north-eastern part of the Eastern Cape province (Figure 3.1). The catchment covers an area of 19 833.17 km^2 and comprises six smaller drainage areas (Figure 3.2a).

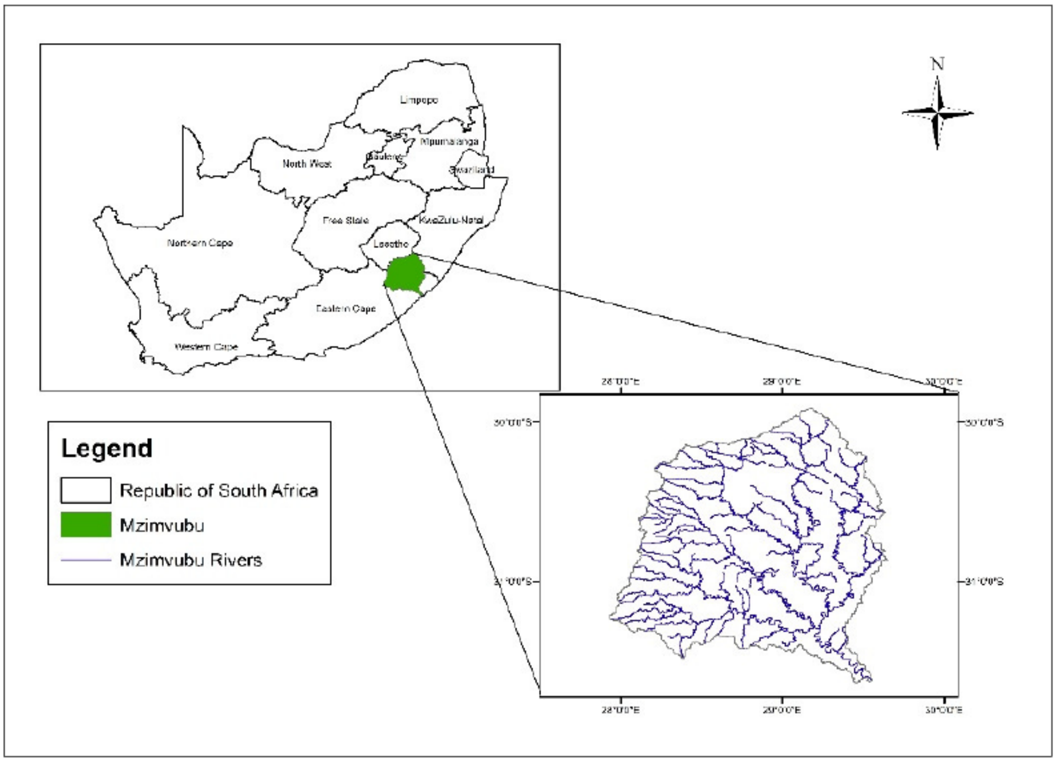


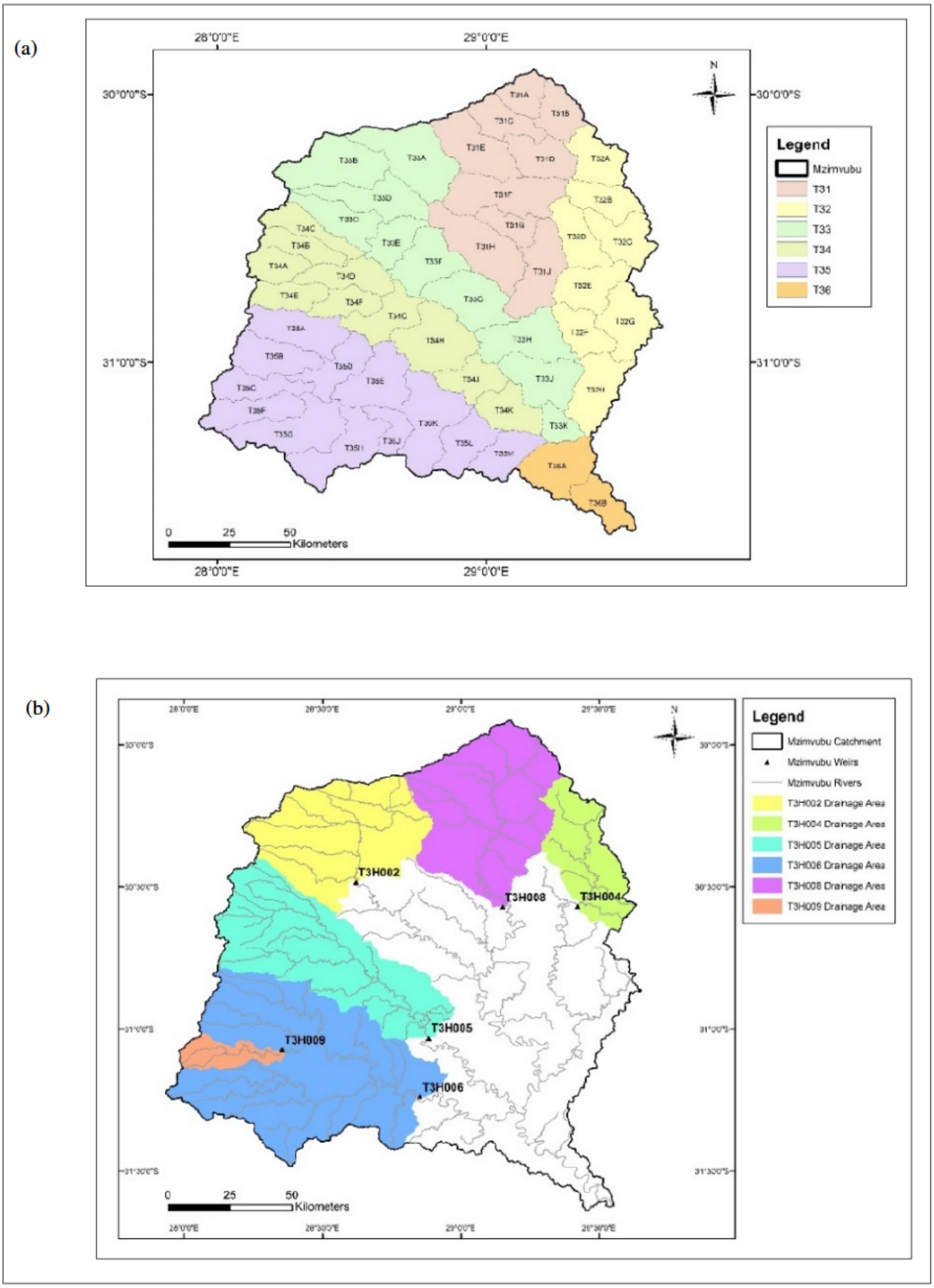
Figure 3.1 Location of the Mzimvubu catchment within South Africa

Catchments with gauging stations at their outlets needed to be identified to allow for observed streamflow data to be compared to the streamflow simulated within the model. However, given that much of the Mzimvubu catchment is unpopulated and the area is historically a very poor one, this presented a challenge. Not only are there very few weirs within the catchment, but, of the existing ones, only a few have an extended length of reliable recorded streamflow data. The drainage areas of most of these weirs (Figure 3.2b, Table 3.1), however, were deemed too large allow for an accurate verification study to be performed. This was owing to the fact that large catchments would require a far greater amount of generalisation of HRUs, to ensure the model would still function, which would then not allow for a truly accurate representation of the actual catchment characteristics. As such, the two smallest drainage areas – i.e. T32A/B/C monitored by T3H004 and T35C monitored by T3H009 – were chosen as the two catchments to be used in the study (Figure 3.2c).

Table 3.1 Details of streamflow gauges within Mzimvubu (taken from Department of Water Affairs, 2018)

Station	Location	Area (km^2)	Length of Record
T3H002	Kinira River @ Kinira Drift	2101	01/08/1949 - Present
T3H004	Mzintlava River @ Slang Fontein	1029	01/09/1947 - Present
T3H005	Tina River @ Mahlangulu	2597	20/09/1951 - Present
T3H006	Tsitsa River @ Xonkonxa	4285	16/10/1951 - Present
T3H008	Mzimvubu River @ Kromdraai	2471	11/09/1962 - Present
T3H009	Mooi River @ Maclear	307	15/08/1964 - Present

These two catchments were chosen as they were the two smallest catchments within the larger Mzimvubu catchment that had functioning weirs at their outlets. Whilst the two catchments were far larger than the recommended < 30 km^2 catchment for use in the ACRU model (Smithers and Schulze, 1995),they were representative of the larger catchment's climate, the land uses present in the larger catchment were represented in these sub-catchments, however, not at the same fraction and were thus deemed representative of the greater Mzimvubu catchment and used in the study. By subdividing the catchments into sub-catchments and then HRUs the limit of 30 km^2 was met. Where the concern sits is that the comparison between observed and simulated streamflows is done at a point where the accumulated catchment areas are far larger than 30 km^2. Any errors in the configuration and model parameters used are cascaded through the HRUs and sub-catchments, either amplified or cancelled out, and essentially obscured by the catchment outlet where the simulated flows are compared to observed flows. An overview of the larger Mzimvubu catchment is given in Table 3.2, along with the two study catchments used.



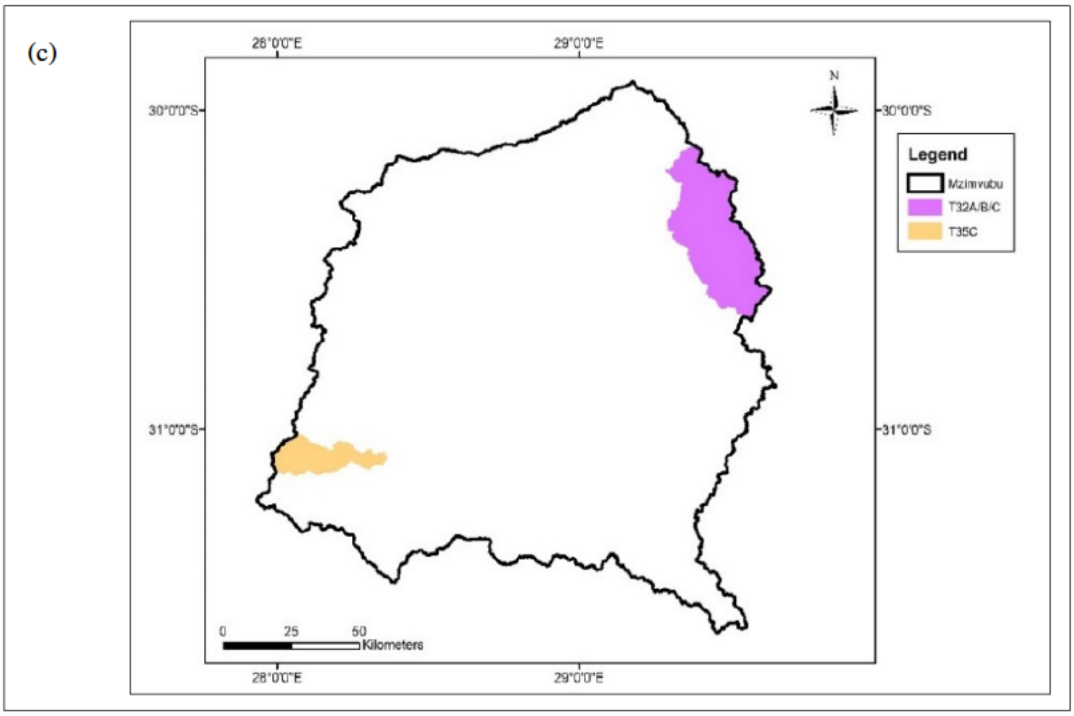


Figure 3.2 (a) Main drainage regions within the Mzimvubu catchment; (b) Drainage areas of Mzimvubu streamflow gauges with sufficient length of record; (c) Catchments selected for model verification and testing of methodologies

Owing to the far greater difference in size between the favoured ACRU catchment and the catchments used, a level of generalization had to be made which would have potentially led to oversimplification of the processes present. However, given that both observed and simulated streamflow was measured at the outlets of the catchments, and that both catchments were deemed representative of the larger catchment, it was decided that the larger catchments would provide a suitable replacement for smaller catchments (given that none smaller than 300 km^2 existed within the larger Mzimvubu catchment.

Table 3.2 Summary of key features of the Mzimvubu catchment and two study catchments

	Mzimvubu	T32A/B/C	T35C
Area (km^2)	19 833	1 029	307
MAP (mm p.a)	782	725	785
Average altitude (m.a.s.l)	1 372	1 555	1 550
Gauging Station	-	T3H004	T3H009

3.1.1 Climate of study area

The climate of the Mzimvubu catchment varies from the inland, head water catchments through to the coastal areas. The average mean annual precipitation for the catchment is 782 mm although parts of the catchment can receive up to 1226 mm whilst other areas are far drier at only 476 mm (Figure 3.3). The two study catchments have similar averages to the Mzimvubu catchment, with T35C having an average of 785 mm and T32A/B/C having an average of 725 mm of rainfall throughout the year. T32A/B/C has a more variable rainfall pattern throughout the year as opposed to T35C, which has a higher average rainfall.

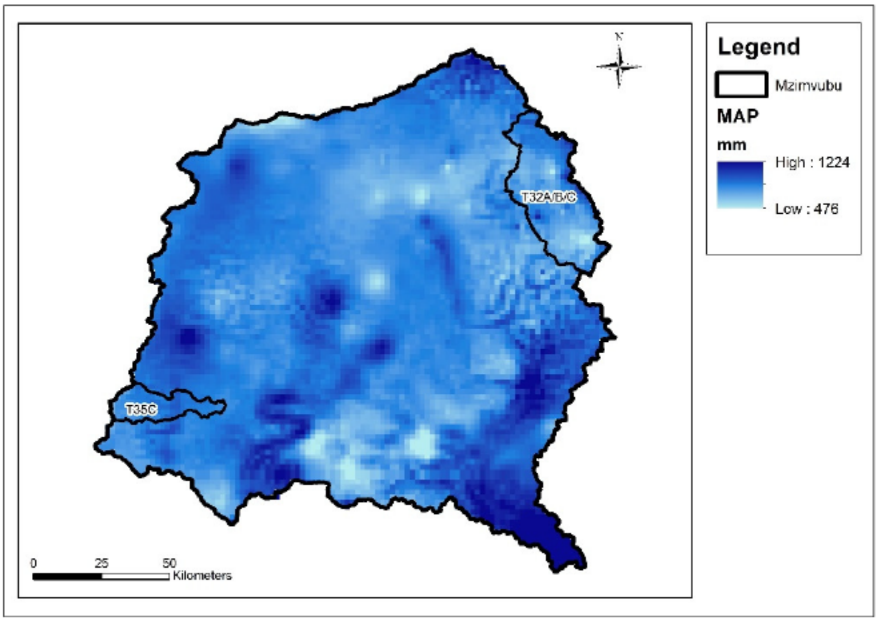


Figure 3.3 Mean annual precipitation (MAP) throughout the Mzimvubu catchment (Lynch, 2004)

The mean annual temperature (MAT) of the Mzimvubu catchment ranges from 6 to 19 °C showing that the catchment has a more temperate climate (Figure 3.4). The two study catchments have similar MATs to the larger catchment, although they differ between each other given that T35C is located further inland than T32A/B/C and has more mountainous areas in the catchment's headwater region, which accounts for the greater range in average annual temperatures.

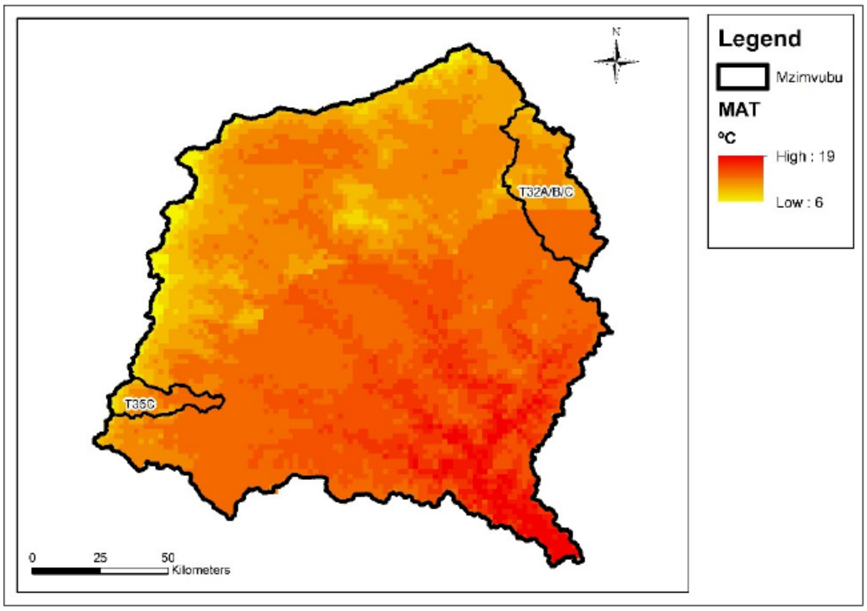


Figure 3.4 Mean annual temperature (MAT) throughout the Mzimvubu catchment

3.1.2 Topography of study area

The altitude of the Mzimvubu catchment varies drastically from the mountainous escarpments along much of the catchment's western boundary and the catchment outlet at Port St John's on the coast. Much of the northern part of the catchment is higher in altitude, with the height above sea level decreasing and levelling out towards the south-eastern parts of the Mzimvubu (Figure 3.5).

The two study catchments are both at higher altitudes than much of the Mzimvubu as both are located inland and in more mountainous parts of the catchment. Whilst T35C follows a natural downwards slope from headwaters to catchment outlet, T32A/B/C differs somewhat as there are more mountainous areas throughout which delineate the catchment into a number of altitudinal catchments.

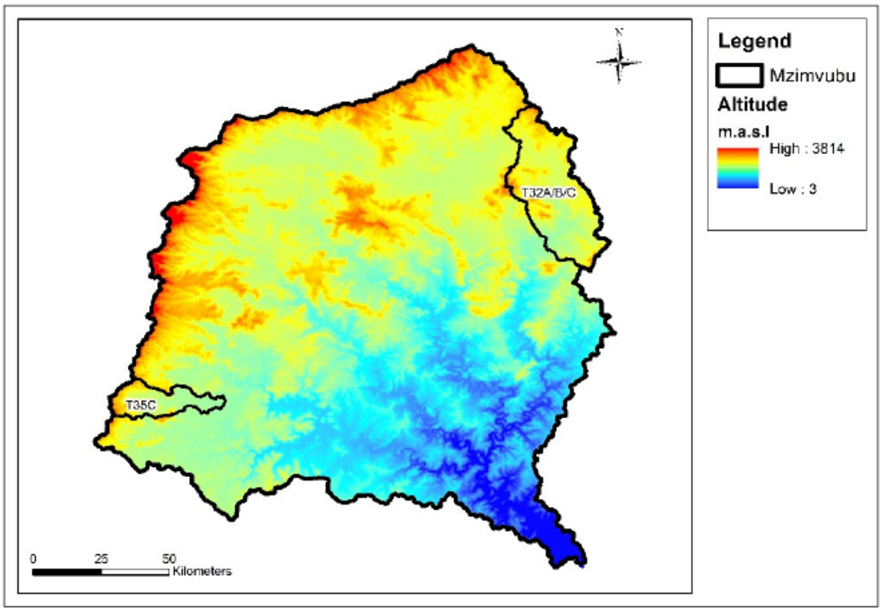


Figure 3.5 Altitude of the Mzimvubu catchment

3.1.3 Soils and vegetative cover of study area

Through the Mzimvubu catchment, several different Acocks veld types (Acocks *et al.*, 1988) are found. Much of the catchment has Highland and Dohne Sourveld (Acocks veld type #44) as the dominant grassland species with smaller areas under Highland Sourveld to Cymbopogon-Themeda Transition (#56) grasslands (Figure 3.6). In the mountainous western parts of the catchment the dominant grassland is Themeda-Festuca Alpine veld (#58), whereas the lower altitude areas, especially those surrounding the river channels, have Southern Tall grassveld (#65) as the dominant veld. Towards the outlet of the catchment, these grasslands are dominated by bushveld (e.g. Valley bushveld (#23) and Eastern Province thornveld (#07)) which then transition into Coastal Forest and Thornveld (#01) towards the coast.

The two study catchments have similar Acocks veld type to the larger catchment, with both having Highland and Dohne Sourveld as the predominating veld type (#44). However, whilst T32A/B/C has small areas of Highland Sourveld to Cymbopogon-Themeda Transition (#56) running through the catchment, the higher altitude of T35C means that small parts are under Themeda-Festuca Alpine veld (#58).

The land types present within the Mzimvubu catchment are shown in Figure 3.7. Sixteen broad Land Types were mapped across the catchment by the Agricultural Research Council - Institute for Soil, Climate and Water. The most dominant Land Type across the catchment is Fa. With fairly large areas of Ac in the higher lying, upper catchment areas. Many of the soils within the catchment are highly degradable and pose erosion risks to large portions of the catchment's vegetation. These land types are represented throughout the two study catchments and could be contributing factors to the degradation problems within the catchments.

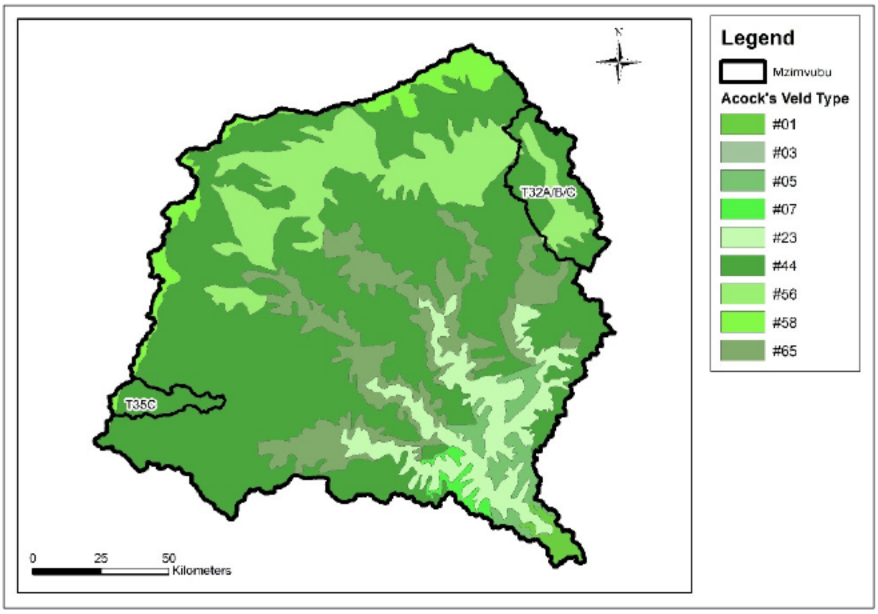


Figure 3.6 Acocks veld types within the Mzimvubu catchment

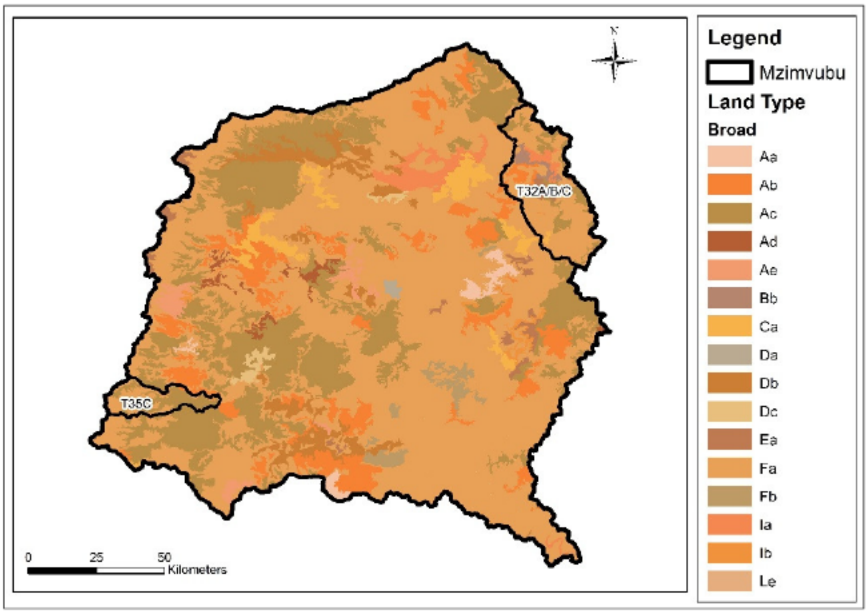


Figure 3.7 Broad land types within the Mzimvubu catchment

3.1.4 Current land use patterns in catchment

Currently, the Mzimvubu area is predominantly under agriculture and natural vegetation (Table 3.2 and Figure 3.8), with almost a fifth of the catchment considered as degraded natural veld. Of the land under agriculture, approximately 75 % is subsistence farming as many of the small communities rely on small plots to grow vegetables and rear small livestock for predominantly personal household use, whilst the remainder of the catchment's agriculture is commercial crop and cattle farming (Van den Berg *et al.*, 2008). The remainder of the catchment has small urban areas scattered throughout, as well as areas of commercial forestry in the higher rainfall parts. The large amounts of degraded veld presented in the upper western parts of the catchment corresponds to the Transkei homeland (Figure 2.1).

Table 3.2 Percentages of different land uses present within the Mzimvubu catchment

Land Use	% of Mzimvubu
Natural vegetation	44.9
Degraded areas	20.3
Waterbodies	6.5
Commercial forestry	5.5
Commercial agriculture	5.4
Subsistence agriculture	15.3
Urban areas	2.1

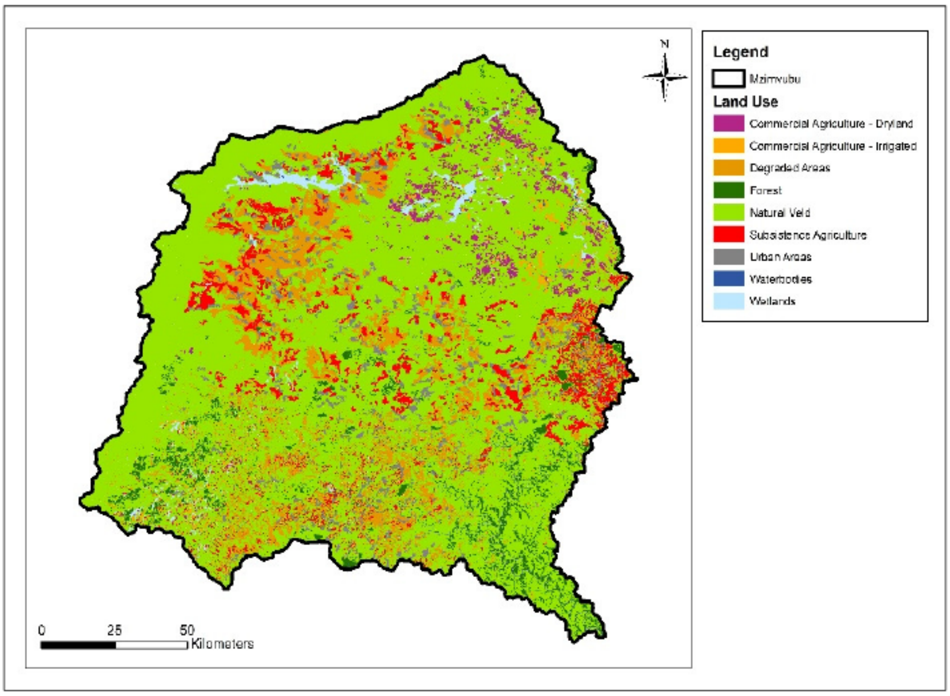


Figure 3.8 Land use classes within the Mzimvubu catchment

The land uses of the two study catchments adequately portray the larger land use patterns. From Figure 3.9 and Figure 3.10 , and Table 3.3, T35C has areas of commercial farming and forestry, as well as areas of degradation and large areas of natural veld, whilst T32 has large areas of commercial agriculture and subsistence farming, as well as urban areas and waterbodies.

Table 3.3 Percentage of total land use within each study catchment

Land Use	**T32A/B/C**	**T35C**
Natural vegetation	83.90	77.27
Degraded areas	1.00	2.40
Waterbodies	0.70	0.03
Commercial forestry	1.90	13.10
Commercial agriculture	11.10	7.10
Subsistence agriculture	0.90	0.00
Urban areas	0.50	0.10

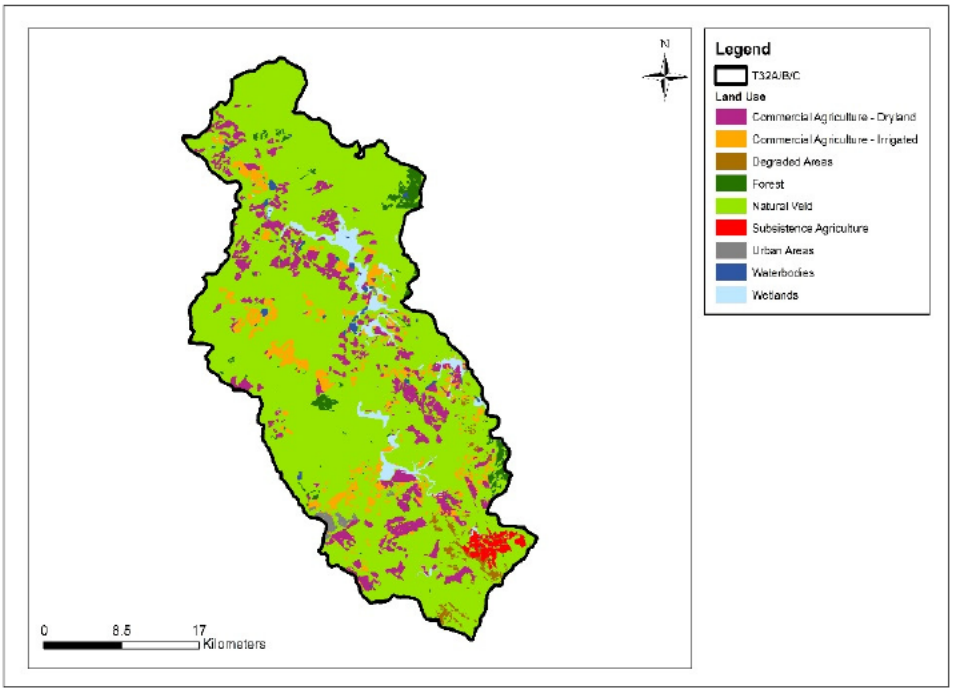


Figure 3.9 Land use classes within the T32A/B/C catchment

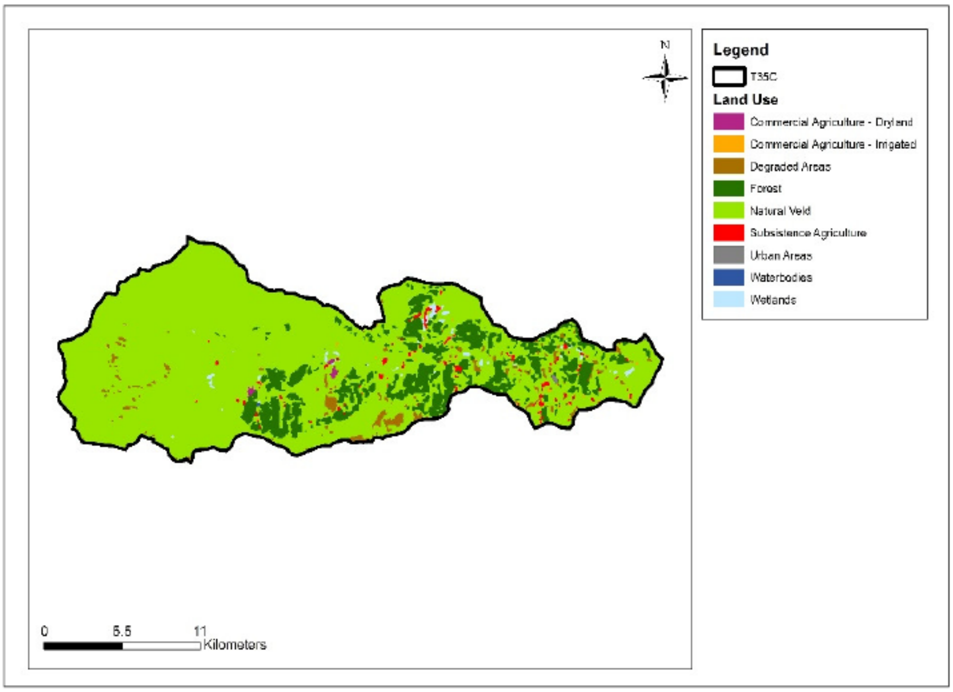


Figure 3.10 Land use classes within the T35C catchment

The methodology used in this study was threefold as it needed to (a) configure the model for each sub-catchment and consider the use of the ACRU model for the study sites through model verification, (b) develop a methodology for the determination of the degraded vegetation parameters using remotely sensed LAI data, and (c) develop methodology for the land use changes scenarios identified within the catchments used in the verification study.

3.2 Configuration and Verification of the ACRU model

The two catchments used in the study were delineated into sub-catchments based on the altitude, soils, land cover type and climate. These subcatchment were further delineated into hydrological response units (HRU's) that reflected similar land use and managerial conditions. These HRUs are not spatially explicit, but rather a grouping of each land use class. The T32A/B/C catchment was delineated into 33 sub-catchments (Figure 3.11), and 119 HRUs; whilst the T35C catchment was delineated into 17 sub-catchments (Figure 3.12) and 50 HRUs. Each of the sub-catchments within T32A/B/C and T35C were then delineated into HRUs based on land use types which varied throughout the individual sub-catchments.

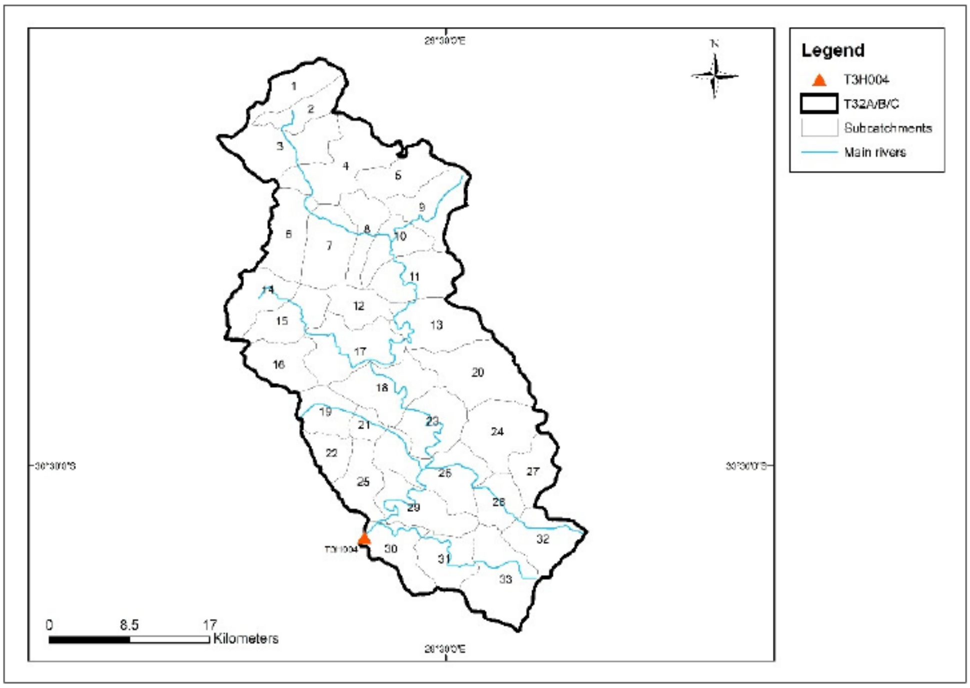


Figure 3.11 T32A/B/C sub-catchment delineations

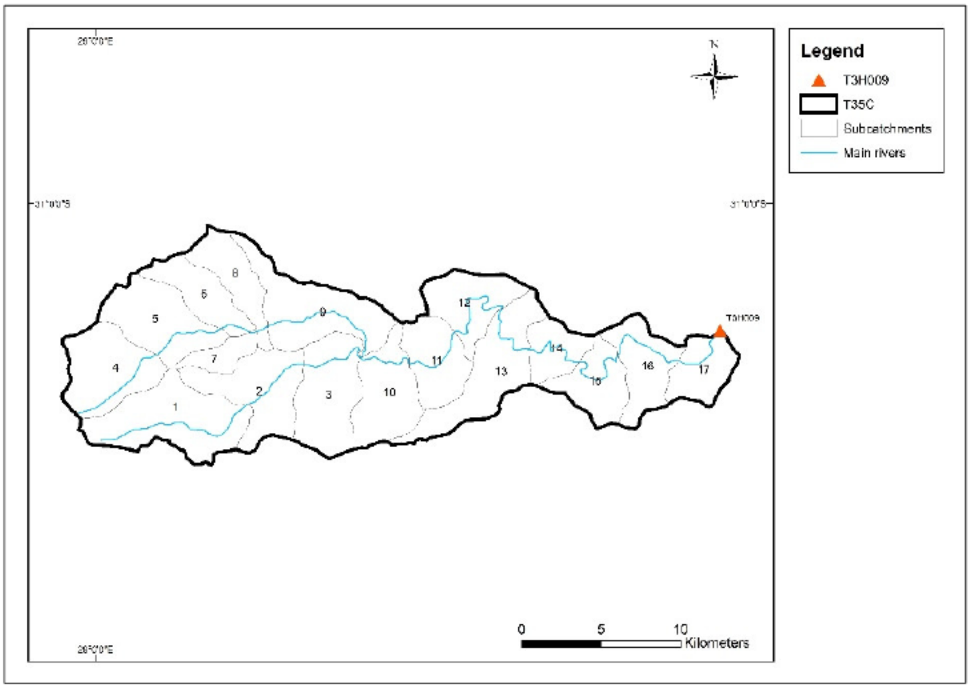


Figure 3.12 T35C sub-catchment delineations

3.2.1 Climatological data

The ACRU model requires a reference climate file for each sub-catchment. A climate file was created for each of the sub-catchments within both the T32A/B/C and T35C catchments. The ACRU model uses a .txt file (example given in Appendix A) type to provide the model with daily climatic data including:

- Daily rainfall (mm)
- Maximum daily temperature, T_{max} (°C)
- Minimum daily temperature, T_{min} (°C)

Owing to rainfall being the most important aspect of climate to be taken into consideration, each sub-catchment required a rainfall station to be determined in order for a rainfall record to be created. These stations were determined by similarities in altitude and MAP, as well as their proximity to the sub-catchment.

Whilst a number of the sub-catchments had rainfall stations next to or within the catchment, some of them were allocated a station a number of kilometres away. The reason for this is the very poor rainfall monitoring network within the Mzimvubu catchment – in a number of instances, stations other than the ones ultimately selected were located within a closer proximity to a sub-catchment but had patched and unreliable rainfall data, and thus were unsuitable for use in the study.

Once the rainfall stations had been selected for each of the sub-catchments (Appendix A), a 35-year daily rainfall record (from 1965 to 1999) was extracted from the South African daily rainfall database (Lynch, 2004) using the Daily Rainfall Data Extraction Utility tool developed by Kunz (2004). Given that the stations used were not all located within the catchment that they were driving, the monthly CORPPT factor within the ACRU model was used to give a more representative view of the catchments' areal rainfall. Driver stations provide a point measure and thus need to be corrected to allow for representation of a spatial sub-catchment. To calculate this factor, the median monthly rainfall was determined for both the individual stations as well as for each sub-catchment (taking the centroid of each to be representative of the larger sub-catchment's mean altitude) using the 1' by 1' latitude/longitude raster database of median monthly rainfall for South Africa (Lynch, 2004). Each individual monthly rainfall correction factor was determined according to Equation 3.1 and is given in Appendix A.

$$CORPPT = \frac{Median\ rainfall\ of\ sub-catchment}{Median\ rainfall\ of\ station} \tag{3.1}$$

To obtain the temperature requirements of each climate file, the daily maximum and minimum temperatures for each sub-catchment were extracted from the 1' by 1' latitude/longitude raster database of daily temperatures for South Africa (Schulze and Maharaj, 2004) for the 35-year record required for the catchment setups. As with the median rainfall data extraction, the daily temperatures were extracted for the sub-catchments using the centroid of each.

Given that there is minimal hydrological monitoring within the Mzimvubu area, daily A-pan evaporation records were not available for the two catchments or their sub-catchments, the Hargreaves-Samani option was used as it is one of the A-pan equivalent evaporation options available within the ACRU model. The 1985 version of the Hargreaves-Samani equation (Hargreaves and Samani, 1985) used in the ACRU model,

$$E_{pan} = 1.25\ x\ 0.0023\ x\ R_a x T_r^{0.5}(T_a + 17.8) \tag{3.2}$$

where $E_{A\text{-}pan}$ = A-pan equivalent reference potential evaporation (mm.day^{-1})

R_a = extra-terrestrial solar radiation (mm equivalent.day^{-1})

T_r = range of daily temperatures (°C) = $T_{max} - T_{min}$

T_a = average daily air temperature (°C) = $\frac{1}{2}(T_{max} + T_{min})$

estimates daily A-pan equivalent evaporation using only the T_{max} and T_{min} climate inputs, as R_a is determined using the latitude of the sub-catchment.

3.2.2 Soils data and streamflow response variables

All soil parameter data for both the A- and B-horizons were extracted from the electronic data of the *South African Atlas of Climatology and Agrohydrology* (Schulze, 2008b; Schulze and Horan, 2008), and included:

- depth of horizon (m),
- wilting point (m.m^{-1}),
- field capacity (m.m^{-1}),
- porosity (m.m^{-1}), and
- soil layer response.

The soil layer response depended on the horizon, with ABRESP parameter being the fraction of soil water that would move from the A- to B-horizon (i.e. from the topsoil to the subsoil) daily, whilst the BFRESP parameter related to the fraction of soil water that would be redistributed between the B-horizon and groundwater (i.e. from subsoil to intermediate or groundwater store) daily. As per the ACRU user manual (Smithers *et al.*, 1995), it was assumed that the percentage of groundwater that would become baseflow on a daily basis was between 0.9 % and 2 % depending on the individual sub-catchment steepness and soil properties.

Given that the ACRU model is based on the soil water budget, the initial soil moisture percentages were assumed to be 50 % for all soils and their horizons given that no field data was available for the sites, and it was assumed that the depth of soil (SMDDEP) from which stormflow generation would occur was equivalent to the depth of the soil's A-horizon. Given that the ACRU model is based on the soil water budget, the initial soil moisture percentages were assumed to be 50 % for all soils and their horizons. This assumption, based on the suggestion of Schulze (1995), was made as no field data was available for the sites. It was assumed that the depth of soil (SMDDEP) from which stormflow generation would occur was equivalent to the depth of the soil's A-horizon. The QFRESP parameter within the model, i.e. the amount of stormflow that would reach and exit the sub-catchment's outlet daily, was set to

0.3 in the lower parts of the sub-catchments and to 0.9 in the steeper headwater regions, as suggested by the user manual, and was sub-catchment specific. The reason for this was that the steepness, total percentage degradation, and type of vegetation within the sub-catchment affected the amount of stormflow that would reach the river course and exit the catchment on a day-to-day basis.

3.2.3 Land type and reservoir parameters

Owing to the very narrow nature of the many NLC 2000 classifications (SABS, 2004; Van den Berg *et al.*, 2008), the land classes identified within T35C and T32A/B/C were generalised into the HRUs given in Table 3.4. In each case, the most prevalent land class was taken to be representative of that land class within each sub-catchment. Whilst not ideal, the size of the study catchments meant that HRUs needed to be limited to ensure that the ACRU model could process the number of HRUs. Further delineation of land classes would have had minimal, if any, improvement on the catchment simulations without improved climate or soils data.

The natural vegetation was assumed to be Acocks #44 for both catchments – although some parts of the T32A/B/C catchment had veld type #56 present, the majority of areas under natural veld across all sub-catchments was #44. Given the lack of data available as to the specific crops under subsistence, dryland and irrigated agriculture for both catchments, the generic crop parameters within the ACRU model had to be used. Whilst not ideal, they adequately represented the majority of crop types within the Mzimvubu catchment.

Table 3.4 Generalised land classes used for the verification of the ACRU model

Land Class	Includes
Commercial Agriculture – Dryland	Permanent and temporary dryland agriculture
Commercial Agriculture – Irrigated	Permanent and temporary irrigated agriculture
Degraded Areas	Degraded areas and those identified as eroded areas
Forest	Commercial forestry
Natural Veld	Areas of natural grassland, shrubland and forests
Subsistence Agriculture	Areas of subsistence agriculture
Urban Areas	Areas of residential dwellings, from smallholdings to townships and suburban areas
Waterbodies	Reservoirs, either along a river course or smaller farm dams off channel
Wetlands	Any wetland area along the catchment's river course

The monthly vegetation parameters for each HRU identified in Table 3.4 were taken from the ACRU database of vegetation parameters (Smithers *et al.*, 1995; Schulze and Smithers, 2004). These parameters used are given in Appendix B and included:

- the crop water use coefficient (CAY),
- the coefficient of initial abstraction (COIAM),
- vegetation interception losses (VEGINT), and
- the fraction of active roots in the A-horizon (ROOTA).

The plant stress fraction (CONST) for all vegetation types was set to 0.40 as per the ACRU user manual recommendation (Smithers *et al.*, 1995).

The parameters for the reservoirs within the catchments were then determined. The surface area of the reservoirs was obtained from the 1:50 000 topographical maps of South Africa, whilst their capacities (DAMCAP) were determined according to the general algorithm for relating surface area with reservoir volume (Tarboton and Schulze, 1992). The monthly reservoir evaporation adjustment factors were determined from Schulze *et al.* (1995c). Given that both catchments sat on the boundary of Zones 1 and 3, the coefficients were adjusted to account for the transition areas (Table 3.5).

Table 3.5 Dam evaporation adjustment factors (after Schulze *et al.*, 1995c; Smithers *et al.*, 1995)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Adjustment Factor	0.700	0.705	0.725	0.720	0.700	0.680	0.630	0.620	0.625	0.640	0.650	0.655

It was assumed that each dam within the two catchments had an initial dam capacity of 70 % of its full capacity, and that the dead storage level was 10 % of the full capacity. The seepage losses from the reservoirs were determined using the suggested rule of thumb from the ACRU manual according to Equation 3.3(Schulze *et al.*, 1995c):

$$Seepage = \frac{1}{1500} x\ DAMCAP \tag{3.3}$$

Lastly, the irrigated areas that had been identified during the initial catchment selection were considered. A more conservative approach was taken with the irrigated areas as the scheduling selected was that of refilling to the drained upper limit of the soil profile (such as drip irrigation or sprinkler systems), rather than a centre pivot system which would incur greater losses. Irrigation conveyance losses were assumed to be 10 %, and spray evaporation and wind drift losses were assumed to be 8 %, in line with ranges given in the ACRU user manual (Smithers *et al.*, 1995).

3.2.4 Flow routing of sub-catchments

The sub-catchments within each of the two study catchments were configured within the ACRU model to allow for a realistic representation of the flow path in the catchments. Within each of the sub-catchments, the different HRUs were routed according to Figure 3.13 whereby individual HRUs were routed into a river node in the ACRU model which were then routed down a river and into another river node before routing through the sub-catchment node. These sub-catchments were then routed to represent the natural flow paths (i.e. the cascading of rivers downstream) in Figure 3.14 and Figure 3.15, with the numbers representing each of the sub-catchments delineated in Figure 3.11 and Figure 3.12.

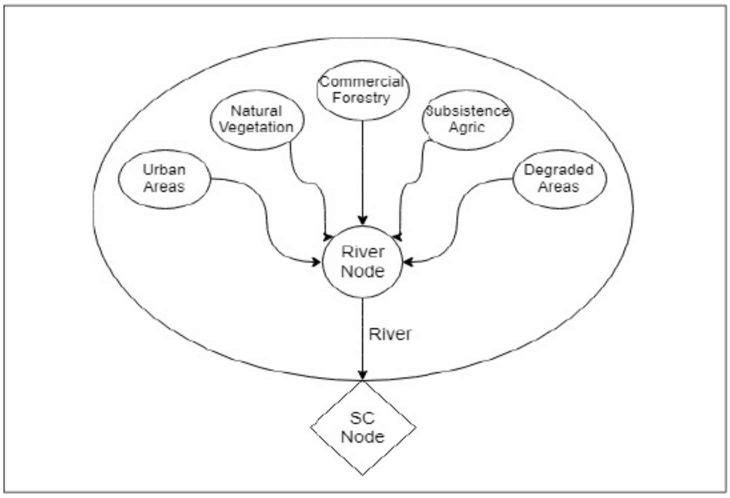


Figure 3.13 Example of the flow routing in a sub-catchment in the ACRU model

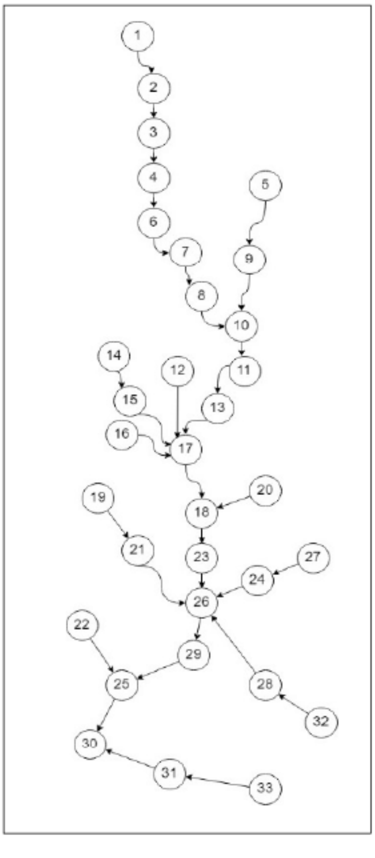


Figure 3.14 Routing of flow through the T32A/B/C catchment

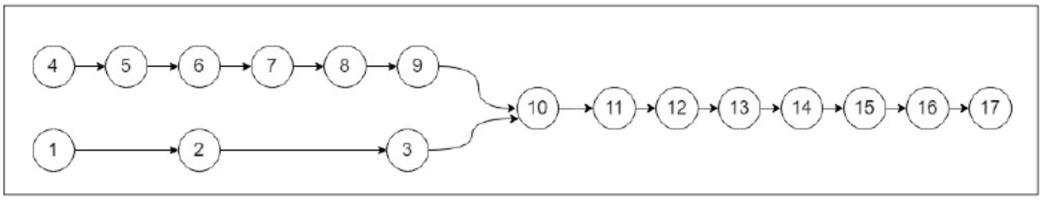


Figure 3.15 Routing of flow through the T35C catchment

3.2.5 Verification of the ACRU model

Once the ACRU menus for each catchment had been created, the menus were run in the model to obtain the simulated streamflow (USFLOW) for each catchment, which was then compared to the observed streamflow (STRMFL). The daily observed streamflow was obtained for the two weirs at the outlets of the two catchments – i.e. T3H004 and T3H009 – from the Department of Water and Sanitation. This observed streamflow data was checked for any problem/flagged records which were then either corrected using the primary raw flow level data, or removed and replaced as a missing data point.

The verification of each catchment was not, however, based on the first model run for either catchment. Once the first model run had been completed, it was evident that neither catchment was meeting all the criteria set for verification. As a result of this, a number of the following adjustments were made, and then run after each change, to the sub-catchments to achieve the most acceptable verifications:

- The ABRESP and BFRESP parameters were adjusted by either increasing or decreasing the individual HRU's values in increments of 0.05.
- The soil horizon depths, especially the B-horizon, were adjusted by either increasing or decreasing the individual HRU's horizons. The first set of soil changes was to those HRUs that had B-horizon depths in excess of 0.5 m, and was followed by adjustments to the remaining B-horizons and in some instances, certain of the A-horizon depths.
- Lastly, the SMDDEP of HRUS, especially those in the more mountainous parts of the catchments, were adjusted in increments of 0.05 m from being the depth of the A-horizon to shallower depths.

The observed streamflows for the two catchments for the full timeseries (1965 to 1999) were assessed and, based on the quality of the data, the verification period was chosen. For the

T32A/B/C catchment, the 1965 to 1980 was chosen whilst the period 1985 to 1999 was selected for the T35C catchment.

Following the selection of these two periods, the statistics of the simulated vs observed streamflows were calculated and compared. In order for the simulations to be deemed acceptable, the following criteria were set based on the recommendations of (Schulze and Smithers, 1995) :

- the total observed and simulated flows should be within a range of ± 10 %,
- the mean observed and simulated flows should be within a range of ± 10 %,
- the differences between means and variances between the simulated and observed flows should be within a range of ± 15 %,
- the coefficient of determination, R^2, should be 0.7 or higher, and
- the Nash-Sutcliffe Efficiency Index, E_f, should be close to the R^2 value to assess the fit between the simulated and observed flows.

Along with these statistics, flow duration curves and accumulated curves of both simulated and observed streamflow were compared to see if any differences in flow type and amount were present.

3.3 Revised Degraded Vegetation Parameters Using Observed LAI Data

As mentioned previously, the parameters used to represent degraded vegetation are in need of revision. Whilst the ACRU model currently has an option for degraded veld, it is a generic set of parameters based on expert opinion that has little correlation to many of the baseline Acocks vegetation types. This is problematic insofar as it allows for little consistency when modelling should a catchment have numerous Acocks veld types and degraded areas – for example, the generic degraded parameters may represent a 10% level of degradation for some Acocks veld types, whilst for others it may be a 50% level of degradation based on the different vegetative parameters. It was thus necessary for a revision of these parameters to be done to allow for a repeatable methodology to be developed that could be used for all types of natural vegetation and corresponding degradation.

In order to determine the difference between crop coefficients between pristine and degraded natural vegetation, a number of sites were required on which to test the methodology. These sites were chosen based on the 2013 NLC's determination of degraded areas and the South African National Protected Areas. The sites initially chosen were located in the Mzimvubu and

Thukela catchments (Figure 3.16) given that there were insufficient sites in only the Mzimvubu catchment and the Thukela was another of the catchments being considered in the larger project to which this study was a component (the Modelling Flows project (Toucher, 2016)). Whilst the Limpopo and Breede-Gouritz catchments were also considered, it was decided from the outset that the study into revising the degradation parameters would not make use of sites within these two catchments. The reasons for this decision were that the dominant vegetation types – shrubland and fynbos, respectively – posed too many additional challenges and factors to consider for the initial testing of the degradation parameter methodology.

Initially, five degraded sites were determined within both the Mzimvubu and Thukela catchments, with pristine veld areas located within adjacent Protected Areas for each degraded site (Figure 3.18). For a number of the degraded sites in the Thukela catchment, a single pristine site was used due to the fact that the location of Protected Areas was a limiting factor.

Another problem encountered in the Thukela catchment was the location of one of the degraded sites and its proximity to a mine dump. Whilst the site had been selected based on the NLC 2013, when checking the sites on Google Earth to ensure their suitability, it was observed that the most northerly site in the Thukela (circled red in Figure 3.17) was immediately adjacent to a mine dump outside the town of Utrecht (Figure 3.18). This meant that another degraded site needed to be chosen and showed one of the shortfalls of using only the NLC to identify land classifications.

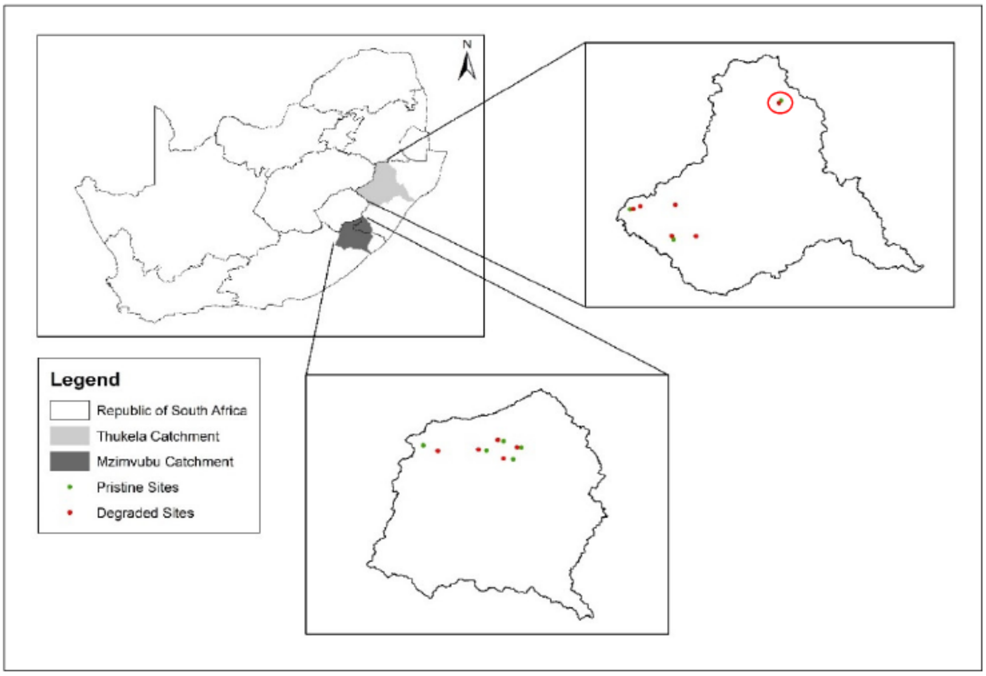


Figure 3.16 Location of sites used in the degradation parameter study

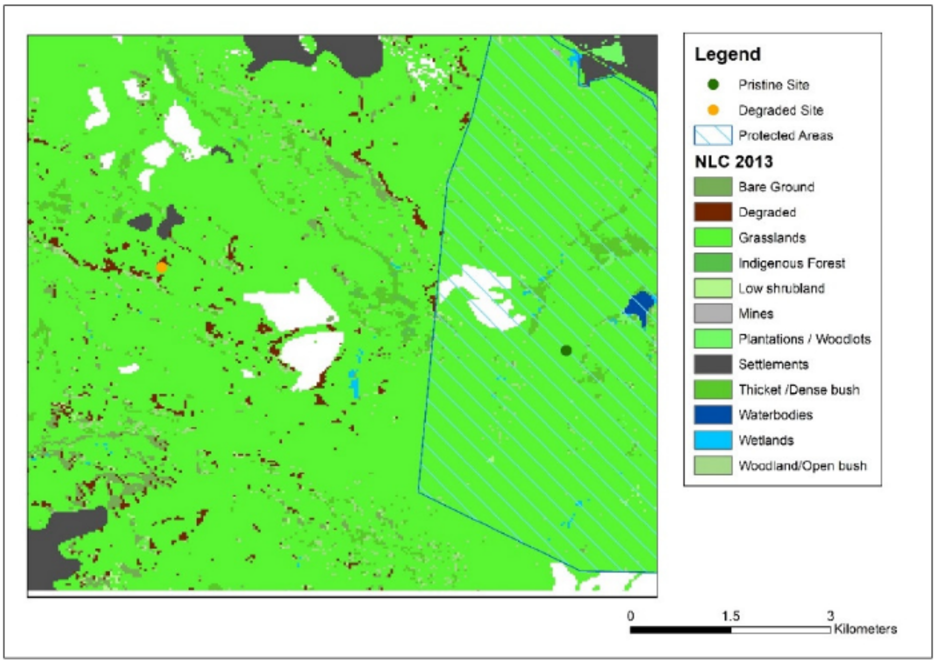


Figure 3.17 Example of the location of sites used in the comparison of degraded and pristine veld

Figure 3.18 Problematic degraded site (in red) identified in Google Earth (DigitalGlobe and AfriGIS, 2018)

Once the sites had been selected, the monthly LAI was determined for the period 2008 – 2017 before being used to calculate the crop coefficient, K_c, using both the standard FAO dual crop coefficient method (Allen *et al.*, 1998a), as well as the Kristensen method (Kristensen, 1974) adopted by Angus (1987).

The LAI data used for this study was extracted from the MODIS LAI product dataset obtained from the Earth Explorer website: https://earthexplorer.usgs.gov/. The MCD15A2H V6 dataset used for this study combines both the Terra and Aqua satellite readings in order to generate the LAI values using a main 3D radiative transfer Look-Up -Table that considers both the MODIS red and near-infrared surface reflectances, which then uses empirical relationships to determine LAI from the NDVI of the pixel (Myneni *et al.*, 2015). Each LAI image consists of 500 m by 500 m pixels and covers a temporal scale of 8 days.

Given that each MODIS image is downloaded as a particular tile with a sinusoidal projection (Figure 3.19), and that the study sites covered two of these tiles, the data had to be converted using the Batch processing method available in the MODIS Reprojection Tool, or MRT, (available at: https://lpdaac.usgs.gov/tools/modis_reprojection_tool). The MRT was used to both reproject the data to a WGS84 projection, as well as mosaic the two tiles for each timestep to create a composite 8-day LAI GeoTIFF file.

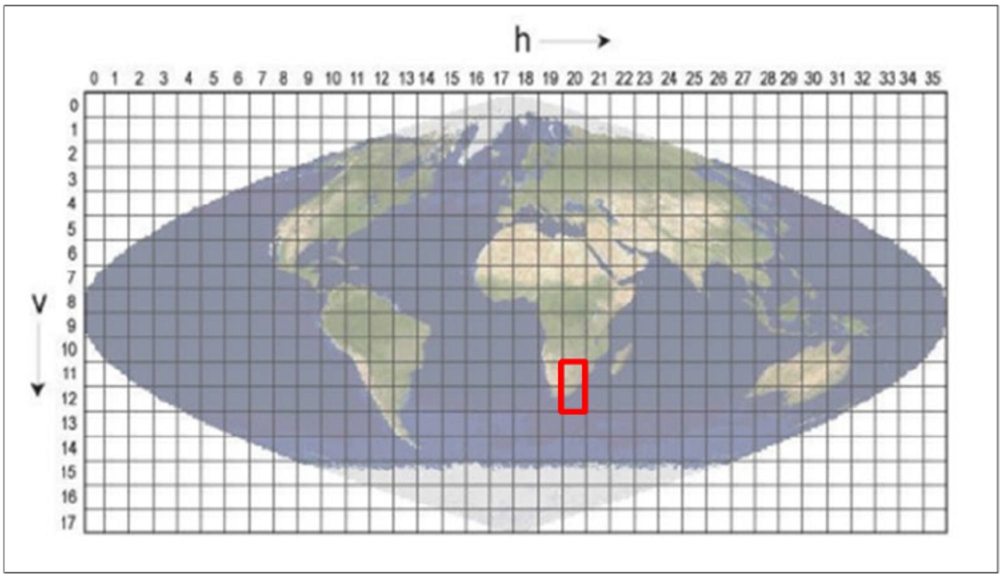


Figure 3.19 MODIS sinusoidal tiling system for data collection showing tiles used in study (after Myneni, 2012)

Once these 8-day composites had been created, the GEOTIFF files were scaled by a factor of 0.1 as per the user manual (Myneni *et al.*, 2015) before being averaged according to month to create monthly LAI datasets from January to December for the period 2008 to 2017. The monthly LAI of each site was then determined so that the crop coefficients, K_c, and vegetation interception could be calculated for each site, and comparisons made between the degraded and pristine veld. The final vegetation parameters are given in Appendix B.

3.3.1 Crop coefficient determination

The two methods used to determine the monthly crop coefficients at each site for the study period were the FAO dual crop coefficient method (Allen *et al.*, 1998a) and the Kristensen method (Kristensen, 1974; Angus, 1987). Both methods of calculating the K_c values were used to allow for comparison once all sites had been calculated.

3.3.1.1 The FAO dual crop coefficient method

This method is the FAO standard procedure for calculating crop coefficients of natural vegetation throughout the year on regular basis (usually taken at a daily timestep). It breaks the K_c value into two components, i.e. the basal crop coefficient (K_{cb}) and the soil evaporation coefficient (K_e) (Allen *et al.*, 1998a) (Equation 3.4),

$$K_c = K_{cb} + K_e \tag{3.4}$$

Whilst K_c comprises of both the basal crop and soil evaporation coefficients, it is assumed that during the initial growth stages K_e will be the dominant contributor owing to a greater amount of soil being exposed due to a small percentage of vegetation growth and cover. As the vegetation grows though, K_c will be dominated by the basal crop coefficient as the vegetation grows and covers the soil below. In order to calculate this basal crop coefficient, Equation 3.5 was used to determine the mid-season coefficient, $K_{cb,mid}$,

$$K_{cb,mid} = K_{c,min} + (K_{cb,full} - K_{c,min})(1 - e^{-0.7LAI}) \tag{3.5}$$

where $K_{c,min}$ = the minimum K_c for bare soil (assumed to be 0.15 for this study)

$K_{cb,full}$ = the estimated K_{cb} value for the vegetation during the mid-season using Equation 3.6

LAI = average monthly LAI value for the site

The basal crop coefficient during the mid-season growth cycle is assumed to provide full ground cover since the vegetation is taken to be at its maximum height and is calculated as,

$$K_{cb,full} = K_{cb,h} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)](\frac{h}{3})^{0.3}) \tag{3.6}$$

where $K_{cb,h}$ = the coefficient for full vegetation cover under sub-humid and calm wind conditions (RH_{min} = 45% and u_2 = 2m.s^{-1}) (Equations 3.7 and 3.8)

u_2 = mean value for wind speed at 2 m height during the mid-season (assumed to be 2 m.s^{-1})

RH_{min} = mean value for the minimum daily relative humidity (%) during the mid-season

h = mean maximum plant height (m)

The value of the $K_{cb,h}$ coefficient was calculated as,

$$K_{cb,h} = 1.0 + 0.1h \quad \text{for } h \leq 2 \text{ m} \tag{3.7}$$

$$K_{cb,h} = 1.2 \quad \text{for } h > 2 \text{ m} \tag{3.8}$$

In order to calculate the soil evaporation coefficient component, K_e, an evaporation reduction coefficient, K_r, would have needed to be calculated along with maximum value of K_c following a wetting event, $K_{c,max}$ (according to Equations 3.9 to 3.11).

$$K_{c,max} = MAX([\, 1.2 + \left[0.04(u_2 - 2) - 0.004(RH_{min} - 45)(\tfrac{h}{3})^{0.3}\right]], [\, K_{cb} + 0.05]) \tag{3.9}$$

where $K_{c,max}$ is taken to be the higher of the two values within the brackets.

The soil evaporation coefficient is determined using the ratio of total evaporable water (TEW) (3.11) to readily evaporable water (REW) using the depth of soil that is dried through evaporation to determine K_r (3.12),

$$TEW = 1000(\theta_{FC} - \theta_{WP})Z_e \tag{3.10}$$

where TEW = the total evaporable water – taken as the maximum depth of water that can be evaporated from the topsoil after a full wetting event (mm)
θ_{FC} = soil water content at field capacity ($m^3.m^{-3}$)
θ_{WP} = soil water content at wilting point ($m^3.m^{-3}$)
Z_e = depth of topsoil that is dried through evaporation (m)

$$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW} \tag{3.11}$$

where $D_{e,i-1}$ = cumulative depth of evaporation for a given day (mm)
REW = the readily evaporable water – taken as the depth of water evaporated after event (mm)

Once these values have been calculated, they can be used to calculate the soil evaporation coefficient, K_e (Equation 3.12).

$$K_e = K_r(K_{c,max} - K_{cb}) \tag{3.12}$$

However, given that the soil evaporation coefficient requires a full soil water budget to have been developed and that minimal data was available for the soil water characteristics of the sites, the crop coefficient was taken to be the $K_{cb,mid}$ coefficient which would be representative of the sites' vegetation. The study done by Corbari *et al.* (2017a) showed that the FAO dual crop coefficient calculation has the greatest sensitivity to LAI, meaning that the coefficient is more affected by changes in $K_{cb,mid}$ than in K_e, and thus did not take K_e into account.

3.3.1.2 Kristensen method

As with the FAO dual crop coefficient method, the Kristensen method relies on the LAI data of the given vegetation to derive a crop coefficient. Based on earlier work carried out by Ritchie and Burnett (1971), Kristensen (1974) showed that, with Equation 3.13, the relationship between actual and reference evapotranspiration approaches 1 as LAI tends towards a value of 3.

$$\frac{ET_C}{ET_O} = -0.21 + 0.7LAI^{0.5} \tag{3.13}$$

Further to this, Angus (1987) used the work done by Kristensen to derive Equation 3.14, which is subsequently known as the Kristensen method of calculating K_c from LAI,

$$LAI = \frac{ln(\frac{K_C - 1.0932}{-0.7947})}{-0.6513} \tag{3.14}$$

or, when rearranged to make K_c the subject of the equation,

$$K_c = 1.0932 - 0.7947e^{-0.6513LAI} \tag{3.15}$$

where K_c is limited to values between 0.2 and 1.05.

The Kristensen method was selected based on its success within a South African context, as it was used as one of the two crop coefficient calculation methods (along with the FAO dual crop coefficient method) to reset the vegetative cover (Warburton Toucher *et al.*, 2018).

3.3.2 Vegetation interception determination

The model used for the interception parameter (VEGINT) determination part of the study was the variable storage Gash model (Gash, 1979; Gash *et al.*, 1995; van Dijk and Bruijnzeel, 2001). The variable storage Gash model works on the following assumptions:

1. Canopy and trunks of vegetation are able to dry between individual storm events, as the rainfall distribution pattern is such that sufficiently long periods exist between successive storm events to allow for drying to occur (Gash, 1979; Gash *et al.*, 1995).
2. Rainfall and evaporation rates are constant for each individual storm event, although the rates can also be considered constant for events occurring during the same timeframe (Gash, 1979; Gash *et al.*, 1995).
3. LAI can be related to the maximum canopy storage capacity, S_c^{max}, via a linear relationship, whilst the storage capacity, S_c, is related to the rainfall intensity, R (van Dijk and Bruijnzeel, 2001).

In order to calculate the storage capacity of the veld, parameters for specific leaf storage (SI), maximum storage capacity of the wooded areas ($S_c^{max}{}_{\_wood}$), and the extinction coefficient (k) were determined for each site using the parameters within the wflow_sbm model (van Dijk and Bruijnzeel, 2001; Schellekens, 2017). Given that all sites were within grasslands, a k parameter of 0.6, an SI parameter of 0.127, and a $S_c^{max}{}_{\_wood}$ parameter of 0 was assumed for all sites.

The interception coefficient, c, was calculated using Equation 3.16.

$$c = 1 - e^{-k \, x \, LAI} \tag{3.16}$$

where c = the interception coefficient
k = the extinction coefficient
LAI = the average monthly leaf area index of each site

The throughfall coefficient, p, was calculated using this interception coefficient (Equation 3.17).

$$p = 1 - c \tag{3.17}$$

The maximum storage capacity of the vegetation of each site was calculated using a non-crop specific estimate developed by von Hoyningen-Huene (1981) (Equation 3.18).

$$S_c^{max} = 0.935 + 0.498\ x\ LAI - 0.00575 x LAI^2 \qquad (3.18)$$

From this, the storage capacity, S_c, was determined as a function of rainfall intensity, R, according to the following:

$$S_c = S_c^{max} \qquad \text{for R} \leq 0.36\ \text{mm.h}^{-1} \qquad (3.19)$$

$$S_c = S_c^{max}\ x\ (0.5 + 0.73e^{-5.5v}) \qquad \text{for R} > 0.36\ \text{mm.h}^{-1} \qquad (3.20)$$

where v = raindrop volume (mm^3)

The raindrop volume used in Equation 3.20 is estimated using the Marshall and Palmer (1948) equation (Equation 3.21).

$$v = a\ x\ R^b \qquad (3.21)$$

where a, b = unitless parameters to scale mm.h^{-1} to mm^3 (a = 0.124 and b = 0.63) (Hall, 2003)

In terms of the climatic variables required by the model for the study sites, gross precipitation (Pg), rainfall intensity (R in mm.hr^{-1}), and mean evaporation rate (E) were required as inputs. Whilst reference crop evaporation (using the Penman-Monteith method (Allen *et al.*, 1998b)) and daily rainfall was available for the study sites, a proxy needed to be determined for the rainfall intensity rates as no data was available for the areas in which the sites were located.

To calculate the rainfall intensity rates, the rainfall distribution zone needed first to be determined for each of the test sites according to the zones delineated in Figure 3.20.

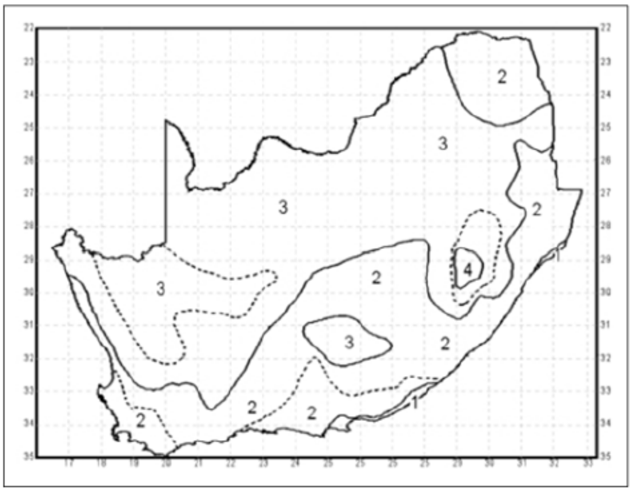


Figure 3.20 Rainfall intensity distribution zones of South Africa (after Weddepohl, 1988; in Smithers *et al.*, 1995)

Once the site had been allocated its relevant zone, the multiplication factor for that zone (Table 3.6) was determined, as was the 2-year one-day rainfall amount based on the driving rainfall station of the site (i.e. the driver station for the quinary catchment in which the site fell).

Table 3.6 Multiplication factor for each storm distribution zone (after Schmidt and Schulze, 1987)

	Storm Distribution Type			
	1	2	3	4
Multiplication Factor	0.430	0.664	0.974	1.236

This rainfall amount was then used in Equation 3.22 to calculate the 2-year 30-minute rainfall intensity which was taken to be the rainfall intensity, R, in the variable storage Gash model (Warburton Toucher *et al.*, 2018).

$$R\ (mm.h^{-1}) = \ Rainfall\ amount_{2yr\ daily}\ x\ Multiplication\ factor \qquad (3.22)$$

Once both the canopy and climatic factors were determined for each site, the variable storage Gash model was run, and monthly interception values were calculated for each site for the period 2008 to 2017.

3.3.3 Remaining Vegetation Parameters

The remaining parameters needed for the degraded vegetation were determined using the working rules from the South African Atlas of Climatology and Agrohydrology (Schulze, 2008a).

3.3.3.1 Coefficient of Initial Abstraction (COIAM)

The coefficient of initial abstractions is taken to be the rainfall that is abstracted from soil water budget before stormflow is generated, and includes interception and surface detention, as well as initial infiltration. Given that the working rules for the determination of COIAM for ACRU require the rainfall seasonality of the area in which the modelling is to be done, Figure 3.21 was used to determine that the catchment has mid to late summer rainfall.

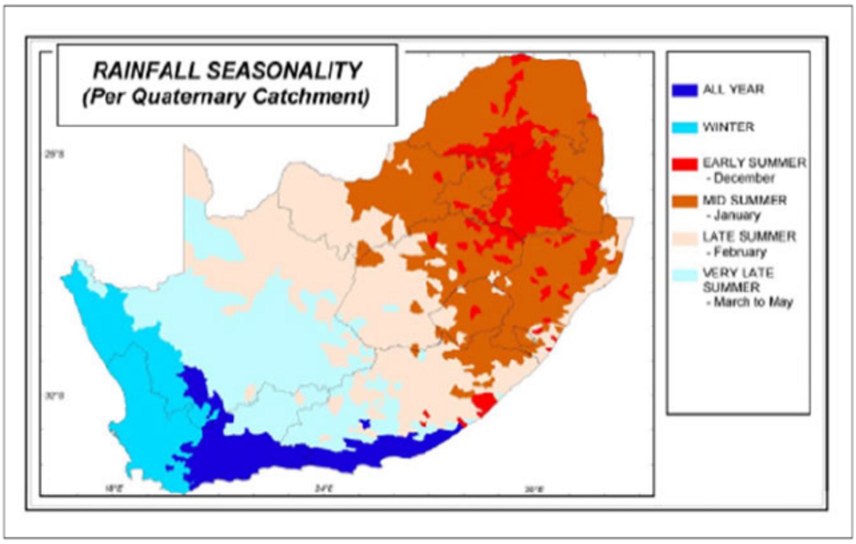


Figure 3.21 Rainfall seasonality of each South African quaternary catchment (after Schulze and Maharaj, 2008)

Based on this, the COIAM values for the pristine vegetation parameters were assigned values as follows (based on Schulze, 2008a):

- COIAM for summer months (from December to February) = 0.15
- COIAM for autumn months (from March to May) = 0.25
- COAIM for winter months (from June to August) = 0.30
- COIAM for spring months (from September to November) = 0.20
- All degraded COIAM parameters were taken to be 0.05 less than those of the pristine veld throughout the year. This was based on the fact that the amount of water abstracted

initially will be less for degraded veld than for pristine veld as there is less biomass/leaf litter available to abstract rainfall. This was similar to the method used by Schulze, (2008a) in the determination of the different land use vegetative parameters for the ACRU model.

3.3.3.2 Percentage surface cover (PCSUCO)

Given that the percentage of the surface under vegetative cover and litter will affect the amount of soil water evaporation and sediment yield, values for the PCSUCO parameter needed to be determined. Based on the working rules for soil surface cover by litter in Schulze (2008a), Equations 3.23 to 3.25 were calculated using the crop coefficients, K_c, calculated prior:

$$PCSUCO = 100(K_c - 0.2) \qquad \text{for } 0.2 \leq K_c \leq 0.40 \tag{3.23}$$

$$PCSUCO = 20 + 177.8(K_c - 0.40) \qquad \text{for } 0.4 < K_c \leq 0.85 \tag{3.24}$$

$$PCSUCO = 100 \qquad \text{for } 0.85 < K_c \tag{3.25}$$

3.3.3.3 Rooting parameters (ROOTA, ROOTB and COLON)

For the rooting parameters of the amended degradation parameters, the working rules given for soil root distribution in Schulze (2008a) were applied with rooting structure being assumed to be the same for both pristine and degraded vegetation. Therefore, assumption regarding the rooting systems of the plants was based on the fact that the type of degradation considered was loss of vegetative cover, meaning that plant type, and subsequently its rooting systems, would remain the same, but the number of plants per unit area would be fewer.

3.4 Modelling of Land Use Changes Scenarios

Once the verification of the ACRU model was complete and the degraded parameters had been determined, the methodology for the modelling of land use changes was developed. The scenarios identified for this study were based on a number of development plans including the NWRS (Republic of South Africa, 2013), the Umzimvubu Spatial Development Framework (Umzimvubu Local Municipality, 2011), and the National Development Plan (Abazaj *et al.*, 2016).The land use changes identified for this study's consideration were based on potential areas of degradation, and included:

a. increases in degraded areas throughout the catchment, as well as the rehabilitation of already degraded land,
b. increases in bush encroachment as a result of overgrazing,
c. increases in the area under burning management regimes,

d. changes in both subsistence and commercial agricultural management practices, particularly changes in the areas under irrigated and dryland agriculture, and
e. changes in dryland crops from current to proposed sorghum biofuel crops.

Each of the scenarios considered was modelled according to the incremental changes in Table 3.8. The results of these simulations were then compared to a natural vegetation baseline run for each catchment and categorized according to the sensitivity of the percentage change in land use (

Table 3.8). The vegetation parameters used in the modelling of these scenarios are given in Appendix B.

Table 3.7 Incremental changes used in modelling of land cover changing scenarios

Level of change	Percentage change in parameters (%)
Minor	10
Notable	20
Moderate	40
Significant	50
Extreme	75
Complete	100

Table 3.8 Sensitivity ranking of percentage change in land use (after Schulze, 1995)

Rank	Definition
Extremely Sensitive (E)	Percentage change in flows is more than 200 % of the percentage change in area under a given land use.
Highly Sensitive (H)	Percentage change in flows is less than 200 %, but more than 100 %, of the percentage change in area under a given land use.
Moderately Sensitive (M)	Percentage change in flows is less than 100 %, but more than 50 %, of the percentage change in area under a given land use.
Slightly Sensitive (S)	Percentage change in flows is between 10 % and 50 % of the percentage change in area under a given land use.
Insensitive (I)	Percentage change in flows is less than 10 % of the percentage change in area under a given land use.

3.4.1 Degradation and rehabilitation of natural vegetation

Given the tendency of the soils within the Mzimvubu catchment to erode and the already large degraded areas present within the catchment, scenarios modelling the further degradation of natural veld or the rehabilitation of already degraded areas were considered. The further degradation of natural veld scenario was modelled by considering the already present natural veld HRUs and then degrading these areas according to the changes in Table 3.8. As degradation increased, the Degraded Areas HRU area would increase accordingly, whilst the Natural Vegetation HRU area would decrease. Conversely, for the rehabilitation scenarios, the Degraded Area HRU area would be decreased whilst the Natural Vegetation HRU area would be increased (Figure 3.22).

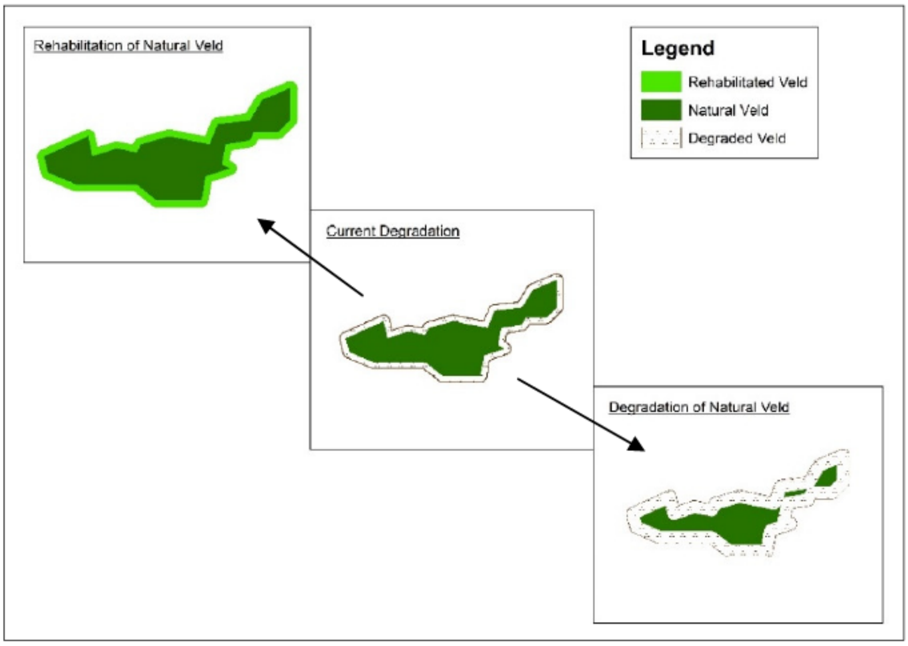


Figure 3.22 Example of how further degradation or rehabilitation of current degraded areas was modelled

3.4.2 Increasing bush encroachment

As identified in the initial site selection phase of the Modelling Flows Project (Toucher, 2016), bush encroachment has been observed in the catchment, meaning that scenarios modelling the potential increased bush encroachment were considered. These increases in levels of bush encroachment were modelled by considering the already present natural veld HRUs and then causing bushveld to encroach within the natural veld areas according to the changes in Table

3.8. The vegetation parameters used for the bushveld encroachment were taken to be that of the Acocks Eastern Province Thornveld (#7) that are available within the ACRU model.

The reason for this choice was due to the fact that it offered what was deemed to be an acceptable average of the dominant bush and thornveld types within the area. As seen in Figure 3.23, the two main Acocks bushveld types present are the Eastern Province Thornveld (#7) and Valley Bushveld (#23). The vegetation parameters in Appendix B show that the Eastern Province Thornveld is taken to be the woodiest bushveld of the two dominant types within the Mzimvubu area and would thus have the greatest impact on the water resources in the area. This higher amount of the forest-based bushveld in the Eastern Province Thornveld is seen in the higher monthly crop coefficient (CAY) values (especially in the winter months), as well as the increased amount of interception losses (VEGINT).

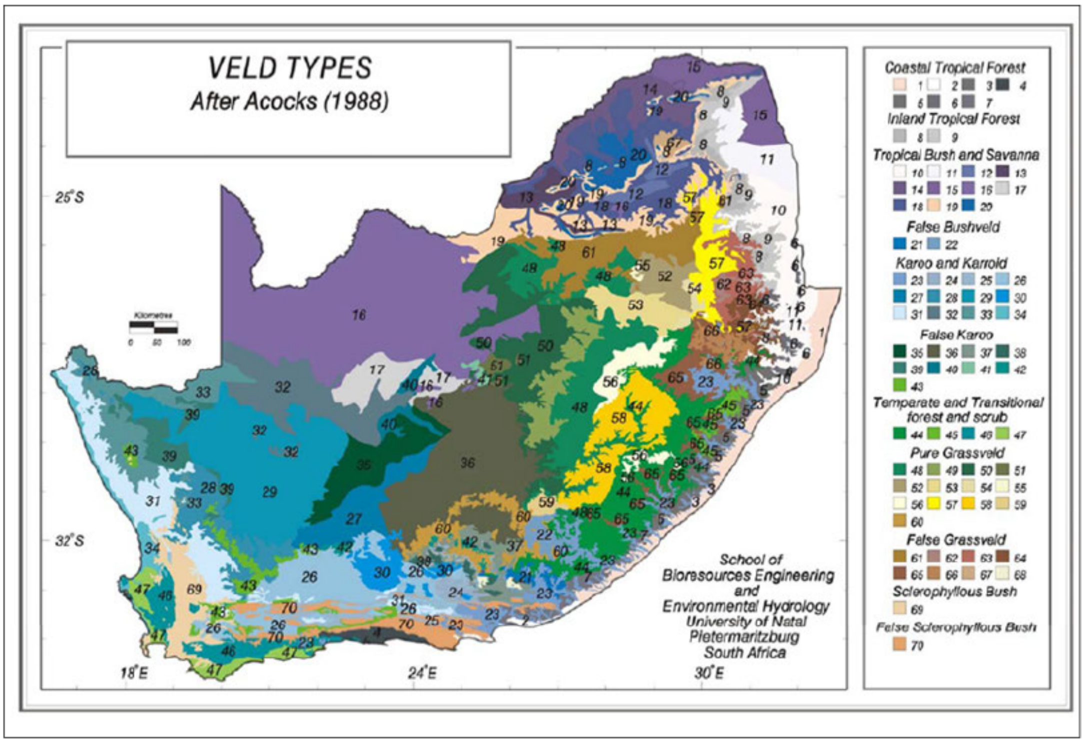


Figure 3.23 Acocks veld types throughout South Africa (after Acocks *et al.*, 1988; Schulze, 2008a)

As greater areas of natural vegetation were lost to bush encroachment, the Bushveld HRU area would increase accordingly, whilst the Natural Vegetation HRU area would decrease (Figure 3.24).

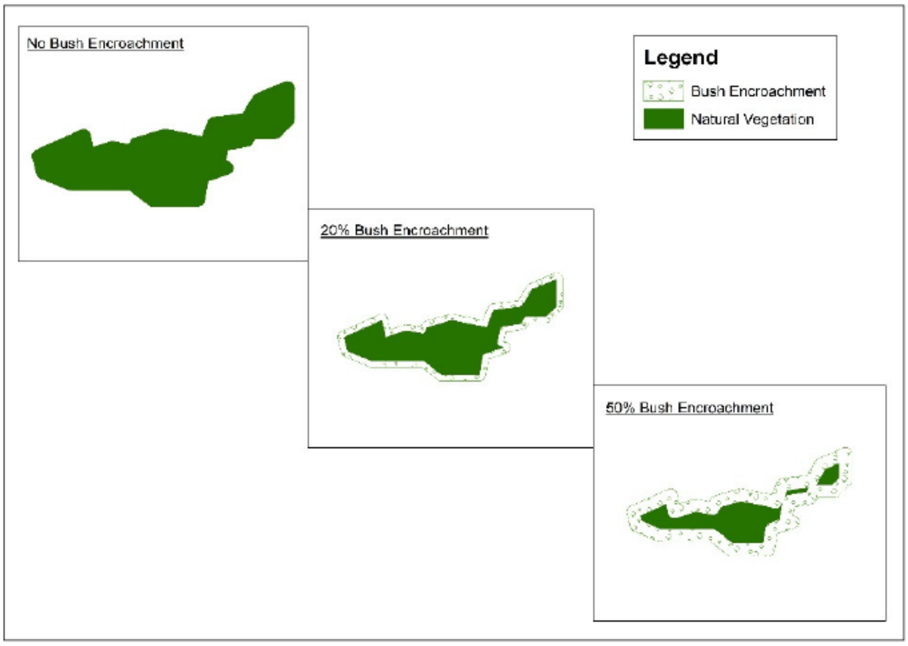


Figure 3.24 Example of how increases in bush encroachment, and subsequent loss of natural vegetation, was modelled

3.4.3 Increasing areas under burning management regimes

Given that there are significant areas of commercial agriculture within the Mzimvubu area, a number of burning regimes and degrees of burn were considered for the burning management scenario (Table 3.9).

Table 3.9 Combinations of burning regime and degree of burn considered

Regime	Degree of burn
Biennial	Moderate
Biennial	70%
Biennial	Severe
Annual	Moderate
Annual	70%
Annual	Severe

Along with changes in burning regimes, increases in the area under burning was also considered. These increases in the amount of land under each burning regime combination were modelled by considering the already present natural veld HRUs and then burning areas within the natural veld areas according to the changes in Table 3.8. The vegetation parameters

(Appendix B) used for the all combinations of burns considered were taken from parameters calculated during the Maloti Project (Mander *et al.*, 2008), and which are available within the ACRU model

As greater areas of natural vegetation were burned (either through controlled burning or through runaway wildfires originating from controlled burns), the Veld Under Burning HRU area would increase accordingly, whilst the Natural Vegetation HRU area would decrease. (Figure 3.25).

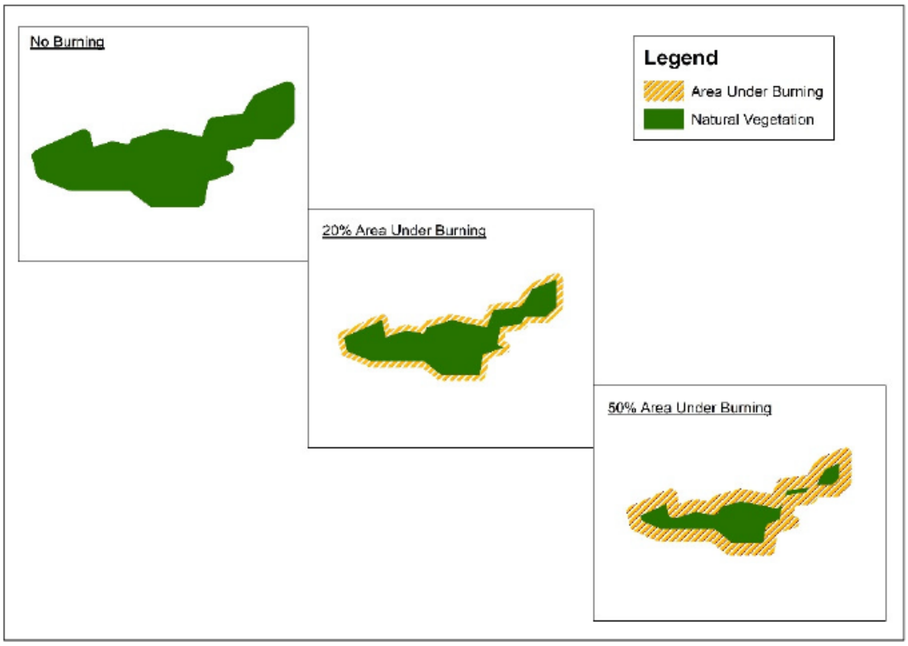


Figure 3.25 Example of how increases in area under burning, and subsequent loss of natural vegetation, was modelled

3.4.4 Changing from dryland to irrigated agriculture

As part of the NWRS (Republic of South Africa, 2013), commercial agricultural areas in the Mzimvubu catchment have been earmarked for the development of irrigation schemes. Therefore, scenarios modelling the changes in agricultural practices – from dryland to irrigated - were considered. The transition from dryland to irrigated agricultural crops was modelled by considering the already present dryland agriculture HRUs and then changing parts of the HRUs to irrigated agriculture according to the changes in Table 3.8. The irrigation systems set up were created using the same parameters as in the verification study. As greater areas of dryland crops were developed into irrigated areas, the Irrigated Agriculture HRU area would increase accordingly, whilst the Dryland Agriculture HRU area would decrease (Figure 3.26).

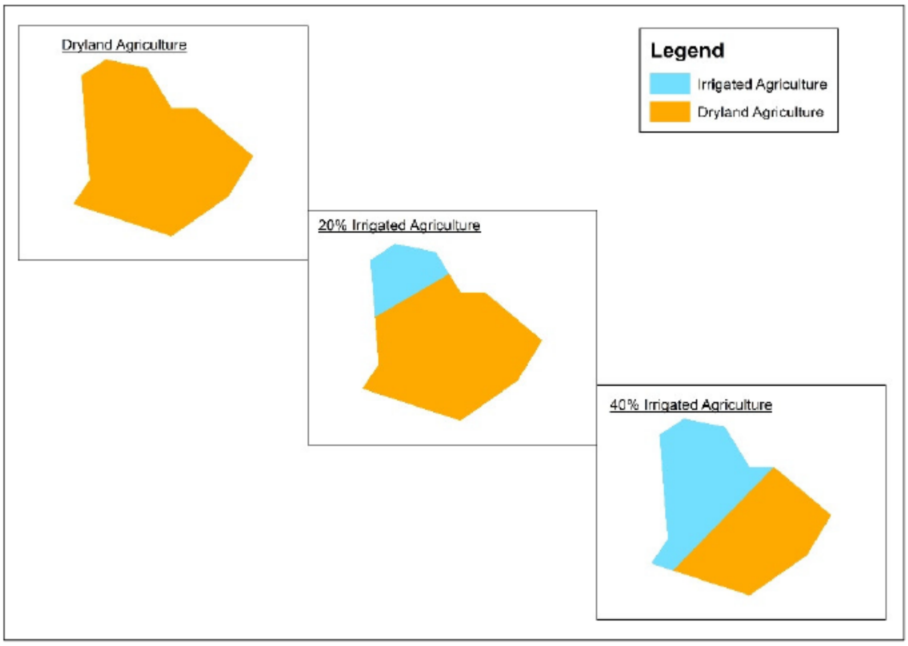


Figure 3.26 Example of how changing the area under dryland cropping to irrigated crops was modelled

3.4.5 Increasing areas of dryland agriculture

The NWRS (Republic of South Africa, 2013) also outlined plans for the increasing of areas of dryland agriculture in the Mzimvubu catchment. Therefore, scenarios modelling the increase in dryland cropping areas were considered. The transition from natural vegetation to dryland agricultural crops was modelled by considering the already present dryland agriculture HRUs and then increasing the area of the HRU according to the changes in Table 3.8. As greater areas of dryland crops were developed, the Dryland Agriculture HRU area would increase accordingly, whilst the Natural Vegetation HRU area would decrease (Figure 3.27).

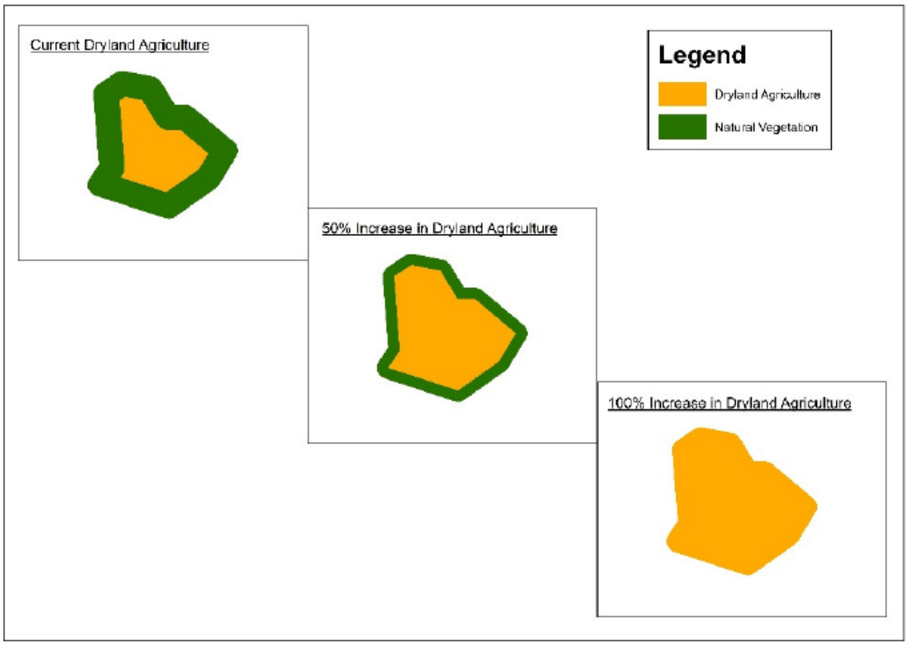


Figure 3.27 Example of how increases in area under dryland cropping, and subsequent loss of natural vegetation, was modelled

3.4.6 Changing traditional crops to biofuels

Given the push towards renewable energy and fuel sources, the impact of changes in dryland crop type – from the more traditional dryland crops to a sorghum crop (Jewitt *et al.*, 2009) – was determined to be an important consideration for the Mzimvubu catchment. Therefore, scenarios modelling the changes in dryland crop types were considered. The transition from traditional to biofuel crops was modelled by considering the already present dryland agriculture HRUs and then changing the type of crop according to the changes in Table 3.8. As a greater area of dryland crops changed from traditional crop types to biofuel crops, the Biofuel Agriculture HRU area would increase accordingly, whilst the Dryland Agriculture HRU area would decrease (Figure 3.28).

Figure 3.28 Example of how changing from traditional crops to biofuel crops was modelled

The different land use change scenarios were run in the ACRU model, along with a natural vegetation baseline for both catchments (i.e. one where the catchments comprised only natural vegetation HRUs). It was these natural vegetation baseline scenarios against which both the NLC 2000 land use verifications and the proposed land use change scenarios were compared to see how much the catchments had already changed and what further impacts would be observed should the scenarios become reality.

4. RESULTS

The results of the study are presented in the order in which the work was done, viz. the initial verification of the ACRU model for the study catchments, followed by the development of a methodology to determine degraded vegetation parameters, and lastly the results of the modelling of different land use change scenarios.

4.1 Results of the Verification Study

Following the configuration of the model for both catchments, the verification simulations were run and compared to the desired range of outcomes to determine the adequacy of the model for the two catchments.

4.1.1 Verification of the T32A/B/C catchment

In order to perform the verification for T32A/B/C, the three sub-catchments, viz. T32A, T32B and T32C, were run for a baseline period of 33 years from September 1965 through to 1980. From this initial baseline, a number of iterations were then run in which predominantly soil parameters were altered in order to best mimic the conditions present within the catchment, as the baseline run was over simulating the streamflow within the catchment. However, whilst these iterations did help to bring the simulated flows more in line with the observed flows, the verification objective of a having percentage difference between the means of the simulated flows and means of observed flows of less than 15 % could not be met.

The most suitable iteration for the verification period of 1965 to 1980 yielded a 36.3 % difference between means, as ACRU was still over simulating streamflow. Whilst the percentage difference between means was not ideal, the other statistics showed a far better performance of the model, as both the differences between observed and simulated variances and standard deviations were well within the desired range of 15 % or less, and the R^2 and E_f factors, though not exceeding 0.7, were relatively close to each other and deemed acceptable (Table 4.1).

Despite the statistics (Table 4.1) not meeting certain of the verification criteria, it can be argued that these results are acceptable given the conditions present within T32A/B/C. Problems such as a malfunctioning streamflow gauge, which was shown in the daily volumes obtained for the gauge that never exceed 38 $m^3.s^{-1}$ and meant that the raw flow level data had to be used and a ratings curve extrapolated for the data, and large farming areas with uncertain irrigation withdrawals, meaning that a worst case scenario was applied to ensure that water extraction was similar to, or slightly over, the realistic extractions rather than being much too low, meant that a number of assumptions had to made regarding both irrigation and streamflow in the catchment. Furthermore, the impact assessments to be carried will consider relative changes between scenarios where any errors in the model configuration and parameterisation will be self-cancelling.

The flow duration curves in Figure 4.1c shows that, while all flows were over simulated, the high flows were the best simulated. The accumulated flows followed a similar pattern but the simulated flow was consistently higher than the observed flow (Figure 4.1d). The small percentage differences in variances and standard deviations can be attributed to the fact that the simulated timeseries shows a good response to the rainfall patterns. Based on the small differences in variance and standard deviation between observed and simulated streamflow for the T32A/B/C catchment, and the streamflow curves and time series in Figure 4.1a - d, that the ACRU model was considered able to mimic the conditions present within the catchment as realistically as could be expected given that the catchment size was larger than the desired 30 km^2 and that there were numerous issues with rainfall and streamflow data.

Table 4.1 Statistics of the ACRU verification simulation of the T32A/B/C catchment for the period 1965 to 1980

	T32A/B/C
Total observed flows (mm)	1377.068
Total simulated flows (mm)	1876.848
Ave. error in flow (mm/day)	0.102
Mean observed flows (mm/day)	0.281
Mean simulated flows (mm/day)	0.384
% Difference between means	-36.293
Variance of observed flows (mm)	0.424
Variance of simulated flows (mm)	0.401
% Difference between Variances	5.372
Std. Deviation of observed flows (mm)	0.651
Std. Deviation of simulated flows (mm)	0.633
% Difference between Std. Deviations	2.723
Correlation Coefficient : Pearson's R	0.687
Regression Coefficient (slope)	0.669
Regression Intercept	0.195
Coefficient of Determination: R^2	0.472
Nash—Sutcliffe Efficiency Index (E_f)	0.366

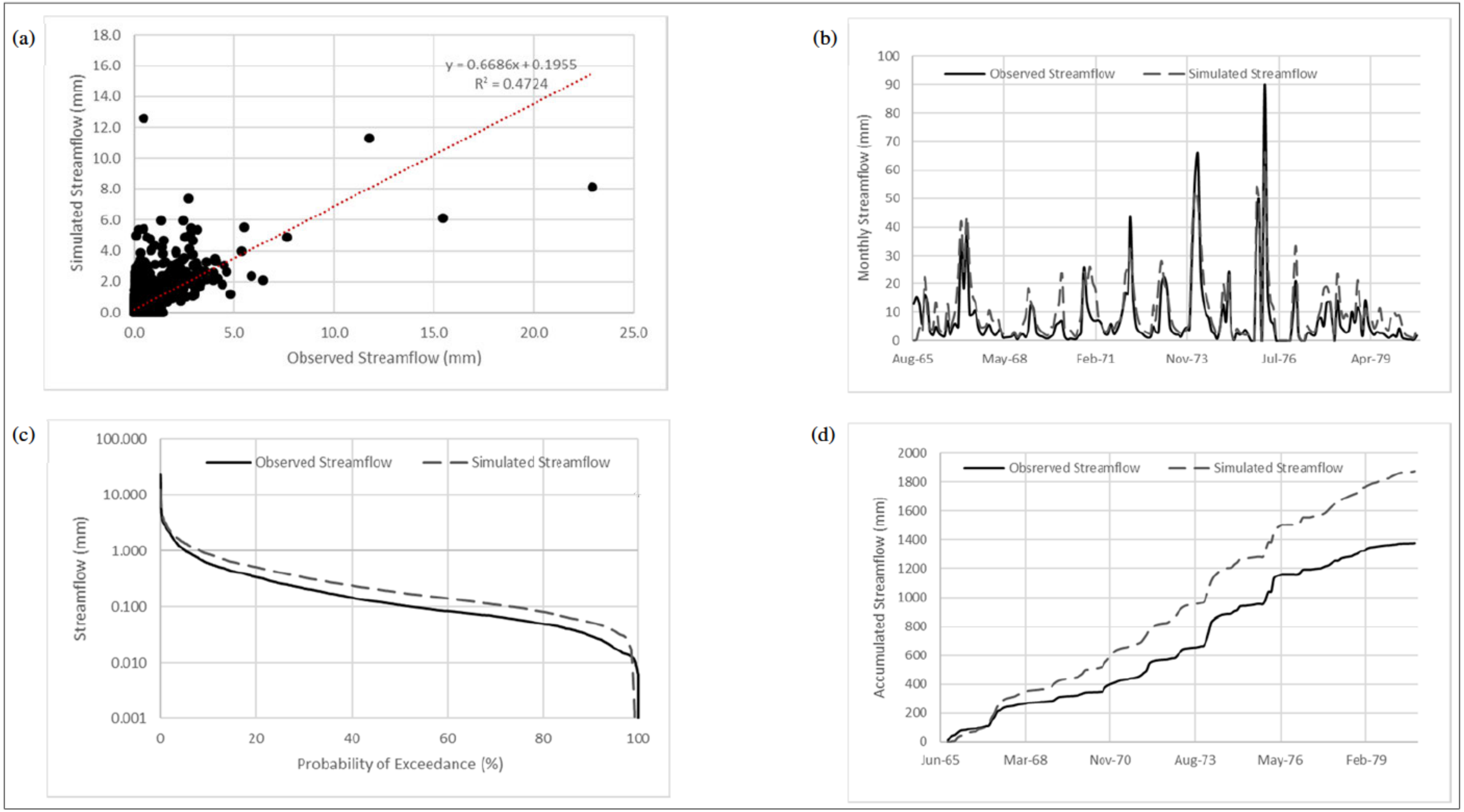


Figure 4.1 (a) Comparison, (b) time series, (c) flow duration curves, and (d) accumulated observed and simulated streamflow curves of the ACRU verification of the T32A/B/C catchment for the period 1965 to 1980.

4.1.2 Verification of the T35/C catchment

The most suitable iteration for the verification period of 1985 to 1999 yielded a 22.4 % difference between means, as the ACRU model under simulated streamflow. Whilst the percentage difference between means was not good, the other statistics showed a far better simulation, as both the differences between observed and simulated variances and standard deviations were close to zero and thus well within the range of 15 % or less. The R^2 and E_f factors, though not exceeding 0.7, were somewhat close to each other and deemed acceptable, although in no way ideal (Table 4.2).

Table 4.2 Statistics of the ACRU verification simulation of the T35C catchment for the period 1985 to 1999

	T35C
Total observed flows (mm)	4146.79
Total simulated flows (mm)	3216.966
Ave. error in flow (mm/day)	-0.176
Mean observed flows (mm/day)	0.786
Mean simulated flows (mm/day)	0.609
% Difference between means	22.423
Variance of observed flows (mm)	2.393
Variance of simulated flows (mm)	2.316
% Difference between Variances	3.219
Std. Deviation of observed flows (mm)	1.547
Std. Deviation of simulated flows (mm)	1.522
% Difference between Std. Deviations	1.622
Correlation Coefficient : Pearson's R	0.573
Regression Coefficient (slope)	0.564
Regression Intercept	0.166
Coefficient of Determination: R^2	0.329
Nash—Sutcliffe Efficiency Index (E_f)	0.147

The verification process for T35C was similar to that of T32, with a baseline run being carried out in order to determine how well the situation modelled was mimicking the real catchment. A number of iterations were run in which both the soil parameters and improved rainfall data and correction factors applied were altered in order to best mimic the conditions present within the catchment, as the baseline run was drastically under simulating the streamflow within the catchment. However, whilst these iterations did help to bring the simulated flows more in line with the observed flows, the verification objective of having a percentage difference between the means of the simulated flows and means of observed flows of less than 15 % could not be met.

The flow duration curves in Figure 4.2c show a different story to those of T32A/B/C as the very high flows are well simulated but the higher flows are largely under simulated while the low flows are over simulated. The accumulated flows followed a similar pattern but the simulated flow was consistently lower than the observed flow (Figure 4.2d). This under simulation could be as a result of the high flows of the catchment being largely under simulated. Similar to T32A/B/C, the small percentage differences in variances and standard deviations can be attributed to the fact that the simulated timeseries shows a good response to the rainfall patterns, albeit it under simulating compared to the observed flows. While certain of the statistics in Table 4.2 do not seem to suggest an acceptable verification of the model, it can be argued that these results are acceptable given the conditions present within T35C, based on the streamflow curves and time series in Figure 4.2a - d. Given that the catchment size was larger than the desired 30 km^2 and that there were numerous issues with rainfall and streamflow data, these needed to be taken into consideration when looking at the results obtained. Whilst the simulation did not meet certain of the criteria set, the streamflow curves and time series showed that the model was simulating streamflow in a similar manner to the observed data, albeit just in smaller quantities.

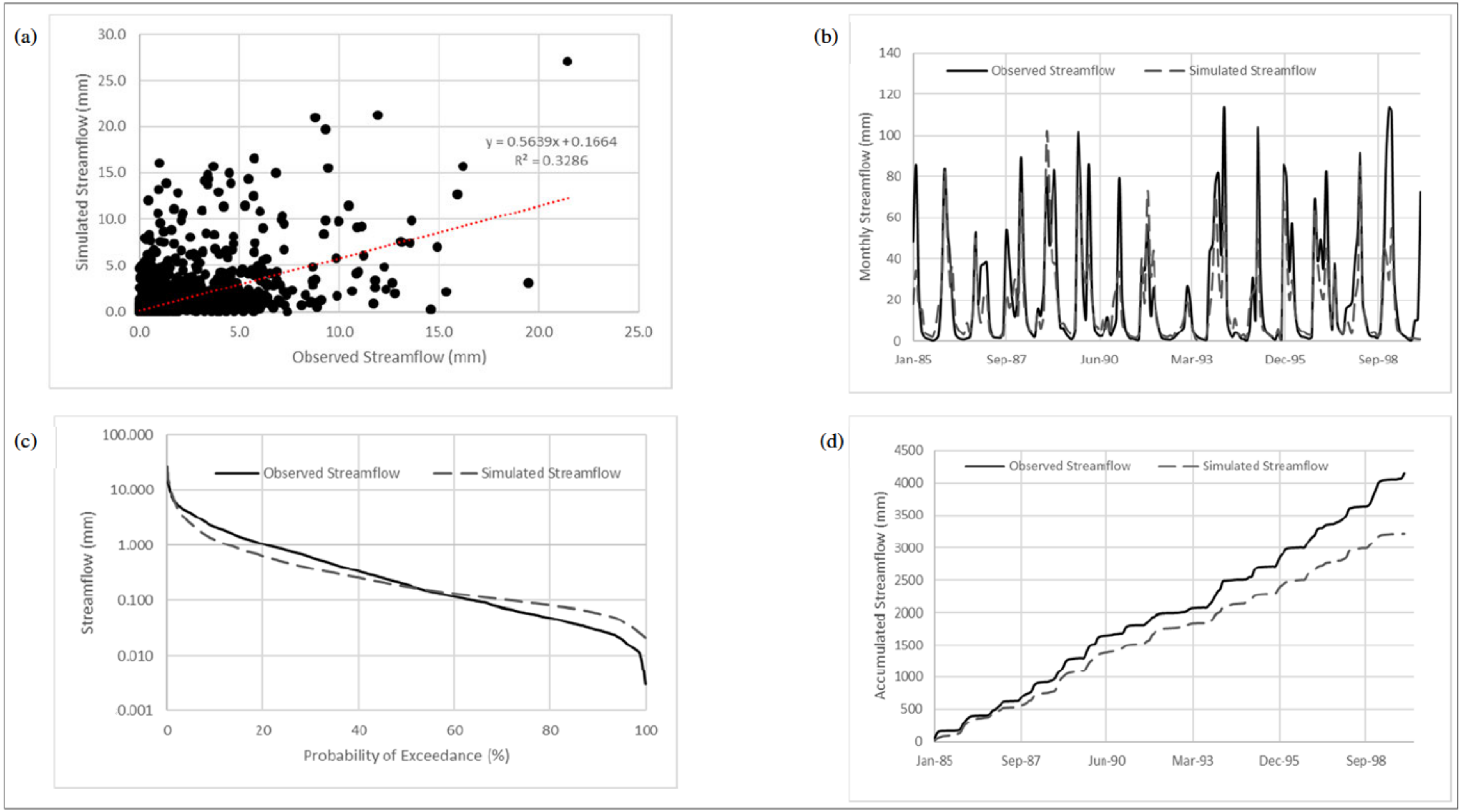


Figure 4.2 (a) Comparison, (b) time series, (c) flow duration curves, and (d) accumulated observed and simulated streamflow curves of the ACRU verification of the T35C catchment for the period 1985 to 1999.

Whilst the percentage difference between the observed and simulated flows was not less than 15% in either catchment which was not ideal, other statistics calculated and the time series for both graphs showed reasonable simulations in both instances. Similarly, the low R^2 and E_f values were well below the criteria of being 0.7 or greater. However, given that the impacts of changes in land use were quantified in terms of a percentage change, rather than a volume change, it was reasoned that, whilst the difference between the observed and simulated flows was not ideal in either catchment, the percentage change between a baseline and the land use change scenarios could still be calculated.

4.2 Revised Degraded Vegetation Parameters

The revised vegetation parameters were determined using the methods described in Chapter 3 and included the recalculation of the degraded and pristine crop coefficients according to the FAO dual crop coefficient and Kristensen methods, as well as the recalculation of the vegetation interception for the different veld types.

4.2.1 Crop coefficients

The crop coefficients (K_c) for the degraded and pristine natural veld sites were calculated according to the FAO and Kristensen methods for the sites selected within the Thukela and Mzimvubu catchments. Once the sites had been selected, the dominant Acocks veld type for that area was determined in order to ensure that the corresponding sites were comparing the same type of natural vegetation and to allow for differentiation between sites (not as a means to create an overarching set of parameters per Acocks veld type). Within the Mzimvubu catchment, the Acocks veld types at the sites used were the Highland and Dohne Sourveld (#44) and the Cymbopogon-Themeda Transition (#56) grasslands. The Thukela catchment also had Highland and Dohne Sourveld grasslands at some of the sites, as well as areas of Southern Tall grassveld (#65).

Both the FAO dual crop coefficient method and the Kristensen method produced similar patterns in the crop coefficients calculated for all the veld types at the chosen sites. Figure 4.3(a) and (b), along with Figure 4.4 (a) and (b), show that during the spring months (from October) there is an increase in the K_c values for both the degraded and pristine sites until it reaches a peak in late summer (February). Following this, the K_c value begins to decrease throughout autumn and reaches a minimum in winter (around July and August) before beginning to increase again. These changes follow the expected crop growth and senescence patterns of the vegetation as the plant transpiration will be at a maximum during the summer months as growth takes place and will then decrease in winter as the plant senesces.

Figure 4.3 and Figure 4.4 both show that for all veld types within the study sites, the degraded sites have lower LAI values and subsequently lower crop coefficients for both the FAO and Kristensen methods. The figures also show a difference in the K_c values across the two catchments for similar veld types, which could be as a result of different rainfall patterns across the two different catchments.

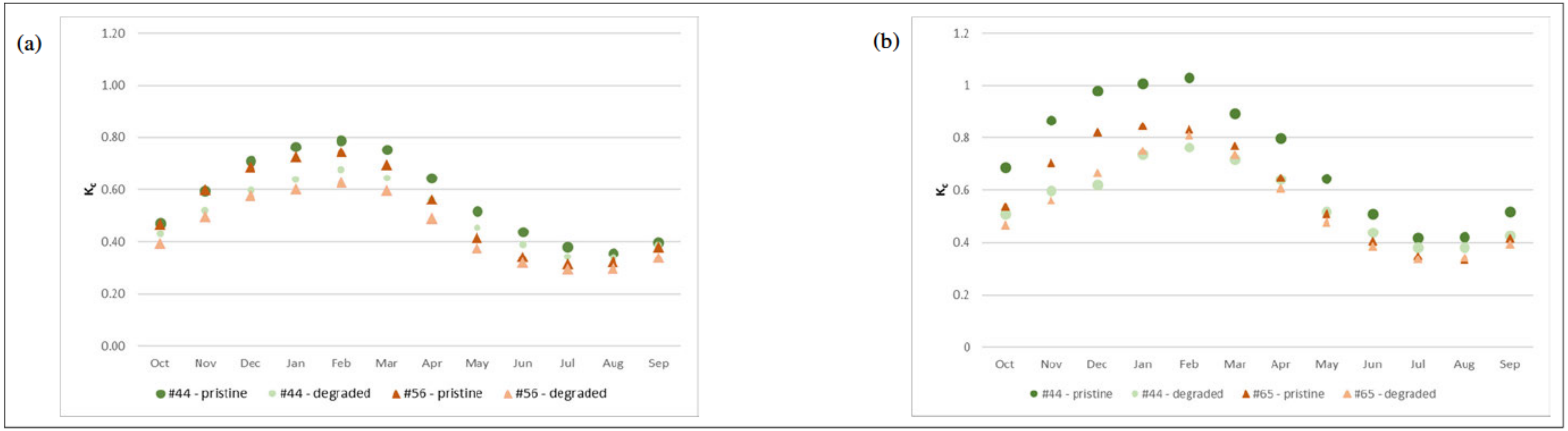


Figure 4.3 Crop coefficients determined using the FAO dual crop coefficient method in (a) the Mzimvubu and (b) the Thukela catchments.

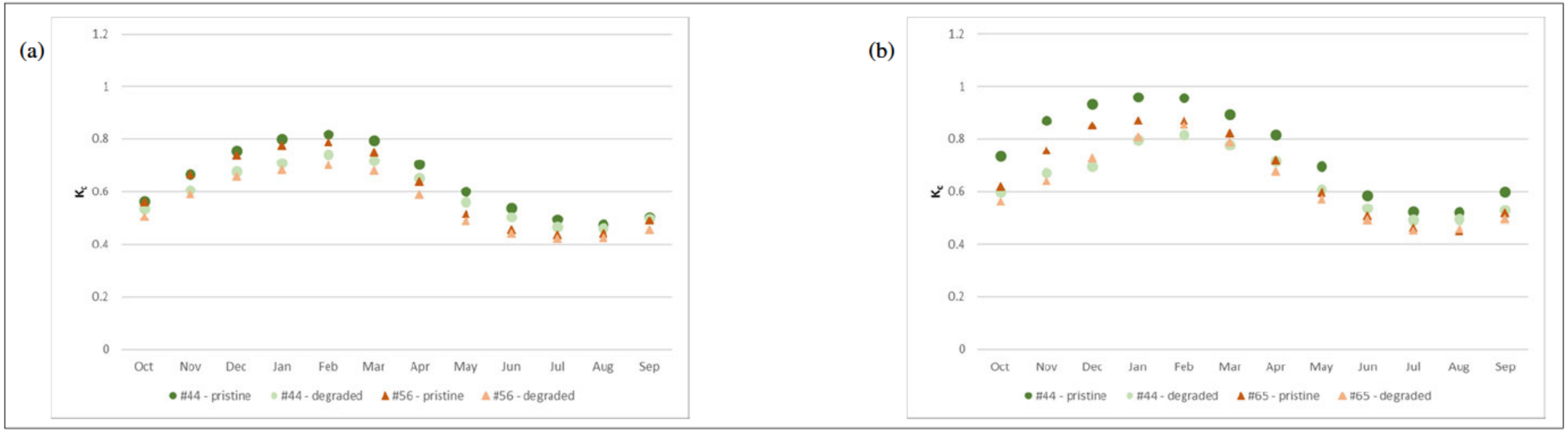


Figure 4.4 Crop coefficients determined using the Kristensen crop coefficient method in (a) the Mzimvubu and (b) the Thukela catchments.

When comparing the two methods used to calculate crop coefficients, Figure 4.5 shows that the Kristensen method yielded consistently higher K_c values than the FAO method throughout the year for the same study sites. The differences observed between the two methods are greater during the summer months than the winter ones and are also greater for the degraded areas than the pristine ones. Given that both catchments have summer rainfall patterns, this could result in the greater differences that could be attributed to the fact that only the basal crop coefficient part of the FAO method was used in its calculation as there was insufficient in situ data to provide for accurate soil evaporation coefficients to be calculated. The Kristensen method, on the other hand, is a lumped equation that incorporates both basal and soil coefficients and could account for the higher crop coefficients during the wetter summer months.

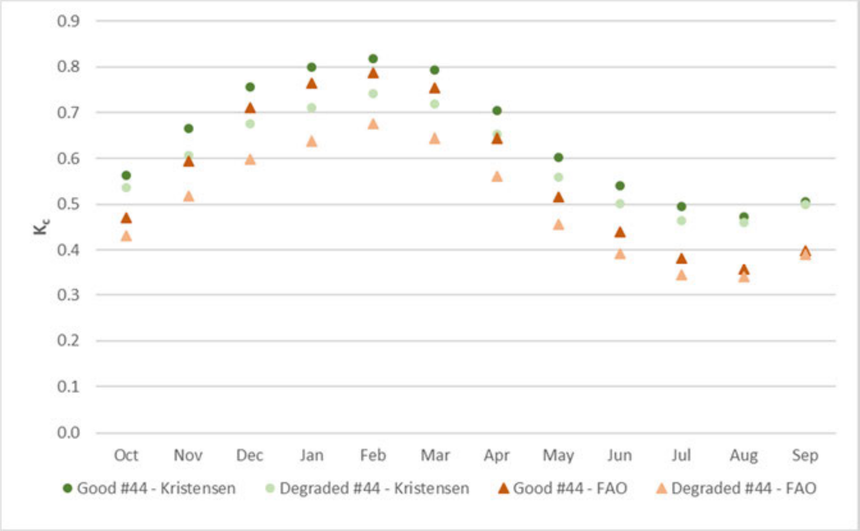


Figure 4.5 Comparison of crop coefficients for sites with Acocks #44 veld types determined using the dual FAO and Kristensen methods

4.2.2 Vegetation interception

The vegetation interception for the degraded and pristine natural veld sites were calculated using the variable storage Gash model for the sites selected within the Thukela and Mzimvubu catchments. Similar to the crop coefficient calculations, the dominant Acocks veld type was used to differentiate between the different sites but was not used to define the interception parameters for the Acocks veld type. Owing to the use of LAI data, burning of ground litter was incorporated into the parameters calculated.

Figure 4.6 (a) and (b) show that during the spring months (from October), interception amounts begin to increase for both the degraded and pristine sites until it reaches a peak in mid- to late summer (February). The amount of interception then starts to decrease throughout autumn and reaches a minimum in winter (around July and August) before beginning to increase again. Much like the crop coefficients calculated, the fluctuations of interception amounts follow the expected crop growth patterns of the vegetation as the vegetative biomass will be at a maximum during the summer months as growth takes place and will then decrease in winter as the plant senesces.

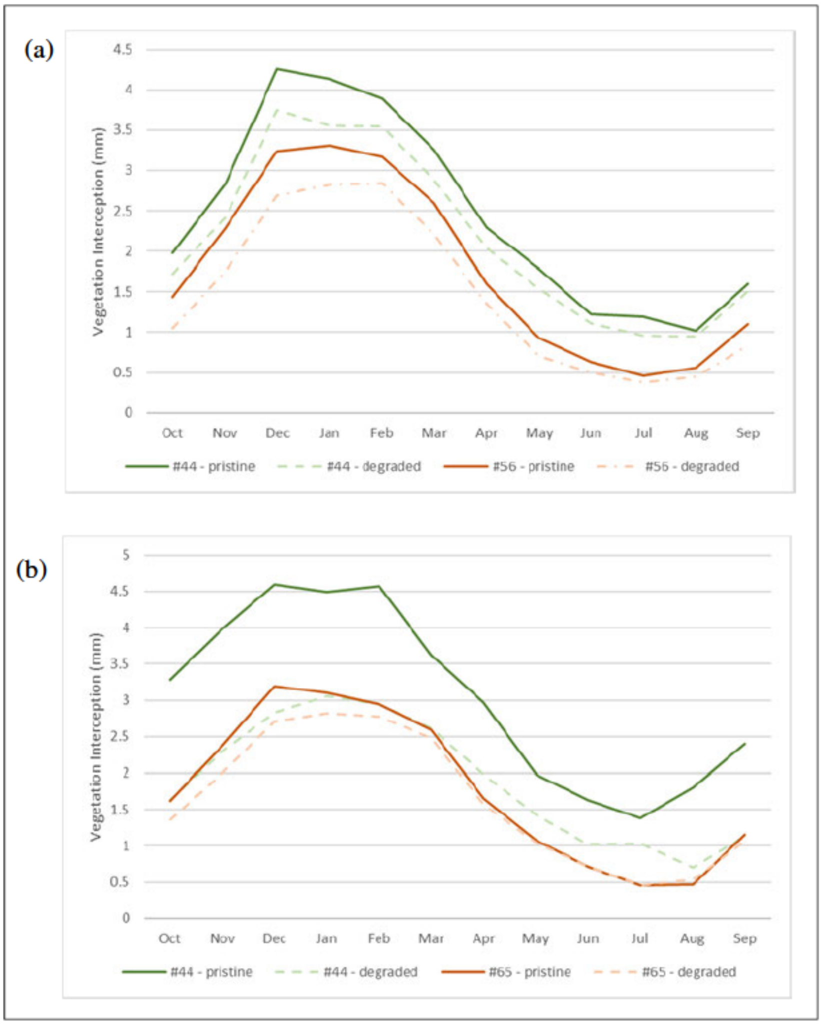


Figure 4.6 Vegetation interception determined using the variable storage Gash model in (a) the Mzimvubu and (b) the Thukela catchments.

The interception calculated by the model also showed a clear trend within both catchments of the degraded veld having a lower amount of rainfall intercepted when compared with the pristine veld. This result would be expected, as a loss of vegetative cover on degraded land would lead to a smaller amount of vegetative biomass available to intercept rainfall, which in turn would lead to reduced interception.

4.3 ACRU Results Using Revised Parameters

The results for the degraded and pristine natural veld parameters were used in three sets of ACRU simulations within both study catchments to gauge the suitability of the revised parameters. The first run was done by calculating the percentage difference between the calculated degraded and pristine veld, and then applying this percentage change to the current Acocks veld parameters within the ACRU model. The remaining two sets of simulations were done by replacing the established parameters within the model for pristine and degraded natural vegetation with the revised values for the Mzimvubu catchment.

4.3.1 Percentage change in current Acocks vegetation parameters

The first set of model simulations was done by calculating the percentage difference, ranging between 5 and 15% dependent on the season (the percentage change was greater during summer than during winter),, between the revised pristine and degraded natural vegetation parameters and then applying the percentage to the pre-existing Acocks parameters within the model to develop a set of degraded vegetation parameters. The Acocks parameters within the model were then used as is for the natural vegetation HRUs, whilst the calculated parameters were used for the degraded areas. These changes were applied to both T32A/B/C and T35C for the same periods as the initial verification simulations in order for comparisons to be made.

Following the changes made to the T32A/B/C catchment vegetation parameters for the period 1965 to 1980, minimal changes to the catchment's observed vs simulated streamflow statistics were detected. Whereas the initial verification of the catchment for the same time period yielded a 36.3 % over simulation of the catchment, the revised run using a percentage change to the ACRU degraded vegetation parameters improved it minimally to a 35.8 % over simulation. The remaining statistics were similarly unchanged (Table 4.3) as were the streamflow curves and time series (Figure 4.7a - d).

Similarly, only small changes were observed in the model run of the T35C catchment with the revised parameters. For the same period 1985 to 1999 used for the verification model run, the difference between the mean observed and simulated flows for the revised run worsened to

26.2 % from an initial under simulation of 22.3 % for the verification run. The remaining statistics were also only minimally changed (Table 4.3) as were the streamflow curves and time series (Figure 4.8a - d).

These minimal changes were attributed to the fact that the percentage differences calculated were small and that did not change the current Acock's parameters much when compared to the revised parameters calculated.

Table 4.3 Statistics ACRU simulation of the percentage change in Acocks vegetation of T32A/B/C catchment for the period 1965 to 1980, and T35C catchment for the period 1985 to 1999.

	T32A/B/C	**T35C**
Total observed flows (mm)	1377.068	4146.790
Total simulated flows (mm)	1869.842	3062.343
Ave. error in flow (mm/day)	0.101	-0.205
Mean observed flows (mm/day)	0.281	0.786
Mean simulated flows (mm/day)	0.382	0.580
% Difference between means	-35.784	26.151
Variance of observed flows (mm)	0.424	2.393
Variance of simulated flows (mm)	0.400	2.220
% Difference between Variances	5.702	7.235
Std. Deviation of observed flows (mm)	0.651	1.547
Std. Deviation of simulated flows (mm)	0.632	1.490
% Difference between Std. Deviations	2.893	3.685
Correlation Coefficient : Pearson's R	0.687	0.569
Regression Coefficient (slope)	0.667	0.548
Regression Intercept	0.195	0.150
Coefficient of Determination: R^2	0.471	0.323
Nash—Sutcliffe Efficiency Index (E_f)	0.366	0.150

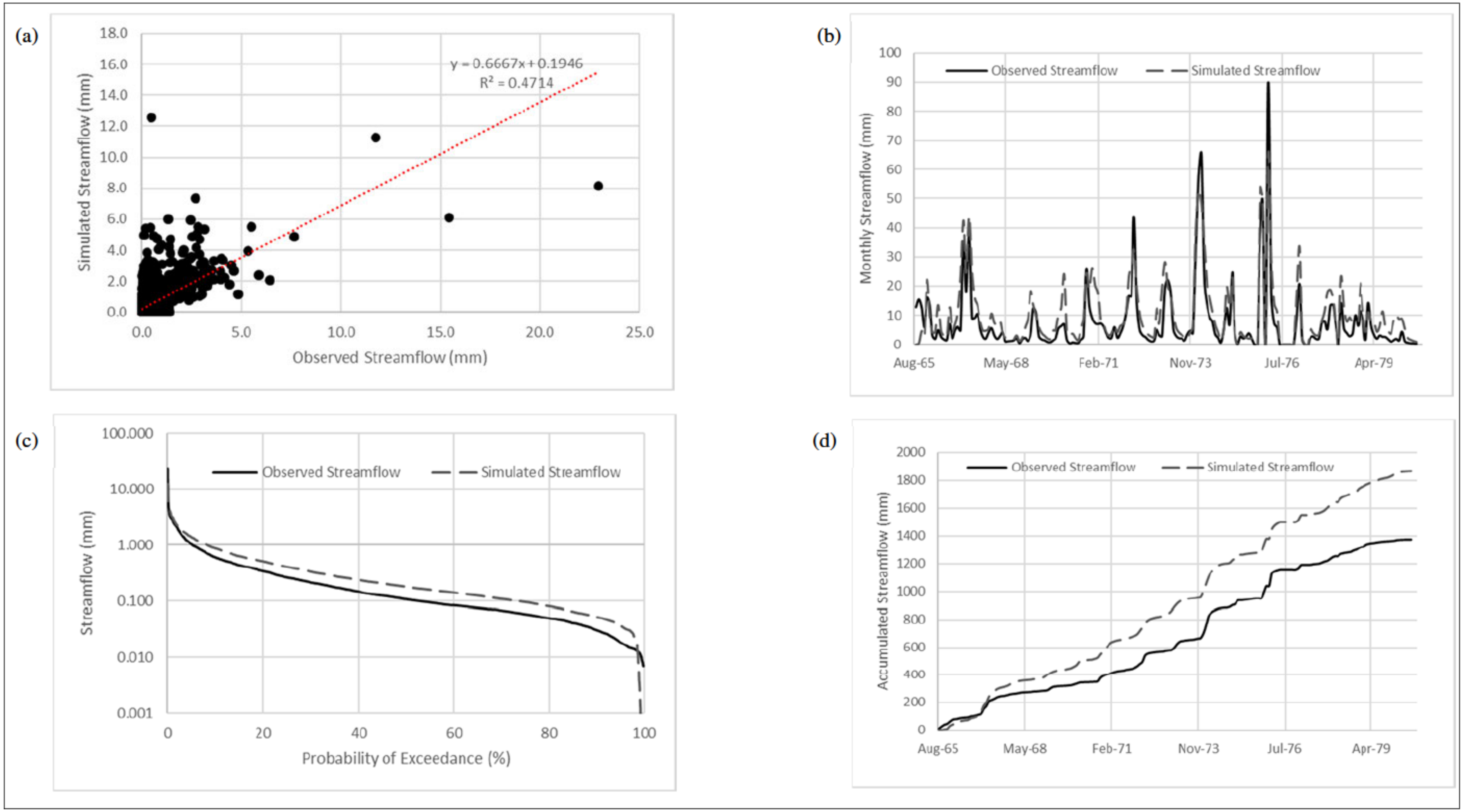


Figure 4.7 (a) Comparison, (b) time series, (c) flow duration curves, and (d) accumulated streamflow curves of the revised percentage degradation in Acocks parameters of the T32A/B/C catchment for the period 1965 to 1980.

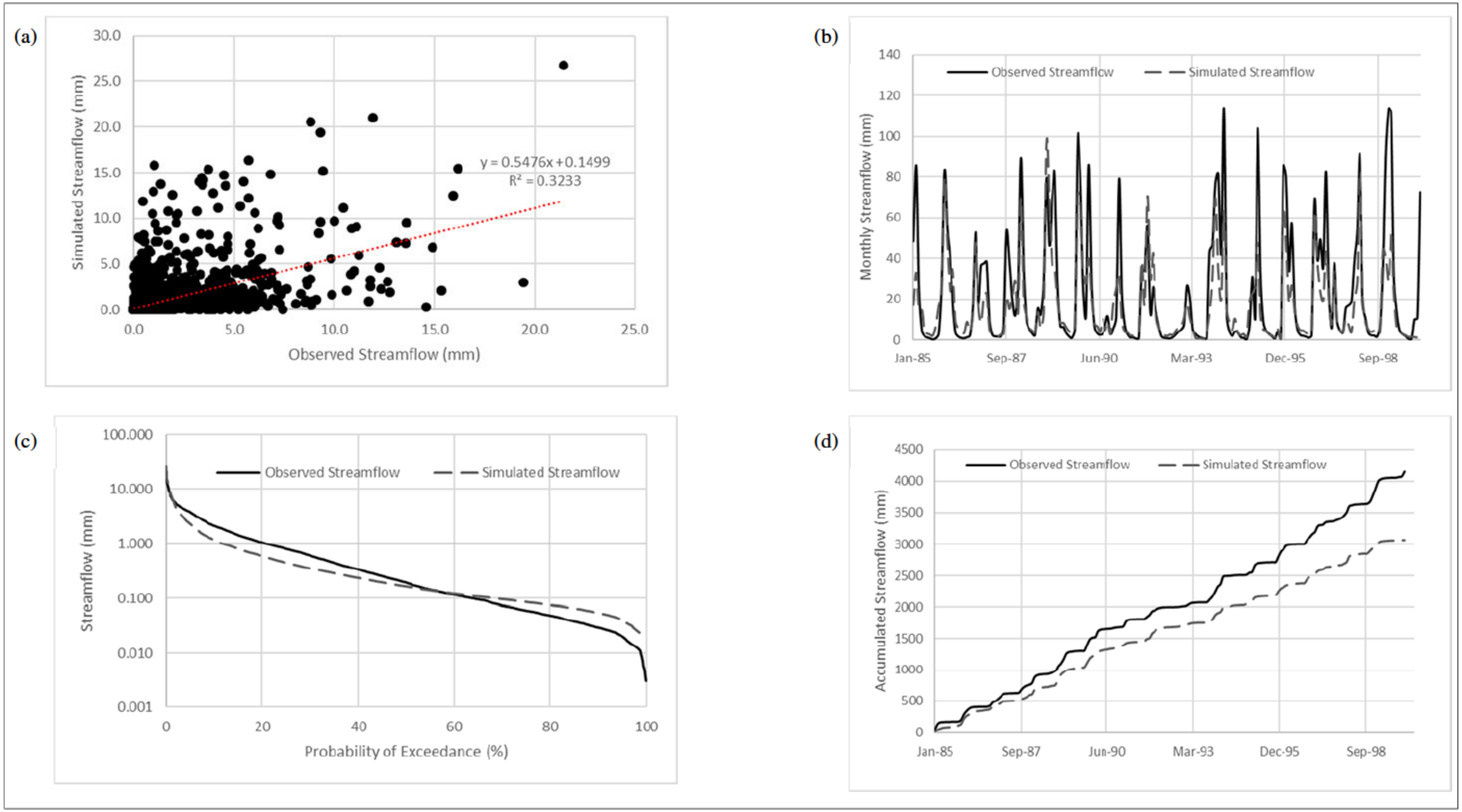


Figure 4.8 (a) Comparison, (b) time series, (c) flow duration curves, and (d) accumulated streamflow curves of the revised percentage degradation in Acocks parameters of the T35C catchment for the period 1985 to 1999.

4.3.2 Revised degraded parameters using FAO dual crop coefficients

Following the percentage change set of model simulations, the next set of simulations to be done used revised parameters for both pristine and degraded vegetation HRUs within the model (Appendix B). The crop coefficients used for this set of simulations were calculated using the FAO dual crop coefficient method, with the changes being applied to both T32A/B/C and T35C for the same periods as the initial verification simulations in order for comparisons to be made.

Following the changes made to the T32A/B/C catchment vegetation parameters for the period 1965 to 1980, changes to the catchment's observed vs simulated streamflow statistics were observed. Whereas the initial verification of the catchment for the same time period yielded a 36.3 % over simulation of the catchment, the revised run using new parameters for both the natural and degraded vegetation HRUs improved the simulation to a 18.2 % over simulation.

Whilst there was a marked improvement in the simulation according to the streamflow curves and time series (Figure 4.9a - d), the standard deviation and variances worsened slightly (Table 4.4). The simulated flow duration curve, whilst still over simulating over the range of flows, showed an improvement as the over simulation lessened. Similarly, the timeseries of both simulated and observed flows, along with the accumulated flows, showed less of an over simulation as the difference between them lessened. As shown in Figure 4.9c, the change in simulated flow duration curve is of particular significance as the change in vegetation parameters created a flow duration curve similar to the observed curve.

Changes were also observed in the model run of the T35C catchment with the revised parameters although, unlike T32A/B/C, the parameters worsened the simulation. For the same period 1985 to 1999 used for the verification model run, the difference between the mean observed and simulated flows for the revised run worsened to 33.1 % from an initial under simulation of 22.3 % for the verification run. The flow statistics (Table 4.4), as well as the streamflow curves and time series (Figure 4.10a - d), worsened when compared to the initial verification run.

Whilst the total simulated flows decreased further compared to the verification run, the time series and flow duration curves (Figure 4.10b and c) show only a slight change throughout with high flows still under simulating and low flows still over simulating. This means that, although the simulation worsened, the model was seemingly still responding well to the rainfall patterns and annual streamflows, albeit whilst under simulating.

Table 4.4 Statistics of ACRU simulation of the revised degraded parameters using the FAO crop coefficient method of T32A/B/C for the period 1965 to 1980, and T35C for the period 1985 to 1999.

	T32A/B/C	**T35C**
Total observed flows (mm)	1377.068	4146.790
Total simulated flows (mm)	1628.247	2773.419
Ave. error in flow (mm/day)	0.051	-0.260
Mean observed flows (mm/day)	0.281	0.786
Mean simulated flows (mm/day)	0.333	0.525
% Difference between means	-18.240	33.119
Variance of observed flows (mm)	0.424	2.393
Variance of simulated flows (mm)	0.328	1.889
% Difference between Variances	22.580	21.087
Std. Deviation of observed flows (mm)	0.651	1.547
Std. Deviation of simulated flows (mm)	0.573	1.374
% Difference between Std. Deviations	12.011	11.167
Correlation Coefficient : Pearson's R	0.663	0.558
Regression Coefficient (slope)	0.584	0.495
Regression Intercept	0.169	0.136
Coefficient of Determination: R^2	0.440	0.311
Nash—Sutcliffe Efficiency Index (E_f)	0.387	0.173

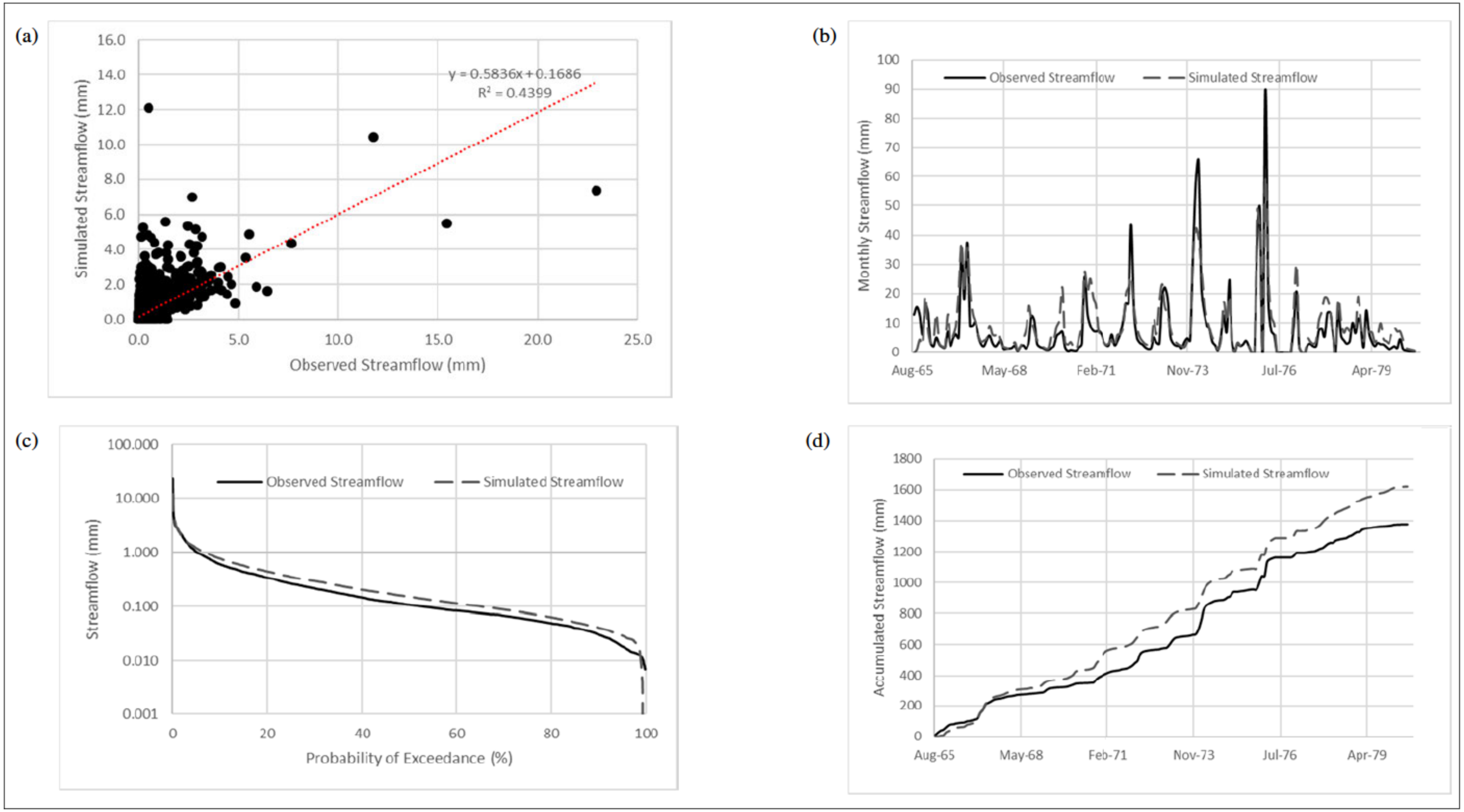


Figure 4.9 (a) Comparison, (b) time series, (c) flow duration curves, and (d) accumulated streamflow curves of the revised degraded parameters (using FAO dual crop coefficient method) of the T32A/B/C catchment for the period 1965 to 1980.

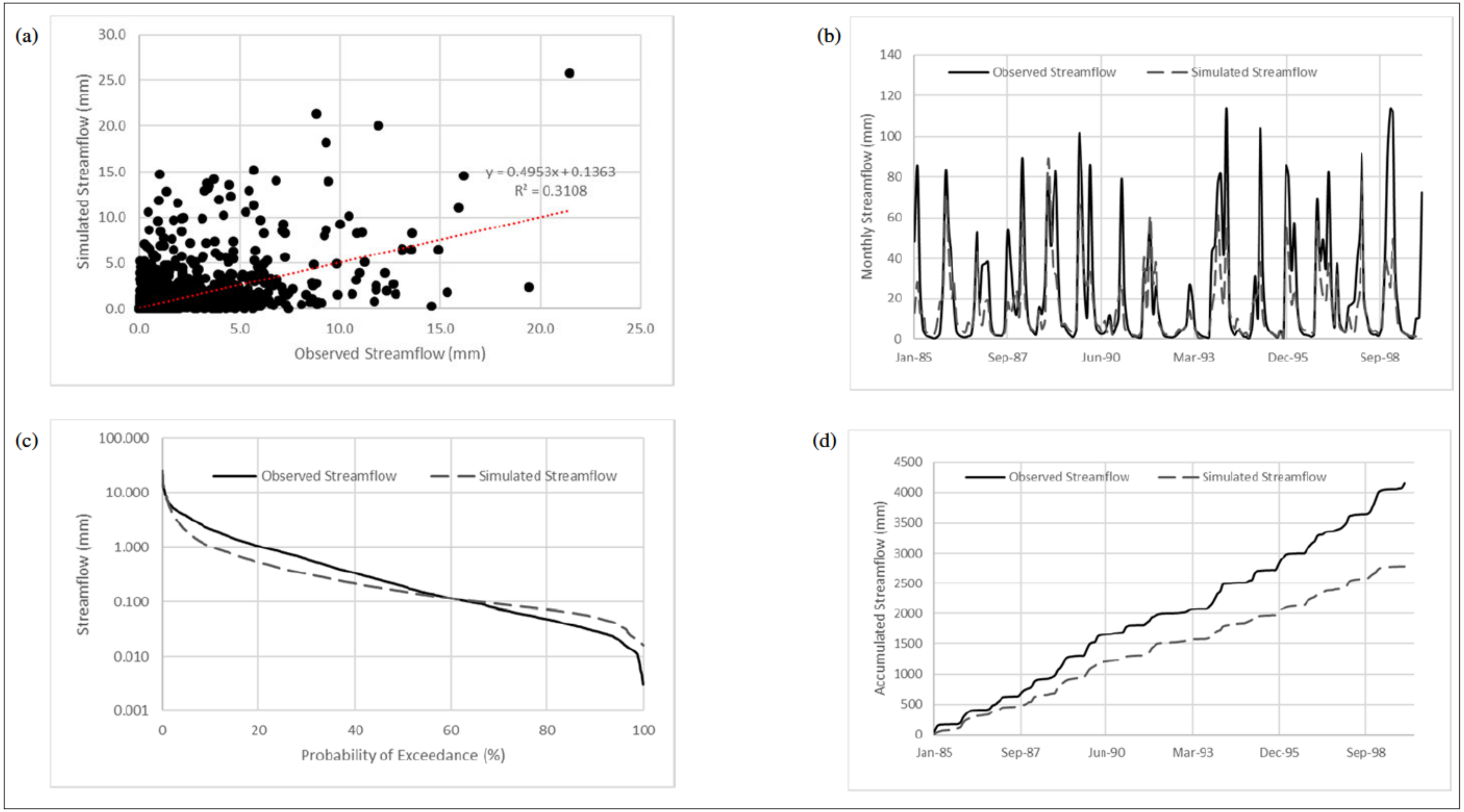


Figure 4.10 (a) Comparison, (b) time series, (c) flow duration curves, and (d) accumulated streamflow curves of the revised degraded parameters (using FAO dual crop coefficient method) of the T35C catchment for the period 1985 to 1999.

4.3.3 Revised degraded parameters using Kristensen crop coefficients

The final set of model simulations done used revised parameters for both pristine and degraded vegetation HRUs within the model (Appendix B). The crop coefficients used for this set of simulations were calculated using the Kristensen crop coefficient method, with the changes being applied to both T32A/B/C and T35C for the same periods as the initial verification simulations in order for comparisons to be made.

Following the changes made to the T32A/B/C catchment vegetation parameters for the period 1965 to 1980, large changes in the catchment's observed versus simulated streamflow statistics were observed. Whereas the initial verification of the catchment for the same time period yielded a 36.3 % over simulation of the catchment, the revised run using new parameters for both the natural and degraded vegetation HRUs improved the simulation to a 11.7 % over simulation.

Whilst there was a very marked improvement in the simulation according to the streamflow curves and time series (Figure 4.11a – d), the standard deviation and variances worsened (Table 4.5). As shown in Figure 4.11c, the change in simulated flow duration curve is of particular significance as the change in vegetation parameters created a flow duration curve almost the same as the observed curve, meaning that the simulation was mimicking the observed flows well. The simulated flow duration curve, whilst still over simulating over the range of flows, showed an improvement as the over simulation further lessened. Similarly, the timeseries of both simulated and observed flows, along with the accumulated flows, both showed less of an over simulation as the difference between them lessened.

Changes were also observed in the model run of the T35C catchment with the revised parameters although the parameters worsened the simulation only slightly more than the FAO crop coefficient run. For the same period 1985 to 1999 used for the verification model run, the difference between the mean observed and simulated flows for the revised run worsened to 33.4 % from an initial under simulation of 22.3 % for the verification run. The flow statistics (Table 4.5), along with the streamflow curves and timeseries Figure 4.10a - d), also worsened when compared to previous model runs.

Whilst the total simulated flows decreased further compared to the verification run, the time series and flow duration curves (Figure 4.10b and c) show only a slight change throughout, with high flows still under simulating and low flows still over simulating. This means that, although the simulation worsened, the model was seemingly still responding well to the rainfall patterns and annual streamflows, albeit whilst under simulating.

Table 4.5 Statistics of ACRU simulation of the revised degraded parameters using the Kristensen crop coefficient method of T32A/B/C for the period 1965 to 1980, and T35C for the period 1985 to 1999.

	T32A/B/C	**T35C**
Total observed flows (mm)	1377.068	4146.790
Total simulated flows (mm)	1538.219	2761.140
Ave. error in flow (mm/day)	0.033	-0.262
Mean observed flows (mm/day)	0.281	0.786
Mean simulated flows (mm/day)	0.314	0.523
% Difference between means	-11.702	33.415
Variance of observed flows (mm)	0.424	2.393
Variance of simulated flows (mm)	0.315	1.889
% Difference between Variances	25.770	21.087
Std. Deviation of observed flows (mm)	0.651	1.547
Std. Deviation of simulated flows (mm)	0.561	1.374
% Difference between Std. Deviations	13.843	11.167
Correlation Coefficient : Pearson's R	0.657	0.557
Regression Coefficient (slope)	0.566	0.495
Regression Intercept	0.155	0.134
Coefficient of Determination: R^2	0.432	0.310
Nash—Sutcliffe Efficiency Index (E_f)	0.388	0.172

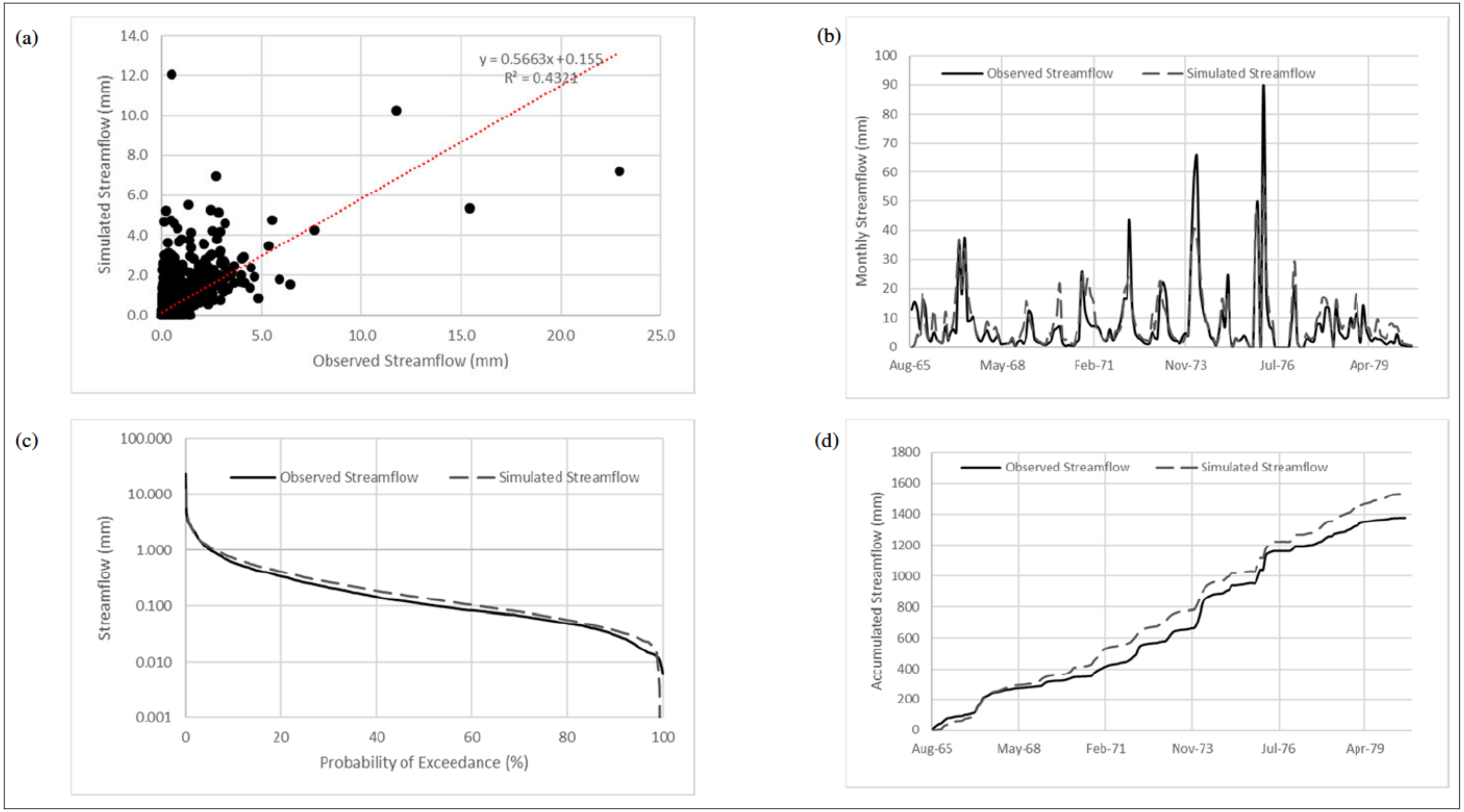


Figure 4.11 (a) Comparison, (b) time series, (c) flow duration curves, and (d) accumulated streamflow curves of the revised degraded parameters (using Kristensen crop coefficient method) of the T32A/B/C catchment for the period 1965 to 1980.

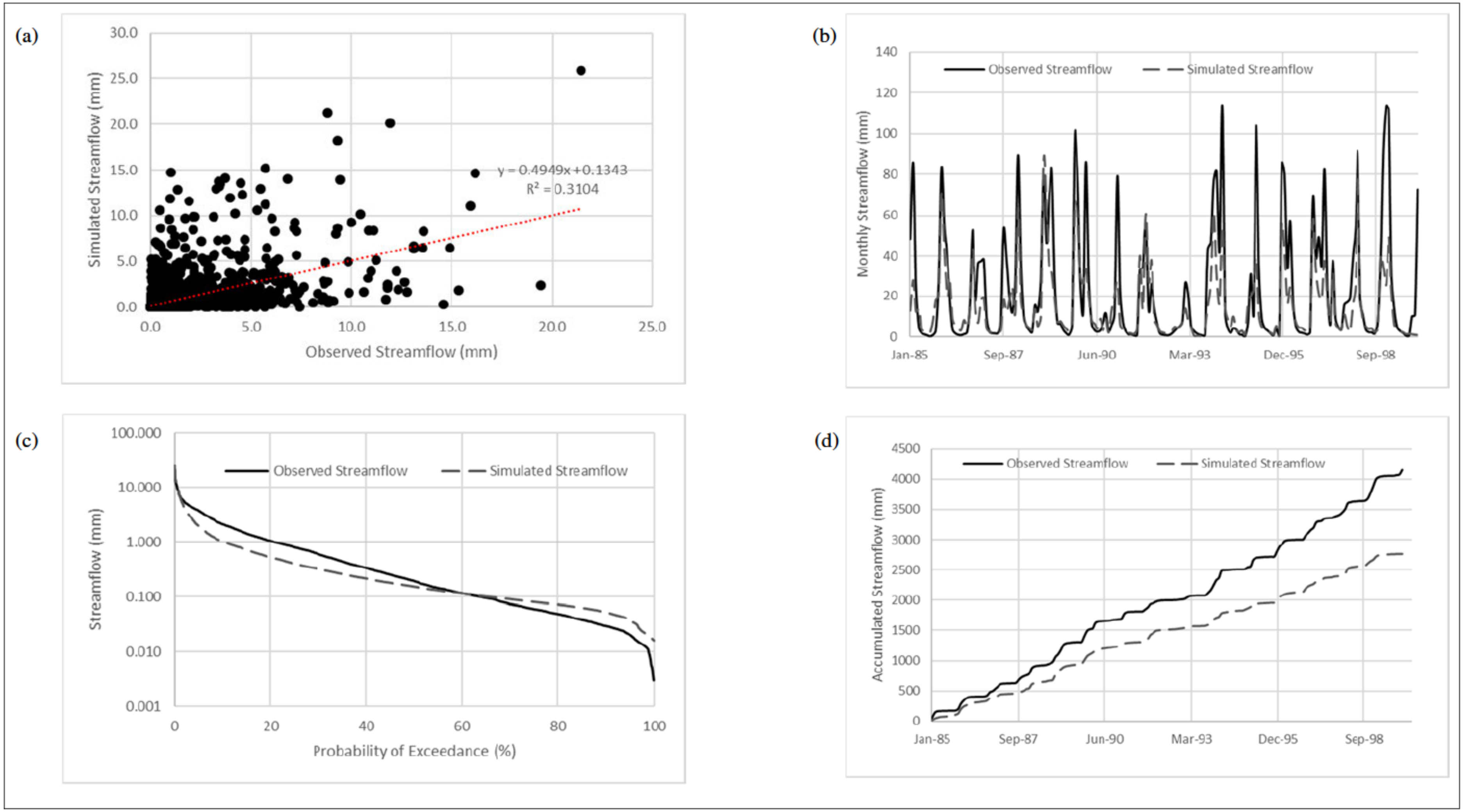


Figure 4.12 (a) Comparison, (b) time series, (c) flow duration curves, and (d) accumulated streamflow curves of the revised degraded parameters (using Kristensen crop coefficient method) of the T35C catchment for the period 1985 to 1999.

4.4 Land Use Management Scenario Results

Owing to the size of the verification catchments in the Mzimvubu catchment and that this study was demonstrating a methodology, it was decided that the development and modelling of the different land use scenarios would be applied to the more applicable of the two selected verification catchments. For each scenario, the impacts on the accumulated streamflow responses at the outlet of the catchments, as well as the impacts on the low (10th percentile), median (50th percentile) and high (90th percentile) flows were considered relative to the baseline natural vegetation taken as the Acocks1988 Veld Types. Further to this, the scenarios were broken down into two main areas for consideration – rangeland management scenarios, and agricultural management scenarios.

4.4.1 Rangeland Management Scenarios

Rangeland management, in the context of this study, related to unimproved natural vegetation and all degraded areas within the catchment. Given the widespread grazing of cattle in the Mzimvubu catchment, overgrazing and subsequent degradation or encroachment by woodier species is a common problem within the area. Whilst burning is believed to assist in the promotion of palatable grass species for grazing livestock, the severity of the burn, as well as the timing, can often have adverse effects to the veld being burned. The rangeland management scenarios undertaken within this study were applied to the T35C verification catchment in the Mzimvubu catchment, with the degraded area scenarios done using the revised Kristensen-based crop parameters.

For the degraded areas scenario, two scenarios were modelled – firstly, increases in degradation from poor grazing practices such as the compaction of soil by animals' hooves and loss of vegetative cover from overgrazing and, secondly, decreases in the already present degraded areas as rehabilitation practices are introduced. The percentage of degradation into the naturally vegetated areas was increased in increments until an increase of 100 % in the initial degraded areas was present, whilst the rehabilitation scenario was done by decreasing the degraded areas, and subsequently increasing the naturally vegetated areas, in increments until 100 % decrease in degraded areas was reached.

From the 2000 land use point in Figure 4.13 (0 on x-axis), increases in degraded areas resulted in increases in quickflow and streamflow, and simultaneous decreases in baseflow. This could be attributed to the loss of vegetative cover, which would result in reduced infiltration of rainfall and increased overland flow into water courses. Rehabilitation, on the other hand had the opposite impact on flows. Decreases in quickflow and streamflow, whilst the baseflow increased, were observed as degraded areas were rehabilitated back to natural vegetation. This could be attributed to the fact that improved vegetative cover would slow overland flow generated from rainfall and increase the amount of infiltration into soil, which would in turn generate more baseflow through the soil as opposed to overland quickflow.

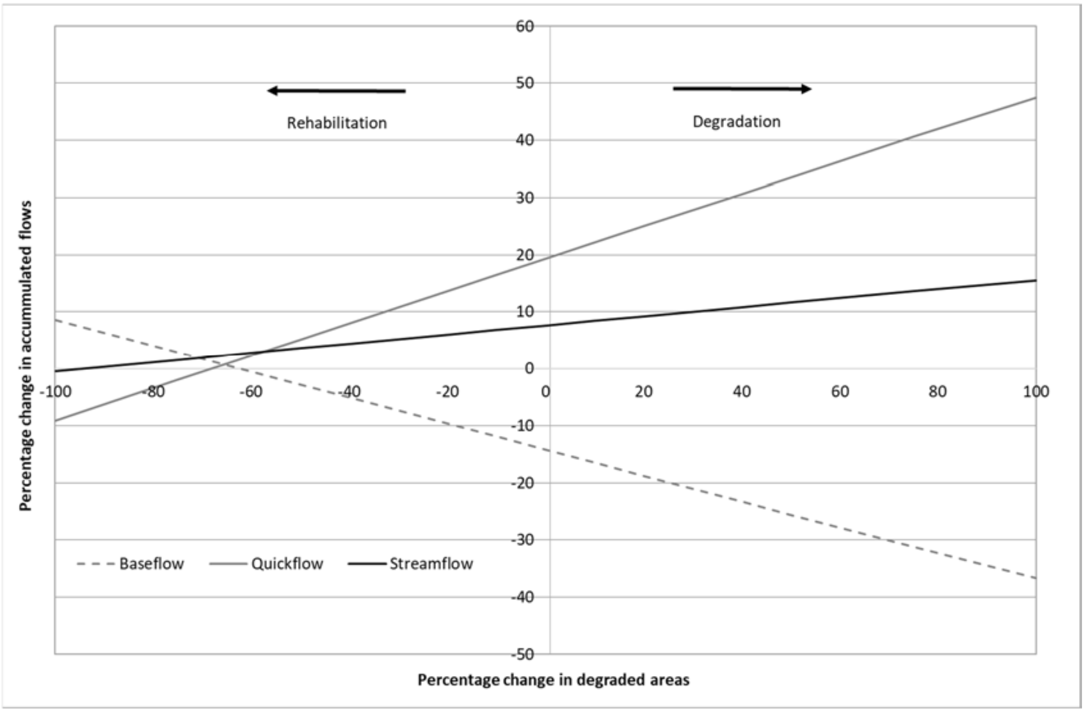


Figure 4.13 Percentage change in accumulated streamflow, quickflow, and baseflow for the period 1965-1999 due to changes in the percentage of degraded and rehabilitated veld relative to the vegetation baseline.

In terms of the flow regimes for these scenarios, degradation of naturally vegetated areas showed increases in the high and median flows in the summer months. However, marked decreases in the median and low flows are evident in the winter months (Figure 4.14). Rehabilitation impacts on flow were not as marked as those of degradation as there were small decreases in the high and median flows during the summer months with no noticeable change in the winter months. Low flows showed minimal changes in the summer months whilst an increase was observed in the winter months with the flows becoming more like those of the natural vegetation baseline (Figure 4.14).

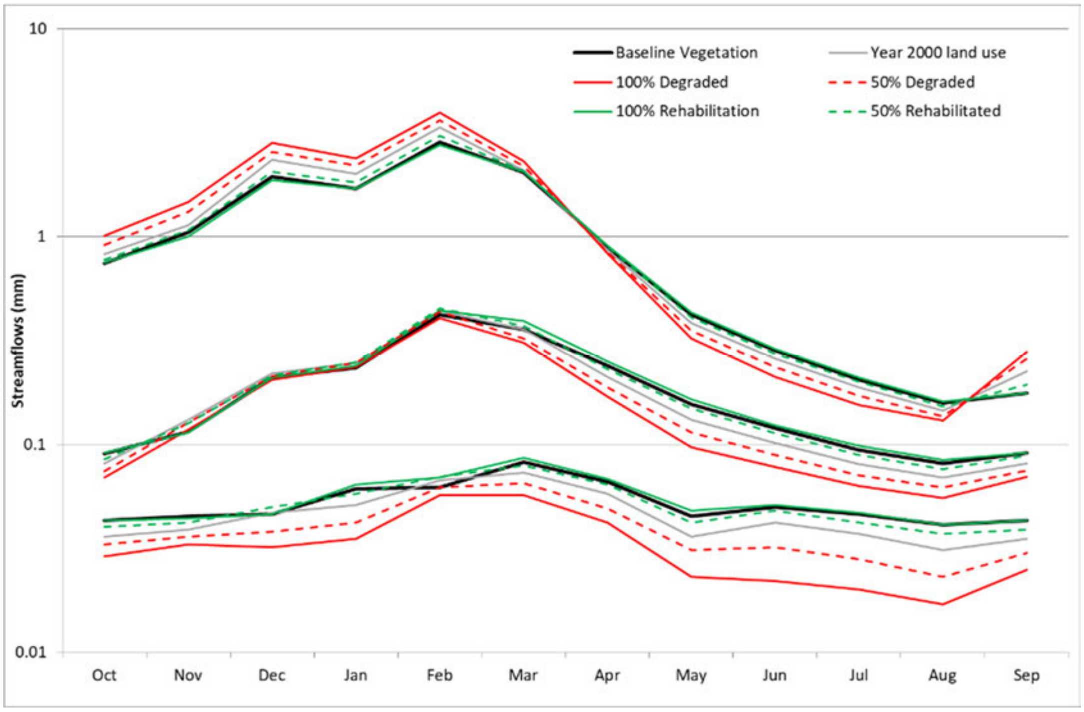


Figure 4.14 One in ten-year High (90th percentile), Median (50th percentile), and Low (10th percentile) monthly accumulated flows at the outlet of T35C for degradation and rehabilitation scenarios.

For the bush encroachment scenario, a more succulent type of bush (i.e. the Eastern Province thornveld or Acocks #7) was chosen given the predominant types of Acocks vegetation in the area. The percentage of bush encroachment into the naturally vegetated areas was then increased in increments until 100 % bush encroachment of the natural vegetation existed. From the 2000 land use in Figure 4.15 (0 on x-axis), it can be seen that as there are increasing percentages of bush encroachment into the natural vegetation, the quickflow and streamflow decrease whilst the baseflow of the catchment increases. However, the increase in baseflow is smaller than the decrease in quickflow which would then result in the decreased streamflow.

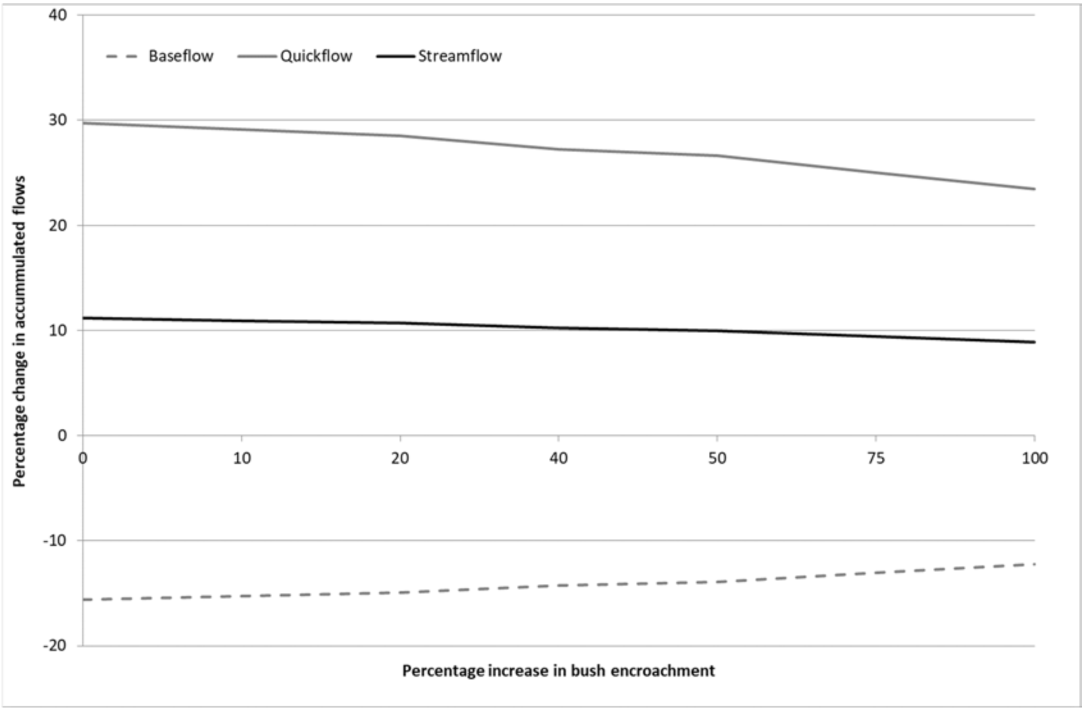


Figure 4.15 Percentage change in accumulated streamflow, quickflow, and baseflow for the period 1965-1999 due to changes in the percentage of bush encroachment.

In terms of flow regimes, the changes were minor for all flows (i.e high, median and low flows), although there were changes in the high flows during the summer months with these flows decreasing from the 2000 land use and tending more towards the baseline vegetation scenario. In terms of bush encroachment focused in either the headwater or higher order catchments, no real difference in flows was shown to exist (Figure 4.16).

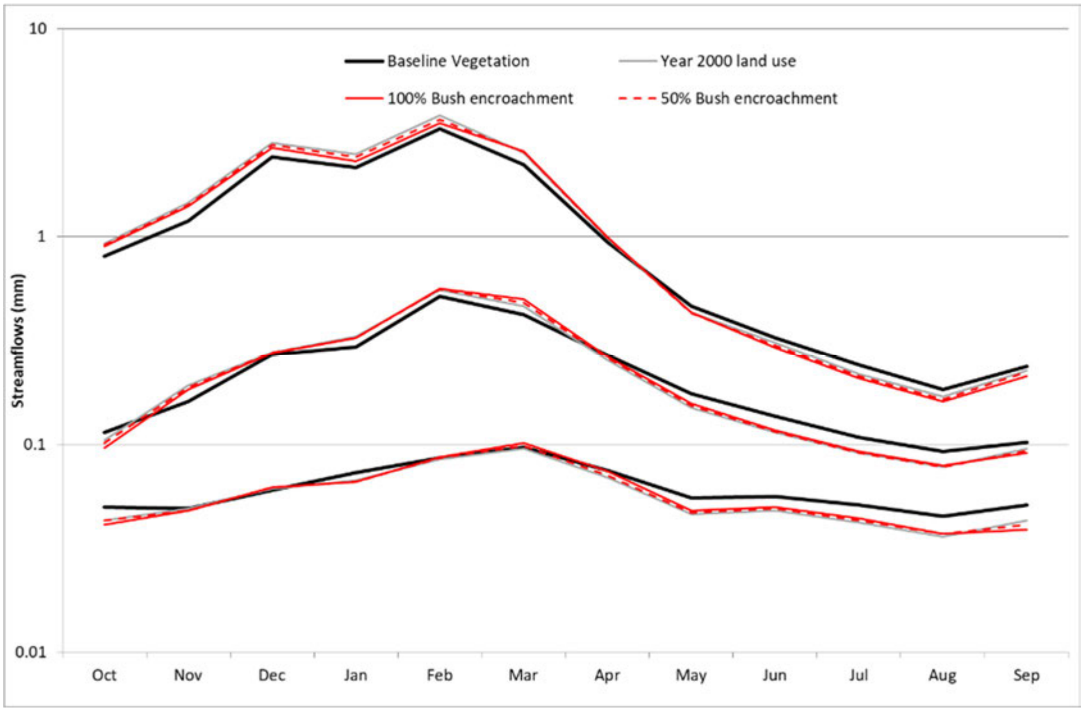


Figure 4.16 One in ten-year High (90th percentile), Median (50th percentile), and Low (10th percentile) monthly accumulated flows at the outlet of T35C for the bush encroachment scenarios.

For the burning scenario, varying degrees of burn were considered as well as the timing of the burn regimes. However, the only burning scenarios to yield significant changes in flows were those of the severe annual and biennial burns, which were the regimes considered below. The percentages of controlled burning on both an annual and biennial scale of the naturally vegetated areas were then increased in increments until 100 % burn of the natural vegetation existed.

From the 2000 land use (Figure 4.17) (0 on x-axis), increases in the area under controlled burn conditions resulted in increased quickflow and streamflow, with simultaneous decreases in baseflow. This could be attributed to the loss of vegetative cover after burning which would result in reduced infiltration of rainfall and increased overland flow into water courses.

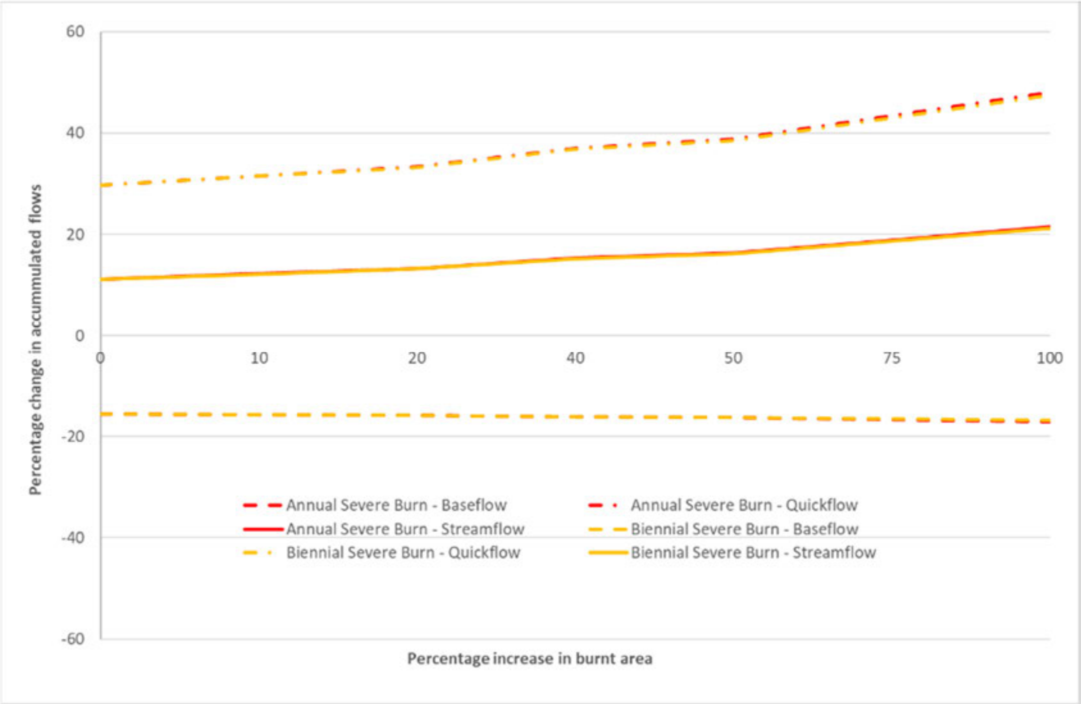


Figure 4.17 Percentage change in accumulated streamflow, quickflow, and baseflow for the period 1965-1999 due to varying burning regimes relative to the vegetation baseline.

In terms of flow regimes, severe burning (both annual and biennial) of natural vegetation and grazing areas showed very little change in the high, median, and low flows during the winter months (Figure 4.18). However, increases in the high and median flows were observed relative to both the natural vegetation and 2000 land use baselines for both durations of burning which could be attributed to the removal of vegetation from the area.

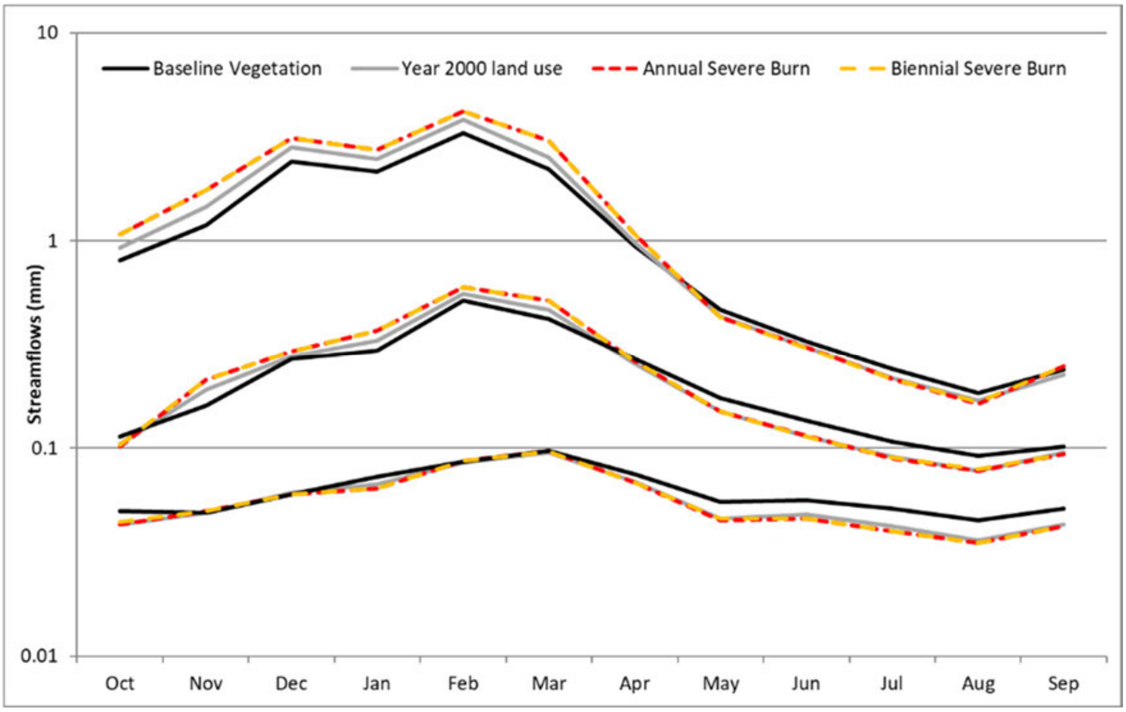


Figure 4.18 One in ten-year High (90th percentile), Median (50th percentile), and Low (10th percentile) monthly accumulated flows at the outlet of T35C for the burning regime scenarios.

4.4.2 Agricultural Management Scenarios

The management scenarios for agricultural land use changes in the context of the Mzimvubu catchment relate to the increases in land under agricultural crops, as well as changes of both the crops type and irrigation application to existing areas under dryland cropping. As part of the developmental plans for the area, there is to be an increase in land under dryland agricultural cropping within Mzimvubu. It has also been proposed that irrigation systems be established in the areas that are currently under dryland agriculture, with the Ntabelanga dam having irrigation as one of the drivers for its construction. Furthermore, the Mzimvubu catchment is an area of potential for the growing of biofuel crops, much of which is to be dryland sorghum, and thus changes from the current agricultural schemes to grain sorghum needed to be considered. These scenarios were applied to the T32 verification catchment in the Mzimvubu catchment.

For the dryland agriculture scenario, increases in the area under dryland cropping practices were considered. The crop selected for this scenario used was that of a generic commercial dryland crop, as different farmers would grow different crops under dryland conditions and the generic crop choice made use of conservative values of crop coefficient, vegetative interception, and coefficient of initial abstraction. This crop choice used for the study was that of the Dryland Commercial Crop set of parameters available within the ACRU model. These standard parameters within the model lie within the range of those for both sugarcane and maize crops, which were identified at the start of the study as two of the predominant dryland crops. The percentage of the dryland areas present within the catchment was increased in increments until the dryland areas were increased by 100 %, with land for the crops being taken from the naturally vegetated areas.

From the 2000 land use (Figure 4.19) (0 on x-axis), it can be seen that an increase in the area under dryland agriculture resulted in increases in baseflow and streamflow, and a simultaneous decrease in quickflow.

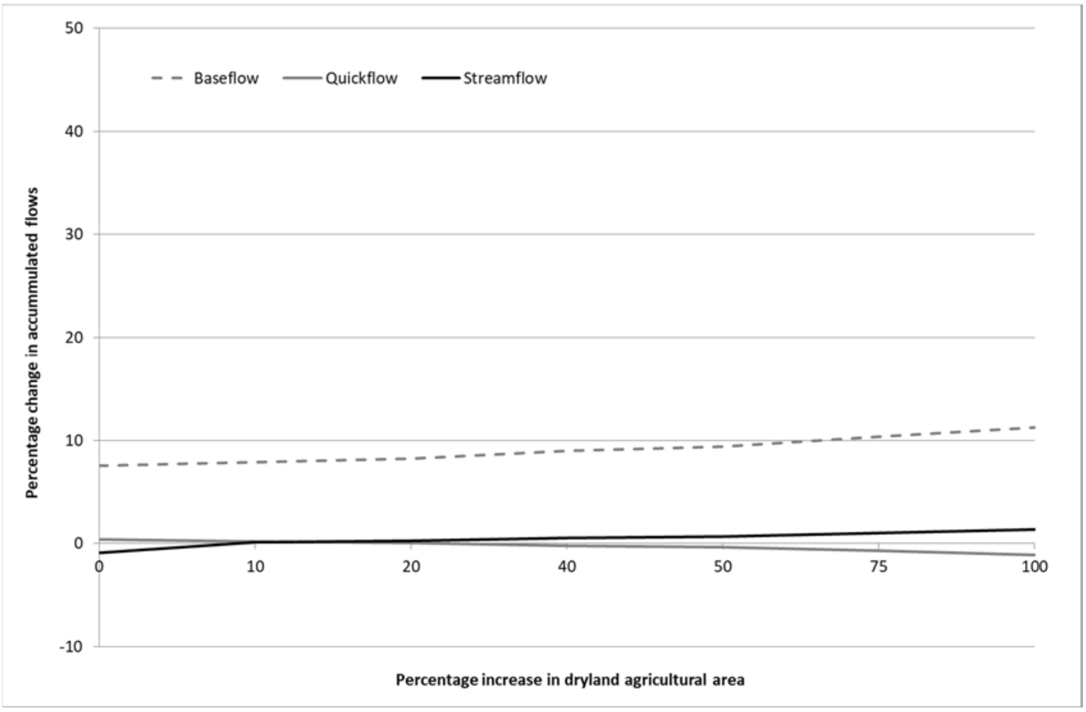


Figure 4.19 Percentage change in accumulated streamflow, quickflow, and baseflow for the period 1965-1999 due to expansion of dryland agriculture relative to the vegetation baseline.

In terms of flow regimes, slight increases in the high, median, and low flows were observed during the summer months whilst minimal, if any, changes occurred during the winter months for all flows (Figure 4.20). This could be attributed to the difference in vegetative properties between the natural vegetation and the dryland crops being grown during the summer months, whilst during winter the agricultural cropland is covered in trash and the natural vegetation undergoes senescence.

It should be noted that a generic annual crop was considered for use during the initial methodology development stage of the study, however it was observed that the differences in crop parameters were negligible during winter as the annual crop would have trash left on the surface that would act in a similar manner to a cover crop.

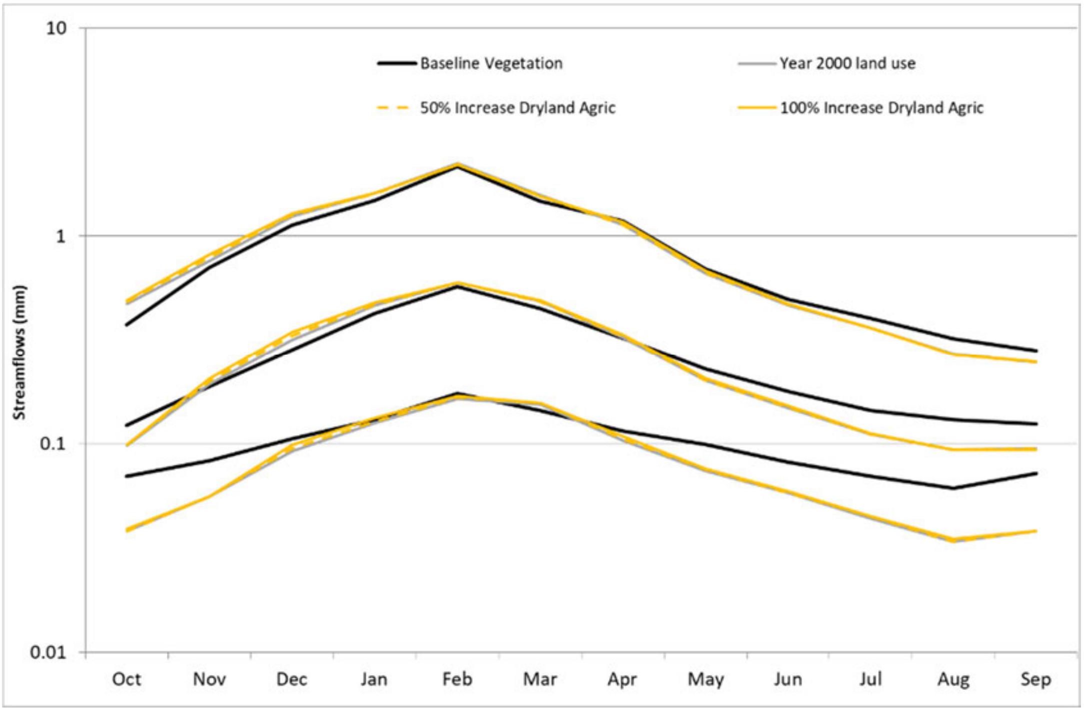


Figure 4.20 One in ten-year High (90th percentile), Median (50th percentile), and Low (10th percentile) monthly accumulated flows at the outlet of T35C for the increased dryland cropping scenarios.

For the irrigated agriculture scenario, increases in the area under irrigated cropping practices were considered. The crop selected for this scenario used was that of a generic commercial irrigated crop, as different farmers would grow different crops under irrigated conditions and allowed for a situation whereby a particular crop, e.g. maize, was grown during the summer months and a cover crop grown during the winter months. The irrigation scheduling used was that of refilling to the drained upper limit (DUL) which was determined during the verification stages to be the more conservative choice and was selected as the method of irrigating during the initial catchment verification. The area under irrigation was taken as the initial area as determined from the NLC 2000, with further incremental increases being dryland agricultural now being taken to be under irrigation.

From the 2000 land use point in Figure 4.21 (0 on x-axis), it was observed that an increase in the area under irrigated agriculture resulted in small increases in baseflow and quickflow, with a simultaneous decrease in streamflow up until a 30 % increase in irrigated areas, after which the streamflow began to increase.

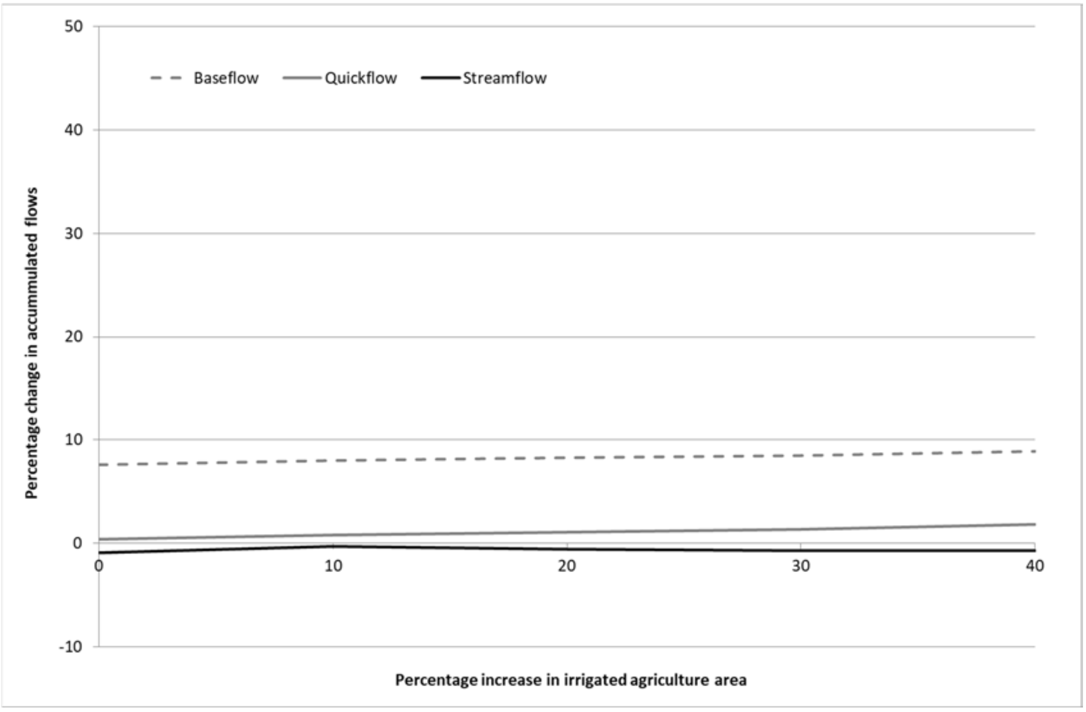


Figure 4.21 Percentage change in accumulated streamflow, quickflow, and baseflow for the period 1965-1999 due to expansion of irrigated agriculture relative to the vegetation baseline.

In terms of flow regimes, no changes to the high flows were noted throughout the year, although slight decreases in median and low flows were seen in the winter months through early summer (Figure 4.22). This could be attributed to the fact that there was an increased demand by the crops, especially the cover crops in winter.

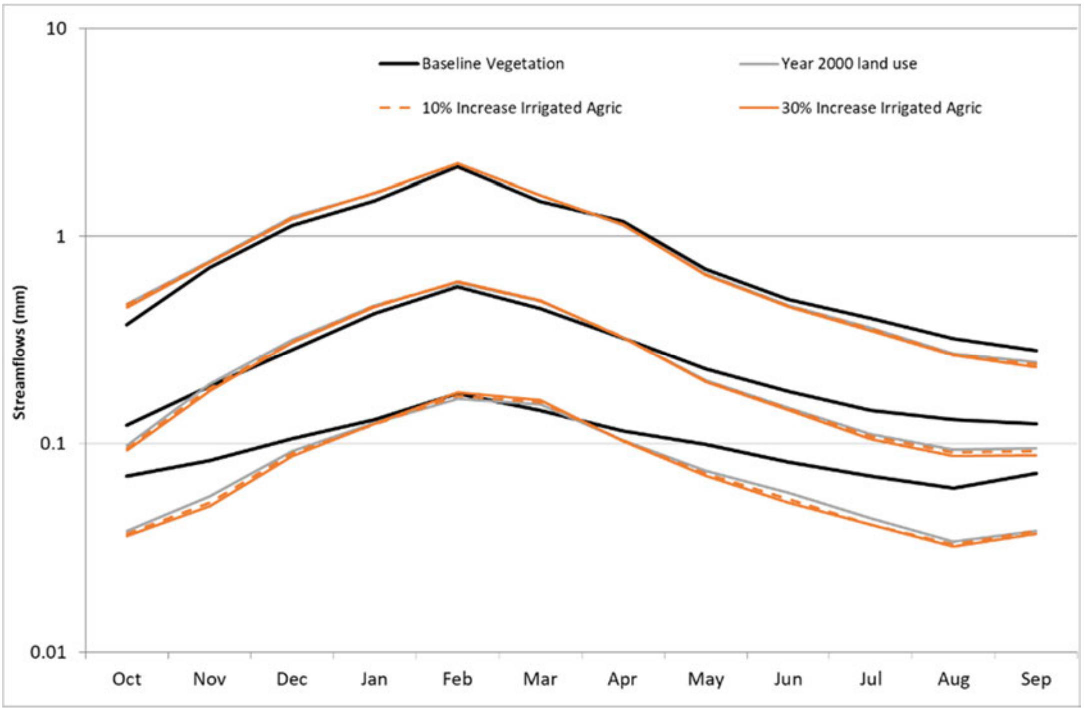


Figure 4.22 One in ten-year High (90th percentile), Median (50th percentile), and Low (10th percentile) monthly accumulated flows at the outlet of T35C for the irrigated agriculture scenarios.

For the change in crop to biofuel crops scenario, changes in the crop type under dryland cropping practices were considered. The crop selected for this scenario used was that of grain sorghum which is the most suitable biofuel crop for the Mzimvubu area, with changes to the existing dryland agricultural areas being changed in increments from generic dryland crops to that of grain sorghum.

From the 2000 land use point in Figure 4.23 (0 on x-axis), increases in the area under sorghum crops resulted in slight increases in baseflow, streamflow, and quickflow. This could be due to the change in the vegetative cover from dryland crops to grain sorghum as the changes in vegetative parameters are only slightly different (as seen in Appendix B).

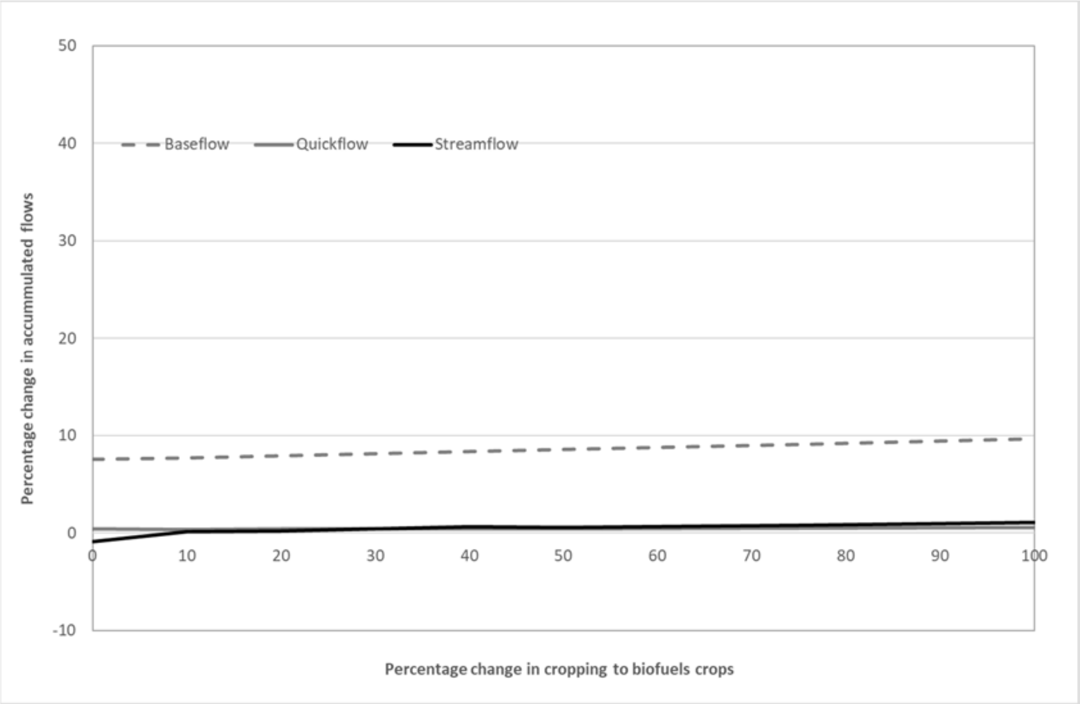


Figure 4.23 Percentage change in accumulated streamflow, quickflow, and baseflow for the period 1965-1999 due to increases in biofuel cropping relative to the vegetation baseline.

In terms of flow regimes, very slight increases in the high, median, and low flows were observed during the summer months whilst very small increases occurred during the winter months for both the median and low flows (Figure 4.24). This could be attributed to the difference in vegetative properties between the natural vegetation and the sorghum crops being grown during the summer months and then harvested, leaving less trash as cover during the winter months.

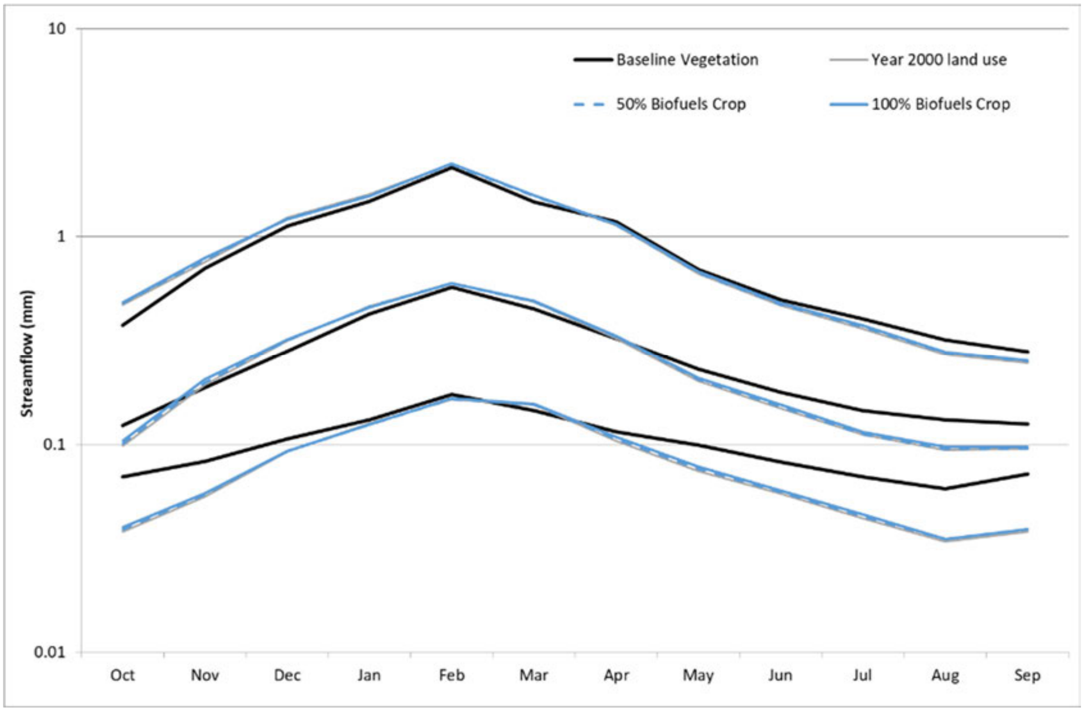


Figure 4.24 One in ten-year High (90th percentile), Median (50th percentile), and Low (10th percentile) monthly accumulated flows at the outlet of T35C for the biofuel crop scenario.

4.4.3 Sensitivity of different land use change scenarios

Using the sensitivity ranking given in the methodology (Table 3.8), the sensitivity of changes in land use and their impact on stream-, base- and quickflow were determined. A common trend throughout all scenarios was that of decreasing sensitivity as the percentage change in land use increased. The initial changes in land use yielded the greatest change in all three flows, although for all scenarios, the base- and quickflows showed greater sensitivities to change than the streamflow.

The land use change scenarios that showed the highest sensitivities were those of further degradation, bush encroachment and burning (Table 4.6). This could be as a result of large-scale changes to the catchments' land use and subsequent changes to the hydrological cycle. The agricultural management practices, on the other hand, showed the least sensitivity to change, which could be attributed to the fact that the changes in flows were small when compared to the increased area. Thus, further degradation of natural vegetation within the catchment would cause significant changes, as opposed to the largely insignificant changes brought about by agricultural changes.

For all scenarios, the decreasing sensitivity of the catchment to change as the area under change increases could be due to the fact that water availability (in the form of rainfall) acts as a limiting agent. When the catchment first experiences a change in land use, the impact on the hydrological cycle is noticeable as either more (e.g. as a result of degradation) or less rainfall (e.g. as a result of bush encroachment) is converted to streamflow. However, given that there is only so much water available within the catchment, further increases in the land use change have a decreasing impact on the hydrological cycle.

From a water resource management perspective, the sensitivity of different land use changes shows that any impacts that further the degradation present within the catchment will cause a significant change to the catchment's hydrology. However, should the development be largely dryland agricultural with control measures in place to prevent degradation, there will be only small changes to the catchment's hydrology.

Table 4.6 Sensitivity of flows to the percentage changes of different land use scenarios

		Sensitivity of Flow		
	% Change	Baseflow	Quickflow	Streamflow
Further Degradation	10	H	E	M
	20	M	H	S
	40	M	M	S
	50	M	M	S
	75	S	M	S
	100	S	S	S
Rehabilitation of Degraded Areas	10	H	H	M
	20	M	M	S
	40	S	S	S
	50	I	I	I
	75	I	I	I
	100	I	I	I
Bush Encroachment	10	H	E	H
	20	M	H	M
	40	S	M	S
	50	S	S	S
	75	S	S	S
	100	S	S	I
Severe Annual Burning	10	H	E	H
	20	M	H	M
	40	S	M	S
	50	S	M	S
	75	S	M	S
	100	S	S	S
Severe Biennial Burning	10	H	E	H
	20	M	H	M
	40	S	M	S
	50	S	M	S
	75	S	M	S
	100	S	S	S
Increased Dryland Cropping	10	M	I	I
	20	S	I	I
	40	S	I	I
	50	S	I	I
	75	S	I	I
	100	S	I	I
Increased Irrigated Cropping	10	M	I	I
	20	S	I	I
	30	S	I	I
	40	S	I	I
	75	-	-	-
	100	-	-	-
Change to Biofue Crops	10	M	I	I
	20	S	I	I
	40	S	I	I
	50	S	I	I
	75	S	I	I
	100	I	I	I

Legend

E = Extremely sensitive

H = Highly sensitive

M = Moderately sensitive

S = Slightly sensitive

I = Insensitive

5. DISCUSSION

5.1 Verification of the ACRU Model

Whilst the setup and running of ACRU model menus is relatively straightforward, the data required by the model poses a challenge in many catchments given that good quality, accurate and up-to-date climate, soils and land use data are rarely readily available. In a South African context, much of the land use data available is outdated or obtained through indirect means – such as using NDVI rather than detailed botanical and land use studies - to determine land use, whilst detailed soils data is not available for large parts of the country. Given the numerous soil types present within South Africa, and the highly varying nature of soil classes, many areas have more generalised soil classifications as detailed soil surveys are too costly or the areas are too rural/inaccessible to allow for work to be done. Thus, resolution issues are present within the soils data available for use, as is the parametrization of the dominant soil characteristics. In order for the ACRU model to create the soil water budget for a catchment, the soil characteristics need to be known. However, these physical characteristics need to be translated into ACRU parameters which can prove problematic as assumptions need to be made. As such, further research into the use of remote sensing and methods of soil and vegetation classification on a large scale needs to be undertaken to help improve the available data.

The gauging of streamflow and rainfall is similarly problematic given that much of the equipment currently in use at weather stations and weirs is old and, in a number of instances, poorly maintained. Not only is the equipment in use problematic, but the network of gauges is decreasing as stations and weirs are shut down due to insufficient funding and expertise. Whilst poor quality data can, in some instances, be corrected through the use of primary flow data, Ratings Tables, and patching from nearby gauges, the discontinuation of many of weirs is far more problematic. Poor quality data can be fixed, but areas with no data present a far greater challenge as there is no record of flow characteristics and modelling in such an area is based on educated assumptions rather than physical data.

The assumptions made throughout the modelling work done would have had an additive impact on the modelling results. Unfortunately, by its very nature, modelling tries to simplify the real-world processes into a set of best-fit algorithms that best mimics reality. This requires assumptions to be made regarding many of the model parameters, including both soil and vegetative parameters, which in turn simplify the complex natural processes and introduces a small level of potential inaccuracy (in the form of oversimplification) to the modelled results.

Given these challenges facing the accurate modelling of catchments, a verification process needs to be done in order to determine the suitability of the model for the objective of the study. This verification allows for potential problem areas in the modelling of the catchment to be identified early on so that any uncertainties or gaps within the model can be understood before the main study is conducted. This understanding allows for results obtained to, in many instances, be justified in terms of any problems observed during the initial verification rather than discarded.

The initial stage of this project involved the verification of the ACRU model for the T32A/B/C and T35C catchments within the Mzimvubu region. Given the high levels of poverty and underdevelopment (both historically and currently) in the region (Van Tol *et al.*, 2014) gauging stations (both streamflow and rainfall) are sparsely situated within the catchment (Toucher, 2016). In total only six gauging weirs with sufficient length of record were identified within the nearly 20 000 km^2 Mzimvubu catchment, with all being over the recommended size for verification purposes. As such, the two smallest gauged catchments were selected for the case study within the Mzimvubu.

The T32A/B/C catchment size of 1029 km^2 was far from the ideal verification size of between 10 – 30 km^2 (Smithers and Schulze, 1995), as was the T35C catchment size of 307 km^2. Whilst the size of the catchments meant that land use had to be more generalised in order for a controlled number of HRUs to be used in ACRU, the greatest problem with the catchments arose in terms of degradation and the quality of climate data. Given that veld degradation is a very subjective term, the size of the areas identified as degraded meant that in some instances, there were large areas shown to be degraded on satellite imagery that were not present in the land use classifications. This, along with missing gauge data and poor-quality rainfall data and monitoring, could be taken as some of the main causes of the problematic difference in means, meaning that the short-coming of the verification for the two catchments was a lack of good-quality observed data rather than a poor model simulation. Whilst the model was run at the HRU scale where the individual units model were smaller than the recommended catchment size, the comparison between observed and simulated streamflow was undertaken at the catchment scale which was larger than the recommended size for ACRU modelling. By comparing at the catchment scale, the errors in the model configuration and input parameters are accumulated in each downstream HRU and subcatchment. These accumulated errors are not simply additive, they may cancel or amplify errors. Thus, comparing observed and simulated streamflow for such a large catchment is complex as the source and reasoning for the error can not be easily attributed. ACRU has been used on far larger catchments than those in this dissertation, for several purposes, however, the verifications, if they were undertaken were done on sub-catchments with small areas. The problems related to the poor quality of the data aggravated these problems.

Despite both gauging stations having over 40 years of recorded streamflow, a number of issues were identified with the streamflow of the two catchments. The T3H004 weir was shown to be exhibiting so-called ‘over-topping’ – no daily average flows exceeded 38 $m^3.s^{-1}$ (Appendix C). When the Ratings Table (Appendix C) for the weir was consulted, it was seen that the most recent Table was from 1951 and made no allowance for flows in excess of 1.07 m deep. Similarly, the most recent Ratings Table (Appendix C) for the T3H009 weir at the outlet of the T35C catchment was from 1964, meaning that the flow characteristics of the two gauges are potentially outdated.

Given that different sources, including the NLC 2000, satellite imagery and soils information, tended to disagree on many of the catchment conditions, soil parameters, including the horizon depths and soil response fractions ABRESP and BFRESP, were adjusted within reason in order to try and improve simulations of each catchments. These adjustments helped to improve both simulations but were not able to completely mimic the simulated with the observed flows. However, given the level of degraded natural veld present within the greater Mzimvubu catchment it was hypothesised that much of the problem in the over- and under simulation of the two catchments was in the modelling of degraded areas within the ACRU model.

5.2 Revision of Crop Parameters

To allow for the degraded areas to be more appropriately modelled within the ACRU model, it was determined that a methodology based on the use of observed data would be developed to allow revising the degraded veld parameters within the model. The ACRU model’s vegetation parameters, whilst based on expert opinion (Schulze, 2008a) are generalised and not based on direct observations. In many studies, LAI data has been used as a proxy for crop evapotranspiration and coefficients (Al-Kaisi *et al.*, 1989; Čereković *et al.*, 2010; Borges *et al.*, 2015; Abedinpour, 2016; Corbari *et al.*, 2017b). Both crop coefficients and vegetation interception can be derived from LAI data using methods such as the Kristensen and FAO dual crop coefficient methods, as well as the variable storage Gash model for the determination of vegetation interception.

However, as was shown during the review of literature on degradation, the very concept of land degradation is a problematic one. Many disciplines have their own definitions of the term making it a highly subjective term – the study by Hoffman and Todd (1999) showed the broad range of definitions. Given that the NLC 2000 was used as the method of land type classification used for the study and that degraded areas within the classification are defined as being areas of reduced natural vegetative cover (SABS, 2004), the revision of degraded vegetation parameters considered this loss of cover to be the form of land degradation.

The crop coefficient and vegetation interception parameters were calculated for both pristine natural vegetation within protected areas as well as for degraded natural vegetation areas near to these protected areas. Given the limited number of protected areas within the Mzimvubu, and therefore a limited number of sites to test the methodology determined, sites were also considered within the Thukela catchment for the initial calculations. This was to allow for a greater study sample to be considered to ensure that the relationship between pristine and degraded vegetation was constant and did not vary with changes in climate and soil types.

Sites in both catchments showed definite trends in changes to crop coefficients and vegetation interception between the pristine and degraded natural vegetation. All degraded sites, in both catchments and under different Acocks veld types, produced lower crop coefficient and interception values due to the reduced vegetative cover at the sites. Owing to this reduced cover, the amount of plant biomass undergoing photosynthesis is less than under full vegetative cover and will therefore have lower rates of evapotranspiration (Hoffman and Todd, 1999). This decreased amount of biomass also affects the amount of rainfall intercepted, meaning that lower interception results would be expected for degraded vegetation.

However, not only were differences between pristine and degraded vegetation to be expected, but differences between crop coefficient calculation methods used were also expected. The FAO dual crop coefficient method considers both the fraction of water evaporated from both the basal crop (i.e. the amount of transpiration of the plant) and the soil (i.e. the amount of evaporation from the soil beneath the plant) (Allen *et al.*, 1998a). The Kristensen method, on the other hand, is a lumped equation which allows for a single calculation to be done based on the LAI of the plant (Kristensen, 1974; Angus, 1987).

Whilst both have been shown to be of use in the determination of vegetation crop coefficients, each particular method has its use in the determination of crop coefficients required by hydrological models. Given the minimal data required by the Kristensen method, it would be of greater use in catchments where very limited data is available about the crop and soil characteristics, and much of the land type observation is reliant on remotely-sensed data. The FAO method, on the other hand, is more suited for use in catchments where data are readily available.

5.3 Revised Parameters within the ACRU Model

Given that a loss of vegetative cover in an area affects the hydrology of an area, the impact of the revised degraded vegetative parameters needed to be considered in the modelling of the catchment. The loss of vegetative cover in an area means that a greater amount of the soil surface is exposed to rainfall, thereby changing the manner in which the soil water budget is determined. By having a greater amount of the soil surface exposed, more rainfall will be available for infiltration into the soil water system whilst, at the same time, less rainfall is intercepted due to a decrease in the amount of plant biomass protecting the soil (Hoffman and Todd, 1999).

However, owing to this increased amount of rainfall reaching the soil surface, overland quickflow tends to be increased due to the lack of vegetative cover and root systems to bind the soil, leading to erosion of the top layers of soil rather than infiltration (Mwendera and Saleem, 1997b; Savadago *et al.*, 2007; Stavi *et al.*, 2011b). Whilst the current ACRU degraded vegetation parameters allow for this loss of vegetative cover through reduced interception amounts and lower crop coefficients, they are not based on observed data (Schulze, 2008a; Schulze *et al.*, 2008) and are estimates of how the degraded areas would be expected to behave.

In order to determine the viability of LAI-derived vegetation parameters for degraded areas, the ACRU model needed to be run using the revised parameters. This would enable a comparison to be done to determine whether the degraded parameters would have any significant impact on the original verification simulations. To do this, three different sets of model simulations were carried out and the results compared to the verification.

The first set of model simulations performed involved the use of the current Acocks veld type parameters available within the model, and a percentage difference calculated between the revised pristine and degraded parameters. This percentage change was used to degrade the current Acocks natural vegetation parameters within the model, whilst keeping the natural vegetation parameters unchanged from the verification setup. For both the crop coefficients and interception parameters, the percentage change for degraded vegetation was a decrease of between 10 and 15 % throughout the year.

Once the model had been run using these parameters, however, it was evident that there had been minimal change in the two catchments' simulations from the initial verification. The reason for this was most likely due to the minimal difference between the current ACRU degraded vegetation parameters and those calculated by degrading the Acocks natural vegetation parameters. Whilst the T32A/B/C simulation improved slightly, the T35C catchment worsened.

The remaining two sets of model simulations performed involved the use of the revised degraded parameters, as well as the pristine natural vegetation parameters. One set of simulations was done using crop coefficients calculated using the FAO dual method and the second set of simulations using the Kristensen method. In both sets, the pristine natural vegetation and degraded parameters were replaced within the model and the two catchments' setups were run using these new parameters.

Both sets of new parameters had similar impacts on the simulations, although the changes were far more pronounced than those of using only a percentage change. In both cases, the T32A/B/C catchment improved drastically and was almost within the desired range of ± 15 % difference between observed and simulated streamflow means for the simulations using the FAO crop coefficients, and within the desired range using the Kristensen coefficients. The T35C catchment, on the other hand, worsened in both sets of simulation when compared to the verification simulation. However, whilst large improvements were observed in the T32A/B/C catchment when using the revised parameters, the worsening of the T35C simulations was disproportionately small in comparison.

The reason for this could be due to land use types present within each of the catchments and the current types of simulation (i.e. over or under). The initial verification simulation of the T32A/B/C catchment was drastically over simulating streamflow within the catchment. Therefore, by improving the modelling of the degraded and pristine natural vegetation via a revision of their parameters, the increased infiltration and interception from degraded areas and the increased interception from the pristine vegetation would allow for a greater amount of rainfall to be retained within the catchment rather than leaving via the outlet as streamflow. However, whilst the revised parameters greatly improved the simulation of the T32A/B/C, an over simulation of 11.7% was still present showing that even with improved crop parameters, a perfect verification of the catchment could not be achieved due to the problems with climate and streamflow data.

Given that the T35C catchment was already under simulating in the verification stage, the worsening of the simulation was to be expected. The revision and improvement of the degradation parameters for the Mzimvubu catchment would have caused an increase in the movement of water throughout the soil profile, whilst at the same time reducing the amount of overland flow owing to the higher crop coefficients and amount of interception when compared to the current ACRU degraded parameters. Due to this, the amount of baseflow within the catchment's degraded areas would increase whilst the quickflow component would decrease. Conversely, the revised natural vegetation parameters would have increased the amount of evapotranspiration as the amount of interception increased.

Owing to the T35C catchment having large areas of commercial forestry (a known streamflow reduction activity), it could be hypothesised that another problem within the catchment is that of poor forestry vegetation parameters. Given that changes in both catchments' simulations were significant, the revision of ACRU parameters needs to be carried out for all vegetation and crop types to allow for improved modelling. The fact that the interception calculated from the variable storage Gash for non-forested areas produced interception amounts greater than those currently in use within the model shows that many of the current model parameters need revision to allow for more accurate modelling of land use change impacts on water quantities, as opposed to determining it as a fraction of the initial amounts.

5.4 Changes in Land Use

Given the amount of proposed development within the Mzimvubu catchment, the impacts of changes in land use need to be considered to ensure that the hydrology of the catchment is not irreversibly changed. Streamflow reduction activities, such as increasing the area of a catchment under commercial forestry, are known to change the catchment's hydrology by increasing baseflow and decreasing streamflow (Smith and Scott, 1992; Sorriso-Valvo *et al.*, 1995; Lane *et al.*, 2005; Tewari, 2005; Nordblom *et al.*, 2012). However, whilst many studies have considered the impacts of rangeland and agricultural management practices internationally, minimal work has been done on the impacts in the Mzimvubu catchment.

Studies in South Africa that have considered the impacts of degradation, both from overgrazing and poorly-managed burning practices, on the hydrological cycle (Mander *et al.*, 2008; Schulze *et al.*, 2009) have all shown that streamflow increases as degraded areas increase due to a reduction in interception losses. These impacts were shown during this study to be similar in nature, as increases in degraded natural vegetation lead to increases in streamflow as a result of increased overland flow. Baseflow is reduced as degraded areas increase, due to the loss of root systems that would bind the soil and allow for lateral water movement through the soil profile. Conversely, the rehabilitation of already-present degraded areas had the opposite impacts on the catchment's hydrology as baseflow increased whilst both streamflow and quickflow decreased.

Given that woodier vegetation such as bushveld and forestry species can have a large impact on the hydrologic cycle, bush encroachment needs to be considered in any naturally vegetated catchment. A change in vegetation from veld to a more succulent type of vegetation would lead to a decrease in overland flow and subsequent decrease in streamflow, despite an increase in baseflow as a greater amount of water infiltrates the soil. Owing to the greater percentage of rainfall being intercepted by the increased amount of plant biomass in the canopy, less rainfall is likely to become overland flow and, ultimately, streamflow.

Due to the Mzimvubu being flagged for agricultural development (Republic of South Africa, 2013; Van Tol *et al.*, 2014), the impacts of increased dryland, irrigated, and biofuel cropping agriculture were considered. The changes in vegetative properties, viz. decreases in interception by the crops and increased coefficients of initial abstraction caused by tillage practices being introduced, result in a greater percentage of rainfall reaching the soil surface and being infiltrated, which then leads to a reduction in overland quickflow and an increased contribution to streamflow through baseflow (Kongo and Jewitt, 2006; Ngigi *et al.*, 2006; Kosgei *et al.*, 2007). A similar response was shown with a change in crop type from a more traditional crop to a biofuel one. The harvesting of much of the sorghum plant matter would leave very little trash on the ground after harvest and would allow for an increase of overland quickflow during the winter months as decreased infiltration occurs when there is no crop growing on the land.

Any increase in the area under irrigation would be expected to cause a decrease in the catchment's streamflow whilst at the same time increasing the baseflow as more water is available for infiltration into the soil (Ghaffari *et al.*, 2010; Gordon *et al.*, 2010; Merchàn *et al.*, 2013b; Stefanidis *et al.*, 2016). The increase in irrigated agriculture in this study was shown to cause this reduction in streamflow, along with a slight increase in both quickflow and baseflow. This is due to the change in vegetative cover from natural veld to irrigated crops which would require larger abstractions from streamflow than would necessarily return to the water courses as runoff or baseflow. After an area increase of 30 %, the streamflow then began to increase which is as a result of there being insufficient water from the river to irrigate the crops. The reason for this increase is due to the fact that there is insufficient water within the model for it to meet the irrigation requirements, and so the model ostensibly experiences a glitch and begins to increase the amount of streamflow. When the model can't meet the full requirements on a given day for a HRU, no irrigation at all is applied. As the area under irrigation increased, the number of HRUs and the number days where the full demand could not met increased, essentially increasing the streamflow as less water was directed to irrigation. As such the impacts of increased irrigation were not as great as expected due to lack of water available to support this increase - the maximum increase in area under irrigated agriculture is based on the water supply available and will thus differ from catchment to catchment.

5.5 Critique of Methodology Developed

Throughout the duration of the study, the lack of sufficient vegetation data for the Mzimvubu catchment proved problematic. Using the fact that the Acocks veld types classification – of which there are only 70 across South Africa – as the natural vegetation baseline poses a number of potential problems when trying to model poorly gauged catchments. The low spatial resolution of the different veld types means that each category is relatively broad and based on a number of common vegetation types, rather than considering the species present within the catchment. The vegetation types are also considered in terms of their agricultural potential and do not represent the actual vegetation type.

A further concern is the parameterisation of the Acocks veld types for use in the ACRU model. The current parameters are based on expert opinion, as opposed to observed data. Whilst these parameters may have been acceptable due to a lack of available observed data, they are in need of revision given the development in remote sensing techniques and the new water use data that is available. The need for parameters based on observed data lead to the development of the methodology used in this study. During the verification part of the study, poor simulations were obtained for both study catchments. The main reasons for these poor simulations were determined to be the lack of good quality climate data and the poor representation of degraded vegetation in the ACRU model. Only one set of generic parameters is available for degraded veld, thus there is no allowance made for different vegetation types and climatic factors. Therefore, this project revised the parameters for degraded areas using an explicit and repeatable methodology that could be used to determine degraded veld parameters for all Acocks veld types.

Using LAI data from 2008-2017 and sites selected within adjoining protected areas (i.e. pristine veld) and degraded areas, the crop coefficient (K_c), vegetative interception, and surface cover of the Mzimvubu catchments were determined for different pristine and degraded natural vegetation sites. Through the use of the Kristensen and FAO dual crop coefficient calculation methods, similar K_c values were obtained for the degraded, as well as the pristine, sites. The variable storage Gash model was shown to model the interception of the different sites well, however, it was restricted by the limited rainfall data available for the area. This problem of poor quality rainfall data was encountered throughout the entire study and was determined to be one of the causes of the poor verification simulations.

Whilst the methodology developed in this study was shown to have a significant impact on the simulations of the two study catchments, a number of flaws were identified that would require further development of the methodology to ensure that they do not negatively impact the results. It was observed that despite protected areas needing to have healthy vegetative conditions, it was possible for a level of degradation to exist even within these protected areas. In order to ensure that pristine sites were not falling within one of these degraded patches within the protected areas, satellite imagery was used. However, further use of the methodology would require ground truthing to ensure no risk of degradation within a pristine site existed.

A further problem that could be encountered with the methodology is that of climate data required for the variable storage Gash model. Given the limited number of rainfall stations within the Mzimvubu, the rainfall data used to calculate vegetation interception was based on the quinary driver station closest to the site. Whilst many of these stations were near to the sites, the rainfall records are a point measure at the station and could require adjustments to be made to provide for more accurate data at the study site.

Of the scenarios run in the land use change part of the study, further degradation of the catchments proved to have the greatest impact on streamflow, quickflow and baseflow, thus proving the importance of accurately modelling degraded areas and the impact that it can have on a catchment. Despite the flaws identified with the methodology, it was shown to work well in one of the study catchments, i.e. T32A/B/C, where the use of both calculated natural and degraded vegetation parameter sets greatly improved the initial verification. Similarly, whilst the T35C total USFLOW worsened with the addition of the new parameter sets, it was shown that the new parameters did not worsen the relationship between the simulated and observed streamflows. Thus, the methodology showed that it had definite possibilities for use in crop parameter calculation for modelling purposes.

5.6 Importance of Study for Water Resource Management in the Mzimvubu

This study has shown that it is possible to model land use change scenarios in under-developed and poorly gauged catchments, successfully. The verification stage of this study allowed for many issues with data quality and quantity to be identified although, despite the correction factors applied (such as the CORPPT factor to adjust rainfall), the simulations of both study catchments were unsatisfactory.

However, they allowed for the development of a methodology that could be expanded upon to allow for improved modelling in the under-developed Mzimvubu catchment. The methodology to revise the degraded vegetation parameters was successfully used to improve the T32A/B/C simulation, showing that the LAI data can be used to improve the vegetation parameters required by ACRU as they are based on observed data rather than opinion/assumptions. This methodology can be used in future studies in the Mzimvubu catchment, or other areas, to provide more accurate vegetation parameters.

Given that the scenarios were considered in terms of a percentage change in flows rather than volumes, the modelled results can be taken to be representative of the impacts of changes in land use management practices. The land use changes scenarios considered were based on spatial development plans for the area as well as the NWRS. The Mzimvubu catchment is earmarked for agricultural development and as the dryland agricultural scenarios modelled showed only small changes to flows, increases in dryland agriculture do not pose an immediate risk to the water resources. Similarly, the changes to biofuel crops showed no significant impact on flows, meaning that the introduction of biofuel crops will have minimal impact on the catchment's water supply. Further research into the impacts of varying tillage procedures need to be done to determine the impact of poor tillage management practices.

However, the results of the land use scenarios for degradation showed the potential risks of allowing the catchment to become further degraded. Should degradation, from overgrazing or poor management practices, increase, the catchment's water resources will be significantly changed. Not only will the increased quickflow increase the risk of soil erosion, but the increase in streamflow could lead to an increase in the risk of flooding during high rainfall events. The reduced baseflow could also lead to a reduction in the soil water table which, given that the area is not a high rainfall one, could cause restrictions in areas that rely on boreholes for water. As such, degraded areas within the catchment need to be monitored to ensure that they do not increase in size or severity.

6. CONCLUSIONS

Throughout the course of the study, the aim of the research was to model the changes in water quantity in the Mzimvubu catchment using the ACRU model in order to determine the impacts on water resources under different land use management scenarios. However, after the initial verification simulations did not perform as required, the effects of degradation throughout the catchment were then considered, with improvements to the degradation parameters used within ACRU proposed.

6.1 Conclusions of the Study

The aim of this research was to model the changes in water quantity in the Mzimvubu catchment using the ACRU model in order to determine what impact the changing in land use would have on the catchment hydrology. Owing to the large degraded areas present within the Mzimvubu catchment, the rangeland and agricultural scenarios selected were those relating to potential degradation of natural vegetation. The effects of degradation throughout the catchment were considered, and an explicit and repeatable methodology developed for the calculation of degraded natural vegetation parameters.

Given that the vegetation parameters used within the ACRU model were developed based on expert opinion and not on observed data, the more generalised parameters such as those given for degraded vegetation are limited in their ability to adequately mimic the actual conditions within the catchment. As such, remotely-sensed LAI data was successfully used to derive vegetative parameters for both pristine and degraded types of vegetation which, whilst not completely different to those currently within the model, showed significant differences between parameters such as the interception of the different vegetation.

These parameters were then used to rerun the verification simulations, with both catchments showing a significant change in the streamflow simulation. Whilst the T35C catchment worsened, the T32A/B/C catchment simulation improved greatly. Both catchments showed that the parameters used for the different vegetation types can have a significant impact on how well the model is able to simulate the catchment, and that further revision needs to be done to update the current ACRU vegetation parameters.

Following this improvement of the ACRU parameters, an assessment of how different land use management scenarios altered the catchment’s water flows was carried out in order to determine the effects of such changes on the catchment’s water flows, including stormflow, streamflow and baseflow amounts. Changes were observed for all the different scenarios considered, with the further degradation of natural vegetation causing the greatest change to the catchments’ flows whilst many of the agricultural scenarios showed only small changes.

6.2 Recommendations for Future Study

Based on the outcomes of this study, the following recommendations are made for future research:

- Given the problems with both rainfall and streamflow records in both study catchments, new methods need to be considered for climate, soils and land use data acquisition. Remote sensing and satellite imagery could provide another source of data in order to create more accurate ACRU simulations. Research has been done internationally but more work needs to be done in South Africa, especially in undeveloped, ungauged catchments.
- Ratings Tables of many weirs throughout the Mzimvubu catchment, and the country as a whole, need to be revised in order to ensure that the flow characteristics of the drainage area and river are up-to-date and realistic. Tables that are over 50 years old are unable to provide a realistic flow depth-rate relationship, as climate change and changing land uses will affect both the amount and nature of the catchment’s flow regimes. Until the Ratings Tables are officially updated, extrapolation measures need to be considered and implemented across many catchments to allow for streamflow data to be determined from the flow depth, rather than just making use of the averaged values available.
- Whilst the methodology used to determine the revised pristine and degraded vegetation parameters was shown to have a significant impact on the model simulations, the method needs to be used on a larger scale and across a number of catchments in order to refine the methodology.
- The methodology used to determine the degraded vegetation parameters can be extended to incorporate the calculation of the parameters of other land uses, such as forestry and agricultural practices. This could be done in conjunction with in situ studies to test whether the methodology works for all types of land use.

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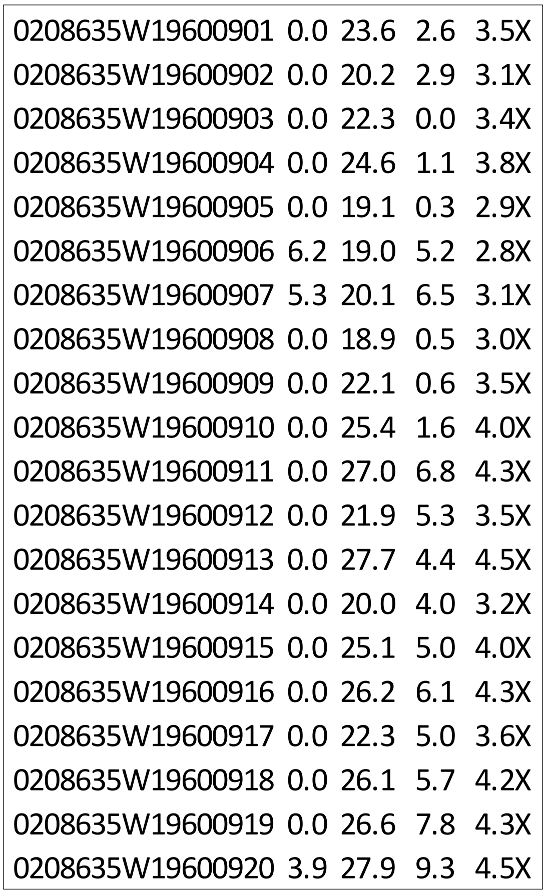
8. APPENDIX A

In order for the climate files created for the model to work, each file needs to follow a particular format. Figure 8.1 gives an example of part of one such file, with each daily entry following the same format of, from left to right:

- rainfall station,
- date of record,
- rainfall (mm),
- maximum temperature (°C),
- minimum temperature (°C), and
- streamflow (mm).



```
0208635W19600901 0.0 23.6  2.6  3.5X
0208635W19600902 0.0 20.2  2.9  3.1X
0208635W19600903 0.0 22.3  0.0  3.4X
0208635W19600904 0.0 24.6  1.1  3.8X
0208635W19600905 0.0 19.1  0.3  2.9X
0208635W19600906 6.2 19.0  5.2  2.8X
0208635W19600907 5.3 20.1  6.5  3.1X
0208635W19600908 0.0 18.9  0.5  3.0X
0208635W19600909 0.0 22.1  0.6  3.5X
0208635W19600910 0.0 25.4  1.6  4.0X
0208635W19600911 0.0 27.0  6.8  4.3X
0208635W19600912 0.0 21.9  5.3  3.5X
0208635W19600913 0.0 27.7  4.4  4.5X
0208635W19600914 0.0 20.0  4.0  3.2X
0208635W19600915 0.0 25.1  5.0  4.0X
0208635W19600916 0.0 26.2  6.1  4.3X
0208635W19600917 0.0 22.3  5.0  3.6X
0208635W19600918 0.0 26.1  5.7  4.2X
0208635W19600919 0.0 26.6  7.8  4.3X
0208635W19600920 3.9 27.9  9.3  4.5X
```

Figure 8.1 Example of climate file used within the ACRU model.

Along with the climate files, each sub-catchment within the two study catchments required rainfall correction factors (Table 8.3 and Table 8.4) based on the rainfall stations selected (Table 8.1 and Table 8.2) to adjust the rainfall record of catchments that did not have the driver station within its boundary.

Table 8.1 Rainfall stations used for each of the T32A/B/C sub-catchments

STATION			**SUB-CATCHMENT**		
ID	**MAP (mm)**	**Altitude (m.a.s.l)**	**ID**	**MAP (mm)**	**Altitude (m.a.s.l)**
0208635W	791	2005	1	777	1955
	791	2005	2	773	1735
0208733W	792	1764	3	754	1670
	792	1764	4	773	1750
	792	1764	5	831	1650
0208528A	648	1595	6	714	1530
	648	1595	7	688	1560
	648	1595	14	705	1540
	648	1595	15	697	1650
0208406W	713	1475	8	696	1610
0209195W	853	1389	9	845	1575
0208799W	549	1542	10	701	1510
	549	1542	11	764	1550
	549	1542	13	769	1565
0208743A	656	1590	12	706	1560
	656	1590	16	734	1700
	656	1590	17	700	1500
	656	1590	19	726	1410
	656	1590	20	782	1695
	656	1590	21	781	1630
0180721A	697	1380	18	715	1500
	697	1380	22	691	1605
	697	1380	23	592	1400
	697	1380	25	767	1675
	697	1380	26	766	1465
	697	1380	27	717	1400
	697	1380	28	700	1375
	697	1380	29	672	1325
0209173W	923	1416	24	652	1330
0180305W	690	1421	30	684	1365
	690	1421	31	668	1380
0180577W	685	1479	32	675	1595
	685	1479	33	697	1550

Table 8.2 Rainfall stations used for each of the T35C sub-catchments

STATION			SUB-CATCHMENT		
ID	MAP (mm)	Altitude (m.a.s.l)	ID	MAP (mm)	Altitude (m.a.s.l)
0150620 W	719	1465	1	731	1770
	719	1465	4	703	2032
	719	1465	5	734	1778
	719	1465	6	759	1777
	719	1465	7	764	1594
	719	1465	8	778	1844
0151402 W	749	1322	2	772	1507
	749	1322	3	781	1462
	749	1322	9	786	1560
	749	1322	10	795	1491
	749	1322	11	807	1467
0151604 W	755	1263	15	776	1337
	755	1263	16	766	1342
	755	1263	17	746	1313
0178689 W	600	1444	12	807	1408
	600	1444	13	797	1431
	600	1444	14	781	1370

SC	January	February	March	April	May	June	July	August	September	October	November	December
1	1.00	0.99	1.03	1.01	0.83	0.86	0.86	0.92	1.02	1.02	1.00	1.05
2	1.00	1.07	0.99	1.28	1.20	2.00	1.13	0.96	1.16	1.00	1.03	1.10
3	1.01	0.99	0.97	1.01	0.78	0.79	0.95	0.85	0.91	0.89	0.95	1.05
4	1.02	1.00	1.00	1.03	0.81	0.82	0.90	0.88	0.94	0.95	0.99	1.04
5	1.09	1.05	1.05	1.07	0.89	0.91	0.94	1.02	1.07	1.07	1.10	1.07
6	1.04	1.03	1.05	1.16	0.96	1.25	1.08	0.98	1.09	1.14	1.11	1.13
7	1.07	1.04	1.08	1.20	0.92	1.22	1.00	0.98	1.04	1.21	1.18	1.09
8	1.00	1.01	1.00	1.10	1.04	1.14	1.03	0.84	0.99	1.13	1.06	0.93
9	0.98	0.98	1.06	0.99	1.13	0.80	1.22	0.79	0.82	0.88	1.01	1.10
10	1.34	1.29	1.41	1.34	1.54	1.17	1.06	1.47	1.24	1.22	1.26	1.30
11	1.44	1.39	1.49	1.43	1.56	1.01	1.20	1.75	1.52	1.39	1.38	1.40
12	1.07	1.16	1.10	1.13	1.13	1.13	0.97	1.05	1.09	1.09	1.12	1.05
13	1.45	1.41	1.52	1.46	1.66	0.95	1.10	1.82	1.55	1.38	1.35	1.41
14	1.04	1.07	1.07	1.10	1.02	1.05	0.93	0.96	1.15	1.16	1.10	1.08
15	1.02	1.07	1.07	1.09	0.96	1.01	0.83	0.89	1.17	1.18	1.11	1.05
16	1.11	1.14	1.11	1.19	1.37	0.94	0.86	1.11	1.22	1.14	1.14	1.09
17	1.06	1.11	1.07	1.13	1.19	0.85	0.77	0.90	1.12	1.07	1.09	1.04
18	1.02	1.08	1.07	1.11	1.03	0.77	0.78	0.85	1.05	1.09	1.03	1.17
19	1.17	1.17	1.19	1.29	1.62	1.43	1.28	1.23	1.34	1.26	1.30	1.15
20	1.15	1.17	1.17	1.37	1.59	1.87	1.36	1.80	1.43	1.28	1.29	1.13
21	1.14	1.18	1.18	1.30	1.65	1.63	1.31	1.28	1.24	1.23	1.28	1.11
22	1.07	1.08	1.11	1.13	1.22	0.93	1.10	1.02	1.21	1.21	1.18	1.20
23	1.01	1.10	1.10	1.16	1.18	0.92	0.83	0.92	0.98	1.05	1.04	1.17
24	0.73	0.90	0.91	0.81	0.79	0.33	0.52	0.45	0.60	0.67	0.74	0.76
25	1.01	1.03	1.03	1.00	1.07	0.76	0.85	0.98	1.05	1.02	1.07	1.05
26	0.93	0.99	1.01	1.07	1.13	0.80	0.97	0.97	0.98	0.97	1.04	1.03
27	0.88	0.97	0.95	1.26	1.18	0.77	1.24	1.03	1.17	1.00	1.10	1.03
28	0.78	0.84	0.85	1.00	0.96	0.65	1.01	0.82	0.88	0.83	0.97	0.85
29	0.91	0.95	0.94	1.04	1.06	0.60	0.84	0.85	0.96	0.94	1.04	0.98
30	0.99	0.99	1.06	1.12	0.96	0.49	0.59	0.79	0.91	0.91	1.16	0.95
31	0.97	0.92	0.94	1.19	1.13	0.37	0.82	0.87	0.99	1.08	1.09	0.96
32	0.98	0.96	0.94	1.18	1.34	0.94	1.07	0.76	1.04	0.96	1.16	0.91
33	1.09	0.95	0.93	1.20	1.47	0.73	1.14	1.00	1.16	1.11	1.14	0.98

Table 8.3 Monthly rainfall correction factors used for the T32A/B/C sub-catchments (SC).

SC	January	February	March	April	May	June	July	August	September	October	November	December
1	1.26	1.27	1.21	0.97	0.68	0.59	0.63	1.15	1.28	1.17	1.23	1.24
2	1.06	0.97	1.05	1.02	1.00	1.38	1.13	1.03	1.19	1.08	0.98	1.22
3	1.09	0.98	1.06	1.03	0.93	1.38	1.00	1.03	1.24	1.07	0.99	1.25
4	1.18	1.19	1.14	0.97	0.79	0.68	0.75	1.11	1.20	1.11	1.14	1.17
5	1.28	1.26	1.20	0.99	0.75	0.67	0.68	1.09	1.22	1.18	1.19	1.27
6	1.34	1.32	1.24	0.98	0.71	0.67	0.69	1.14	1.23	1.25	1.24	1.33
7	1.36	1.36	1.27	0.96	0.60	0.52	0.54	1.17	1.25	1.26	1.27	1.35
8	1.40	1.38	1.28	0.97	0.61	0.53	0.54	1.18	1.28	1.28	1.29	1.41
9	1.11	0.98	1.06	1.02	0.99	1.33	0.88	1.06	1.27	1.10	1.00	1.26
10	1.12	1.00	1.09	1.05	1.00	1.38	1.13	1.03	1.27	1.08	1.01	1.27
11	1.14	1.01	1.10	1.06	1.00	1.42	1.08	1.07	1.28	1.10	1.03	1.30
12	0.95	1.08	1.00	1.02	1.21	1.10	0.94	0.76	1.04	1.04	1.10	1.07
13	0.93	1.07	1.00	1.01	1.17	1.07	1.00	0.75	0.97	0.99	1.10	1.06
14	0.91	1.05	0.99	0.96	1.13	0.90	1.00	0.75	0.95	0.99	1.08	1.06
15	1.03	1.17	1.01	1.13	1.04	1.13	1.33	1.10	1.07	1.10	1.03	1.00
16	1.03	1.13	1.01	1.08	1.04	1.00	1.17	1.03	1.07	1.07	1.03	0.99
17	1.01	1.07	1.00	1.04	1.04	1.00	1.17	1.03	1.03	1.02	1.01	0.99

Table 8.4 Monthly rainfall correction factors used for the T35C sub-catchments (SC).

9. APPENDIX B

The monthly vegetation parameters used in the verification of the ACRU model were those already available within the model. Many of these parameters were developed during the creation of the South African Quaternary Database (Schulze *et al.*, 2008) (Table 9.1), whilst others such as the burning parameters (Mander *et al.*, 2008) in Table 9.2 are from other ACRU studies. Table 9.3 gives the revised degraded and pristine natural vegetation parameters calculated from LAI data and working rules used.

Each of the HRU types in Table 9.1, Table 9.2 and Table 9.3 consist of the following parameters:

- the crop coefficient (CAY),
- coefficient of initial abstraction (COIAM),
- the plant stress fraction (CONST),
- fraction of plant roots within the A-horizon (ROOTA), and
- vegetation interception (VEGINT).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
CAY	0.2	0.2	0.4	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.3	0.2	COMMERCIAL AGRICULTURE - IRRIGATED
COIAM	0.15	0.15	0.35	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.15	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	1	1	1	0.92	0.75	0.65	0.55	1	1	1	1	1	
VEGINT	0.5	0.5	0	0.5	0.7	0.8	1	1.2	1.2	0.5	0.5	0.5	
CAY	1.07	1.01	0.55	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.36	0.75	COMMERCIAL AGRICULTURE - DRYLAND
COIAM	0.2	0.2	0.25	0.3	0.3	0.3	0.3	0.3	0.3	0.35	0.3	0.25	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.77	0.75	0.81	0.93	1	1	1	1	1	1	0.99	0.86	
VEGINT	0.82	1.27	1.25	1.06	0.33	0.3	0.3	0.3	0.3	0.3	0.3	0.35	
CAY	0.55	0.55	0.55	0.45	0.2	0.2	0.2	0.2	0.4	0.45	0.55	0.55	DEGRADED AREAS
COIAM	0.1	0.1	0.1	0.15	0.15	0.2	0.2	0.2	0.2	0.15	0.1	0.1	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.9	0.9	0.9	0.94	1	1	1	1	0.95	0.92	0.9	0.9	
VEGINT	0.8	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.65	0.75	0.8	0.8	
CAY	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	FOREST- EUCALYPTUS
COIAM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	
CONST	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
ROOTA	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	
VEGINT	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	
CAY	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	FOREST - PINE
COIAM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	
CONST	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	
ROOTA	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	
VEGINT	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	
CAY	0.9	0.9	0.9	0.88	0.85	0.86	0.89	0.9	0.92	0.92	0.9	0.9	FOREST - WATTLE
COIAM	0.25	0.25	0.25	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.25	0.25	
CONST	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
ROOTA	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	
VEGINT	2	2	2	2	1.9	1.85	1.85	1.85	1.9	1.95	2	2	
CAY	0.7	0.7	0.7	0.5	0.3	0.2	0.2	0.2	0.5	0.65	0.7	0.7	NATURAL VELD - HIGHLAND AND DOHNE SOURVELD (#44)
COIAM	0.15	0.15	0.25	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.15	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.9	0.9	0.9	0.95	1	1	1	1	0.95	0.9	0.9	0.9	
VEGINT	1.6	1.6	1.6	1.4	1.2	1	1	1	1.3	1.6	1.6	1.6	
CAY	0.8	0.7	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.35	0.6	SUBSISTENCE AGRICULTURE
COIAM	0.15	0.15	0.25	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.15	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.74	0.78	0.91	1	1	1	1	1	1	1	0.92	0.79	
VEGINT	1	1	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0	0.5	0.8	
CAY	0.7	0.7	0.6	0.5	0.45	0.4	0.4	0.4	0.4	0.6	0.7	0.7	URBAN - HIGH-DENSITY
COIAM	0.2	0.2	0.2	0.25	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.9	0.9	0.9	0.95	0.95	0.95	0.95	0.95	0.92	0.92	0.9	0.9	
VEGINT	1.4	1.4	1.3	1.2	1.1	1	1	1	1	1.3	1.4	1.4	
CAY	0.75	0.75	0.75	0.65	0.55	0.4	0.4	0.5	0.65	0.75	0.75	0.75	URBAN - SMALLHOLDINGS
COIAM	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8	
VEGINT	2.5	2.5	2	2	2	2	2	2	2	2.5	2.5	2.5	

Table 9.1 ACRU crop parameters used in the modelling of the T32A/B/C and T35C study catchments

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
CAY	0.75	0.75	0.75	0.65	0.5	0.4	0.4	0.4	0.6	0.7	0.75	0.75	BUSHVELD - EASTERN PROVINCE THORNVELD(#07)
COIAM	0.25	0.25	0.25	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.25	0.2	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.85	0.82	0.8	0.8	0.8	
VEGINT	1.6	1.6	1.6	1.5	1.4	1.3	1.3	1.4	1.6	1.6	1.6	1.6	
CAY	0.75	0.75	0.75	0.65	0.55	0.2	0.2	0.4	0.6	0.75	0.75	0.75	BUSHVELD - THE VALLEY BUSHVELD (#23)
COIAM	0.2	0.2	0.25	0.3	0.3	0.3	0.3	0.3	0.3	0.25	0.2	0.2	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.8	0.8	0.8	0.85	0.9	1	1	0.95	0.9	0.8	0.8	0.8	
VEGINT	2.5	2.5	2.5	2.2	2	2	1.9	1.9	2.2	2.5	2.5	2.5	
CAY	0.7	0.7	0.7	0.6	0.3	0.2	0.2	0.2	0.35	0.55	0.68	0.7	BURNING - BIENNIAL, MODERATE
COIAM	0.15	0.15	0.25	0.3	0.3	0.3	0.3	0.3	0.2	0.23	0.18	0.15	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.9	0.9	0.9	0.95	1	1	1	1	0.95	0.9	0.9	0.9	
VEGINT	1.6	1.6	1.6	1.4	1.2	1	1	1	0.8	1.25	1.45	1.6	
CAY	0.7	0.7	0.7	0.5	0.3	0.2	0.2	0.3	0.4	0.6	0.65	0.7	BURNING -ANNUAL, MODERATE
COIAM	0.15	0.15	0.25	0.3	0.3	0.1	0.1	0.2	0.25	0.3	0.2	0.15	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.9	0.9	0.9	0.95	1	1	1	1	0.95	0.9	0.9	0.9	
VEGINT	1.6	1.6	1.6	1.4	1.2	0.3	0.3	0.45	0.8	1.2	1.4	1.6	
CAY	0.65	0.65	0.65	0.5	0.28	0.2	0.2	0.2	0.3	0.5	0.62	0.65	BURNING - BIENNIAL, 70 %
COIAM	0.15	0.15	0.25	0.3	0.3	0.3	0.3	0.3	0.2	0.23	0.18	0.15	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.9	0.9	0.9	0.95	1	1	1	1	0.95	0.9	0.9	0.9	
VEGINT	1.5	1.5	1.5	1.3	1.1	0.9	0.9	0.9	0.7	1.15	1.35	1.5	
CAY	0.65	0.65	0.65	0.5	0.28	0.2	0.2	0.3	0.4	0.55	0.62	0.65	BURNING - ANNUAL, 70 %
COIAM	0.15	0.15	0.25	0.3	0.3	0.1	0.1	0.2	0.25	0.3	0.2	0.15	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.9	0.9	0.9	0.95	1	1	1	1	0.95	0.9	0.9	0.9	
VEGINT	1.5	1.5	1.5	1.3	1.1	0.3	0.3	0.35	0.65	1.15	1.35	1.5	
CAY	0.55	0.55	0.55	0.45	0.25	0.2	0.2	0.2	0.4	0.45	0.55	0.55	BURNING - BIENNIAL, SEVERE
COIAM	0.1	0.1	0.1	0.15	0.15	0.2	0.2	0.2	0.2	0.15	0.1	0.1	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.9	0.9	0.9	0.95	1	1	1	1	0.95	0.9	0.9	0.9	
VEGINT	0.8	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.65	0.75	0.8	0.8	
CAY	0.55	0.55	0.55	0.45	0.25	0.2	0.2	0.2	0.4	0.45	0.55	0.55	BURNING - ANNUAL, SEVERE
COIAM	0.1	0.1	0.1	0.15	0.15	0.1	0.1	0.2	0.2	0.15	0.1	0.1	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.9	0.9	0.9	0.95	1	1	1	1	0.95	0.9	0.9	0.9	
VEGINT	0.8	0.8	0.8	0.7	0.6	0.3	0.3	0.3	0.4	0.75	0.8	0.8	
CAY	1.1	0.95	0.46	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.49	0.98	DRYLAND CROP - SORGHUM
COIAM	0.2	0.2	0.25	0.3	0.3	0.3	0.3	0.3	0.3	0.35	0.3	0.25	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.74	0.78	0.91	1	1	1	1	1	1	1	0.92	0.79	
VEGINT	0.64	0.64	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0	0.5	0.6	

Table 9.2 ACRU crop parameters used in the modelling of land use changes with the T32A/B/C and T35C study catchments.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
CAY	0.7	0.7	0.7	0.5	0.3	0.2	0.2	0.2	0.5	0.65	0.7	0.7	NATURAL VEGETATION - % CHANGE
COIAM	0.15	0.15	0.25	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.15	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.9	0.9	0.9	0.95	1	1	1	1	0.95	0.9	0.9	0.9	
VEGINT	1.6	1.6	1.6	1.4	1.2	1	1	1	1.3	1.6	1.6	1.6	
CAY	0.61	0.61	0.63	0.45	0.27	0.19	0.19	0.19	0.47	0.61	0.61	0.61	DEGRADED VEGETATION - % CHANGE
COIAM	0.1	0.1	0.1	0.15	0.15	0.2	0.2	0.2	0.2	0.15	0.1	0.1	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.9	0.9	0.9	0.95	1	1	1	1	0.95	0.9	0.9	0.9	
VEGINT	1.41	1.41	1.41	1.23	1.06	0.88	0.88	0.88	1.16	1.42	1.42	1.41	
CAY	0.80	0.82	0.79	0.70	0.60	0.54	0.50	0.47	0.50	0.56	0.67	0.76	NATURALVEGETATION - FAO CAY
COIAM	0.15	0.15	0.25	0.25	0.25	0.3	0.3	0.3	0.2	0.2	0.2	0.15	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.9	0.9	0.9	0.95	0.95	1	1	0.95	0.95	0.9	0.9	0.9	
VEGINT	4.1	3.9	3.3	2.3	1.8	1.2	1.2	1.0	1.6	2.0	2.8	4.3	
CAY	0.76	0.79	0.75	0.64	0.52	0.44	0.38	0.36	0.40	0.47	0.60	0.71	DEGRADED VEGETATION - FAO CAY
COIAM	0.15	0.15	0.25	0.25	0.25	0.3	0.3	0.3	0.2	0.2	0.2	0.15	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.9	0.9	0.9	0.95	0.95	1	1	0.95	0.95	0.9	0.9	0.9	
VEGINT	4.1	3.9	3.3	2.3	1.8	1.2	1.2	1.0	1.6	2.0	2.8	4.3	
CAY	0.64	0.68	0.65	0.56	0.46	0.39	0.34	0.34	0.39	0.43	0.52	0.60	NATURAL VEGETATION - KRISTENSEN CAY
COIAM	0.1	0.1	0.2	0.2	0.2	0.25	0.25	0.25	0.15	0.15	0.15	0.1	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.9	0.9	0.9	0.95	0.95	1	1	0.95	0.95	0.9	0.9	0.9	
VEGINT	3.6	3.5	2.9	2.0	1.5	1.1	1.0	1.0	1.5	1.7	2.4	3.7	
CAY	0.71	0.74	0.72	0.65	0.56	0.50	0.46	0.46	0.50	0.54	0.61	0.68	DEGRADED VEGETATION - KRISTENSEN CAY
COIAM	0.1	0.1	0.2	0.2	0.2	0.25	0.25	0.25	0.15	0.15	0.15	0.1	
CONST	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
ROOTA	0.9	0.9	0.9	0.95	0.95	1	1	0.95	0.95	0.9	0.9	0.9	
VEGINT	3.6	3.5	2.9	2.0	1.5	1.1	1.0	1.0	1.5	1.7	2.4	3.7	

Table 9.3 Revised pristine and degraded ACRU crop parameters used in the modelling of the T32A/B/C and T35C study catchments

10.APPENDIX C

In many parts of the Mzimvubu catchment, no streamflow monitoring is undertaken meaning that few catchments have any, or adequate length of, record. Catchments that are monitored in the area, however, are very rarely maintained on a regular basis or have their Ratings Tables updated as the flow patterns of the area change.

Within the two study catchments, the T3H004 gauging weir in the T32A/B/C catchment posed a challenge at the beginning of the verification stage of the study. When the average daily flows of the weir were obtained[1] and plotted for the time period 1960 to 2000, a problem was immediately observed. As shown in Figure 10.1, no flows over the weir exceeded a flow of approximately 38 $m^3.s^{-1}$. Whilst the maximum flow volumes over a given weir are not generally expected to exceed a range of maximum flows, the fact that no flows ever exceeded the same flow volume meant that there was a problem with the weir.

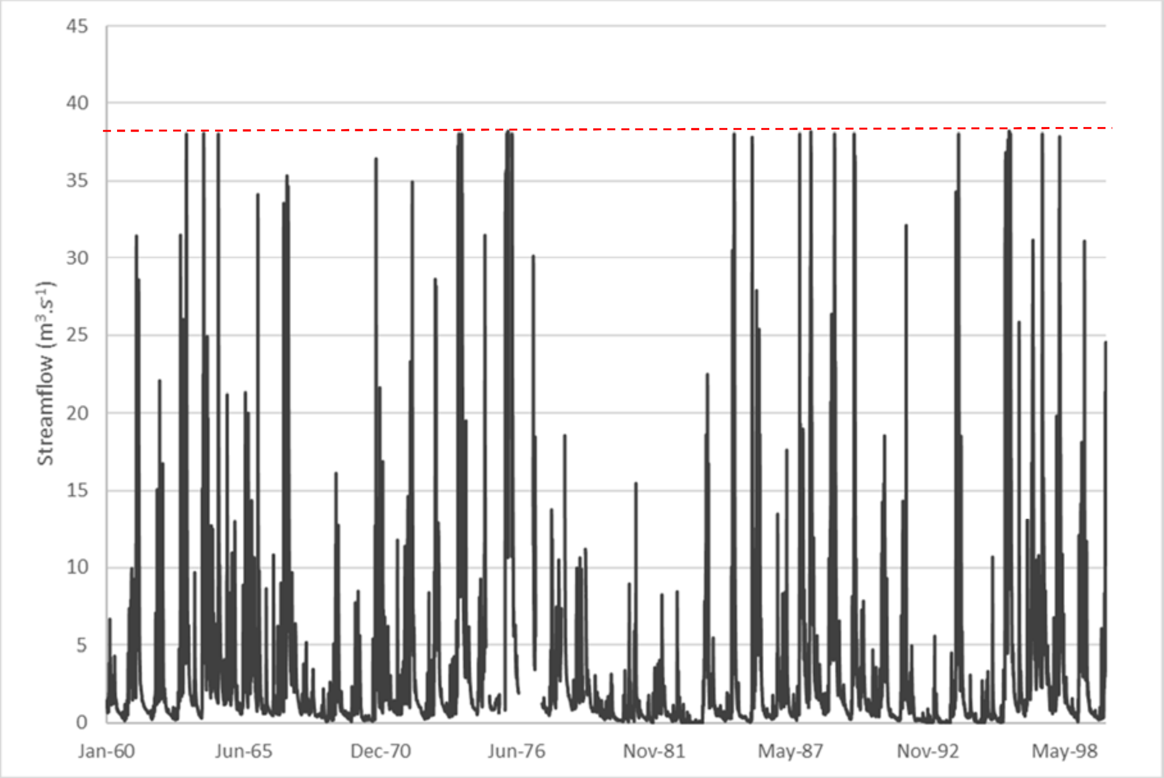


Figure 10.1 Average streamflow measured at the T3H004 weir for the period of 1960 – 2000.

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[1] Data downloaded from: http://www.dwa.gov.za/Hydrology/Verified/HyDataSets.aspx?Station=T3H004

When the Ratings Table (Table 10.1) for the weir was consulted, it was shown that the table had not been updated since 1951 (similarly, the T3H009 Table was last updated in 1964 (Table 10.2)) and assumed that any flow over 1.07 m would produce the same flow volume. Realistically, 1 m streamflow would not produce the same volume as 4 m of streamflow meaning that the streamflow data had to be calculated using the daily depths of flow to determine the flow of the T3H004 weir. The Ratings Table was used to develop an exponential relationship between the depth of flow and flow rate (Figure 10.2), which was then applied to the daily flow depths to give a more accurate representation of flow for the study period (Figure 10.3).

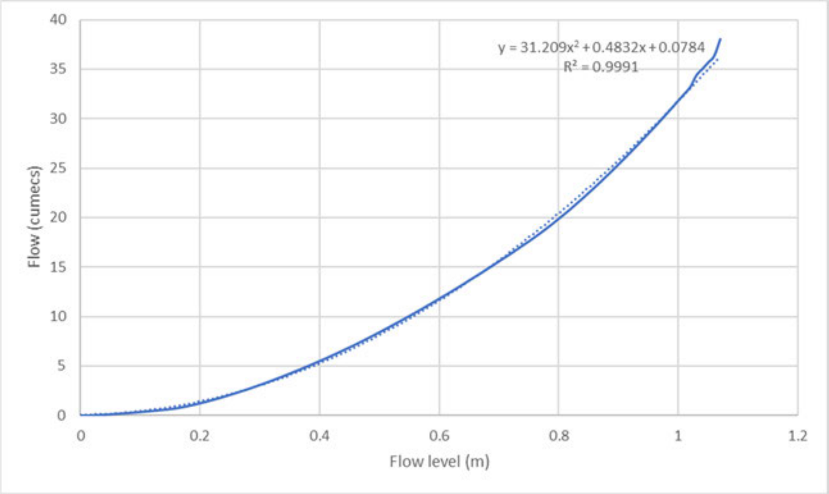

Figure 10.2 Relationship between flow depth and average flow for the T3H004 weir.

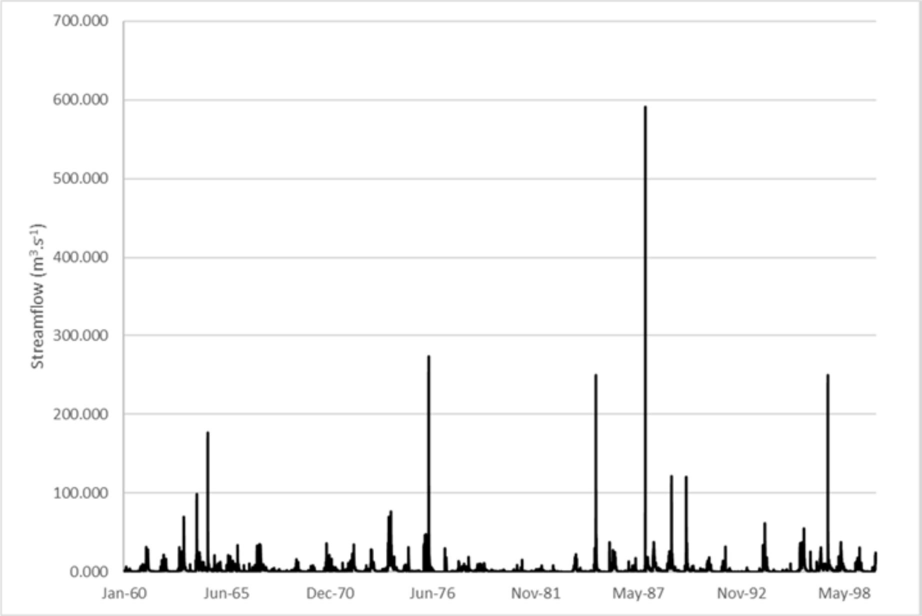

Figure 10.3 Revised flow rates of the T3H004 weir using Ratings Table relationship

STATION NO T3H004
DATE OF APPLICATION 1951-08-21
DT NO 7
DISCHARGE IN CUMEC FOR 1CM RISE IN WATER LEVEL

METRE	0	0.01	0.02	0 03	0.04	0.05	0.06	0.07	0.08	0.09
0	0	0.0124	0.0358	0.0651	0.099	0.1367	0.1778	0.222	0.2689	0 3183
0.1	0.3702	0.4243	0.4805	0.5388	0.599	0.6611	0.7429	0.8527	0.9773	1.113
0.2	1.259	1.413	1.576	1.745	1.921	2.104	2.293	2.487	2.687	2.893
0.3	3.104	3.32	3.546	3.777	4.013	4.253	4.498	4.748	5.003	5.262
0.4	5.525	5.793	6.065	6.342	6.622	6.907	7.197	7.499	7.806	8.117
0.5	8.433	8.753	9.077	9.405	9.738	10.07	10.42	10.76	11.11	11.46
0.6	11.82	12.18	12.54	12 91	13.28	13.66	14.04	14.42	14.81	15.2
0.7	15.6	15.99	16.39	16.8	17.21	17.62	18.05	18.49	18.95	19.42
0.8	19.91	20.4	20.91	21.44	21.97	22.52	23.07	23.64	24.22	24.8
0.9	25.4	26.01	26.62	27 24	27.88	28.52	29.16	29.82	30.48	31.16
1	31.84	32.52	33.22	34 38	35.03	35.69	36.36	38.04	38.04	38.04
1.1	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
1.2	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
1.3	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
1.4	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
1.5	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
1.6	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
1.7	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
1.8	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
1.9	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
2	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
2.1	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
2.2	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
2.3	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
2.4	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
2.5	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
2.6	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
2.7	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
2.8	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
2.9	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
3	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
3.1	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
3.2	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
3.3	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
3.4	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
3.5	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
3.6	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
3.7	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
3.8	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
3.9	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
4	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
4.1	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
4.2	38.04	38.04	38.04	38 04	38.04	38.04	38.04	38.04	38.04	38.04
4.3	38.04	38.04	38.04							

Table 10.1 Ratings Table for the T3H004 weir[1]

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[1] Table available from: http://www.dwa.gov.za/Hydrology/Verified/HyDataSets.aspx?Station=T3H004

STATION NO T3H009
DATE OF APPLICATION 1964-08-15
DT NO 4
DISCHARGE IN CUMEC FOR 1CM RISE IN WATER LEVEL

METRE	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0	0	0.0082	0.0295	0.0581	0.0899	0.1263	0.1667	0.2109	0.2585	0.3094
0.1	0.3589	0.4109	0.4699	0.5368	0.6124	0.7165	0.8563	1.013	1.186	1.377
0.2	1.587	1.817	2.067	2.338	2.618	2.854	3.101	3.36	3.629	3.909
0.3	4.2	4.502	4.815	5.14	5.475	5.822	6.18	6.55	6.931	7.323
0.4	7.726	8.141	8.568	9.006	9.456	9.917	10.39	10.87	11.37	11.88
0.5	12.4	12.93	13.47	13.97	14.08	14.19	14.31	14.42	14.54	14.66
0.6	14.77	14.89	15.01	15.13	15.25	15.37	15.49	15.62	15.74	15.86
0.7	15.99	16.12	16.24	16.37	16.5	16.63	16.76	16.89	17.02	17.16
0.8	17.29	17.43	17.56	17.7	17.84	17.98	18.12	18.26	18.4	18.54
0.9	18.69	18.83	18.98	19.12	19.27	19.42	19.57	19.72	19.87	20.02
1	20.18	20.33	20.49	20.64	20.8	20.96	21.12	21.28	21.44	21.61
1.1	21.77	21.93	22.1	22.27	22.44	22.61	22.78	22.95	23.12	23.3
1.2	23.47	23.65	23.82	24	24.18	24.36	24.55	24.73	24.99	25.28
1.3	25.58	25.87	26.17	26.46	26.76	27.06	27.36	27.66	27.97	28.27
1.4	28.58	28.88	29.19	29.5	29.81	30.12	30.43	30.74	31.06	31.37
1.5	31.69	32	32.32	32.64	32.96	33.28	33.6	33.93	34.25	34.58
1.6	34.9	35.23	35.56	35.89	36.22	36.55	36.88	37.22	37.55	37.89
1.7	38.23	38.56	38.9	39.24	39.58	39.92	40.27	40.61	40.96	41.3
1.8	41.65	42	42.34	42.69	43.04	43.4	43.75	44.1	44.46	44.81
1.9	45.17	45.53	45.88	46.24	46.6	46.96	47.33	47.69	48.05	48.42
2	48.78	49.15	49.52	49.89	50.26	50.63	51	51.37	51.74	52.12
2.1	52.49	52.87	53.25	53.62	54	54.38	54.76	55.14	55.53	55.91
2.2	56.29	56.68	57.07	57.45	57.84	58.23	58.62	59.1	59.63	60.16
2.3	60.7	61.24	61.79	62.34	62.89	63.45	64.01	64.58	65.14	65.72
2.4	66.29	66.88	67.46	68.05	68.64	69.24	69.84	70.45	71.06	71.67
2.5	72.29	72.91	73.54	74.17	74.8	75.44	76.09	76.73	77.39	78.04
2.6	78.7	79.37	80.04	80.71	81.39	82.07	82.76	83.45	84.15	84.85
2.7	85.55	86.26	86.98	87.7	88.43	89.15	89.89	90.62	91.37	92.12
2.8	92.87	93.63	94.39	95.16	95.93	96.71	97.49	98.28	99.07	99.87
2.9	100.7	101.5	102.3	103.1	103.9	104.8	105.6	106.4	107.3	108.1
3	109	109.8	110.7	111.6	112.4	113.3	114.2	115.1	116	116.9
3.1	117.8	118.7	119.6	120.6	121.5	122.4	123.4	124.3	125.3	126.2
3.2	127.2	128.2	129.2	130.1	131.1	132.1	133.1	134.1	135.1	136.2
3.3	137.2	138.2	139.2	140.3	141.3	142.4	143.4	144.5	145.6	146.7
3.4	147.8	148.8	149.9	151.1	152.2	153.3	154.4	155.5	156.7	157.8
3.5	159	160.1	161.3	162.5	163.6	164.8	166	167.2	168.4	169.6
3.6	170.8	172.1	173.3	174.5	175.8	177	178.3	179.6	180.8	182.1
3.7	183.4	184.7	186	187.3	188.6	189.9	191.3	192.6	194	195.3
3.8	196.7	198	199.4	200.8	202.2	203.6	205	206.4	207.8	209.3
3.9	210.7	212.1	213.6	215	216.5	218	219.5	221	222.5	224
4	225.5	227	228.5	230.1	231.6	233.2	234.8	236.3	237.9	239.5
4.1	241.1	242.7	244.3	245.9	247.6	249.2	250.9	252.5	254.2	255.8
4.2	257.5	259.2	260.9	262.6	264.4	266.1	267.8	269.6	271.3	273.1
4.3	274.8	276.6	278.4	280.2	282	283.8	285.7	287.5	289.3	291.2
4.4	293.1	294.9	296.8	298.7	300.6	302.5	304.4	306.4	308.3	310.3
4.5	312.2	314.2	316.2	318.2	320.2	322.2	324.2	326.2	328.2	330.3
4.6	332.3	334.4	336.5	338.6	340.7	342.8	344.9	347	349.2	351.3
4.7	353.5	355.7	357.8	360	362.2	364.4	366.7	368.9	371.1	373.4
4.8	375.7	377.9	380.2	382.5	384.8	387.2	389.5	391.8	394.2	396.6
4.9	398.9	401.3	403.7	406.1	408.6	411	413.4	415.9	418.4	420.8
5	423.3	425.8								

Table 10.2 Ratings Table for the T3H009 weir[1]

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[1] Data downloaded from: http://www.dwa.gov.za/Hydrology/Verified/HyDataSets.aspx?Station=T3H009