LINKAGES BETWEEN SELECTED HYDROLOGICAL ECOSYSTEM SERVICES AND LAND USE CHANGES, AS INDICATED BY HYDROLOGICAL RESPONSES

A CASE STUDY ON THE MPUSHINI/MKHONDENI CATCHMENTS, SOUTH AFRICA

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Dissertation

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PREFACE

I, Stefanie Schütte declare that:

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ABSTRACT

Nature provides essential services to humans, including climate regulation, water provisioning and regulation. These so-called ecosystem services have economical, societal and environmental value. This research aims at improving the knowledge on the linkages between selected hydrological ecosystem services and current and proposed land uses within the water-limited Mpushini/Mkhondeni Catchments in South Africa. The research contributes to the recognition of feedback and linkages within the complex ecological-human system, so that informed land use decisions can be made. The research aim is achieved by first reviewing the literature on hydrological ecosystem services, land use in an ecosystem services context and the links between the two. The study area is then sub-delineated into land use determined hydrological response units for baseline natural land cover, as well as for current and proposed land use scenarios. Using an appropriate model, selected hydrological processes are simulated in order to isolate the effects of individual land uses on hydrological responses, both on a local and a more catchment-wide scale.

Various land uses were found to affect hydrological responses, such as runoff and its components of stormflows and baseflows, as well as transpiration and sediment yields, differently. These responses were found to be suitable indicators of selected ecosystem services such as water provisioning or flow regulation. Irrigation and high biomass crops, such as sugarcane and wattle plantations were found to reduce downstream water provisioning services. Degraded lands were found to reduce physical water quality through increased sediment yield, to reduce water provisioning during low flow periods, while the degraded lands increased stormflows, thereby reducing regulation of high flows. Urban land uses were found to significantly increase runoff, with increased impervious areas causing a shift from evaporation and transpiration towards runoff. Stormflows increased, with high flow regulation being reduced. Baseflows increased as well, as a result of a spill-over of runoff from impervious to pervious urban areas, which led to increased low flow regulation. In addition, in this study area urban return flows are generated from externally sourced water, further increasing streamflows and especially low flows. While urban areas showed an increase in downstream water quantity provision, the water quality was reduced. The combined effects of the current land use mosaic on the annual streamflows partially cancel each other out, while the proposed urbanisation dominated hydrological responses. Influences

of various land uses on hydrological ecosystem services were thereby shown, which contributes to a better understanding of the linkages between the two.

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1. INTRODUCTION

The natural environment provides services to humans in the form of climate regulation, water provisioning and regulation, biodiversity-related and other services. These so-called ecosystem services have economical, societal, as well as environmental value. At this point in time, decisions about changes in land use are often made without taking into account what the impacts of those changes would be on the ecosystem services which this land provides to both individuals and to society. However, increasing tracts of land are being transformed from their natural state to human-influenced land uses (Foley *et al.*, 2005). This can also be observed in the province of KwaZulu-Natal, South Africa (Jewitt, 2012), where the Mpushini/Mkhondeni study catchments are situated. These water-limited study catchments, which form part of the larger uMgeni Catchment, have to date experienced a degree of transformation through agricultural development and urban sprawl and there are currently various proposals for land use change, from natural and agricultural, to more concentrated urban land uses. The current and proposed land use influences on ecosystem services should be recognised and accounted for and should include feedback and links within the complex ecological-human system, in order to make informed land use decisions for a sustainable future.

This research aims at improving the knowledge on linkages between hydrological ecosystem services, which Brauman *et al.* (2007) define as the benefits to humans produced by terrestrial ecosystem effects on freshwater, and the current and proposed land uses within the study area. The objectives are to model changes in hydrological responses as a result of land use modification and then to relate these response changes to changes in ecosystem services.

In this document, a literature review on ecosystem services, hydrological ecosystem services, land use and the links amongst these, is presented in Chapter 2. A need for improved knowledge on the links between land use change, hydrological responses and ecosystem services is established from the literature, and this research aims to contribute towards these links. In Chapter 3 background information is given on the water-limited study catchment, on the scenarios of baseline natural land cover, of current and of proposed land uses. Methods of analysis are described in Chapter 4, starting with the hydrological implications of the scenarios, a description of the delineation of the study area into catchment units and further into hydrological response units, a description of the hydrological model that was used and of the relevant hydrological model inputs, as well as the outputs of hydrological responses. Results are presented in Chapter 5, starting with the results of hydrological analyses from the baseline, i.e. pre-human, untransformed land cover, which is used as a reference. Thereafter, an interpretation of changes in hydrological responses between current land uses and the baseline land cover follows, as well as an interpretation of differences in hydrological responses between proposed urbanisation and current land uses. The hydrological responses are used as indicators for selected provisioning, regulating and supporting hydrological ecosystem services. The land use changes are then linked with those selected ecosystem services. Finally, in Chapter 6, the significance of the results is discussed, conclusions are drawn and further research is recommended.

An overview of the outline of the dissertation, as presented above, is provided in Figure 1. This overview will be used to introduce each chapter, with emphasis on where a respective chapter fits into the overall objectives of this research.

Objective: To evaluate changes to selected hydrological responses and associated selected ecosystem services provided by the study area, as a result of current and proposed land use modifications					
Approach: The objective is to be achieved by identifying the scenarios of baseline land cover as well as current and proposed land uses; sub-delineating the study area into land use determined hydrological response units; applying an appropriate hydrological simulation model to assess changes in hydrological responses from baseline land cover as well as current and proposed land uses; and relating these changes in hydrological responses to changes in selected ecosystem services					
Sections					
Chapter 1 Introduction	Chapter 2 Literature Review	Chapter 3 Background Information	Chapter 4 Methods	Chapter 5 Results	Chapter 6 Discussion

Figure 1 Overview of the objective of this study, the approach adopted and the sections making up the dissertation

2. LITERATURE REVIEW

2.1 Research Overview and Introduction

The literature review fits into the overall research objective and approach adopted, as shown in the overview provided in Figure 2.1.

Objective: To evaluate changes to selected hydrological responses and associated selected ecosystem services provided by the study area, as a result of current and proposed land use modifications

Approach: The objective is to be achieved by identifying the scenarios of baseline land cover as well as current and proposed land uses; sub-delineating the study area into land use determined hydrological response units; applying an appropriate hydrological simulation model to assess changes in hydrological responses from baseline land cover as well as current and proposed land uses; and relating these changes in hydrological responses to changes in selected ecosystem services

Sections

Chapter 1 Introduction	Chapter 2 Literature Review	Chapter 3 Background Information	Chapter 4 Methods	Chapter 5 Results	Chapter 6 Discussion

Chapter Outline:
- Ecosystem Services
- Hydrological Ecosystem Services
- Land Use within an Ecosystem Services Context
- The Link between Land Use and Hydrological Ecosystem Services

Figure 2.1 The literature review within the context of this dissertation

The state of relevant existing knowledge, as reviewed in the literature, will be presented in this chapter. Ecosystem services will be explained first, followed by a description of hydrological ecosystem services. An overview of land use within an ecosystem services context will then be given, as will the links between land use and hydrological ecosystem services.

2.2 Ecosystem Services

Ecosystems, their functioning and resilience and associated ecosystem services will be introduced first. After this, declining ecosystem services and their consequences, as well as ecosystem services assessments for decision-making will be described, with examples of investments in ecosystem services. The section will conclude with an assessment of ecosystem services in the South African context.

2.2.1 Ecosystems functioning and resilience

Ecosystems may be defined as a dynamic complex of plant, animal and micro-organism communities and the non-living environment, interacting as a functional unit (MEA, 2005). Ecosystems are variable, dynamic and self-organising systems (MEA, 2005). When considering the earth as an ecosystem, the term biosphere is often used. The diversity and structure of the ecosystem are important for its functioning. There are feedbacks and links within an ecosystem, and these are generally complex adaptive systems. These feedbacks might be linear, but more often take place in increments or even lead to sudden shifts in ecosystem composition or functioning (Scheffer *et al.*, 2001). Such changes may result in a permanent reduction or loss of associated ecosystem services (Jewitt, 2002) and will be explained in more detail in Section 2.2.3.

Maintaining the diversity and connectedness of ecosystems fosters resilience against disturbances. Resilience determines the scale of disturbance that can be absorbed, before irreversible changes, within the structure of the system, take place. Slow resistance loss sets the stage for larger changes if the ecosystem is subjected to a random event, such as a major climate fluctuation or when the ecosystem crosses a threshold (Scheffer *et al.*, 2001; Carpenter *et al.*, 2006). Scheffer *et al.* (2001) gives examples of ecosystem shifts, including:

a) the sudden eutrophication in a shallow lake as a result of increased nutrient load reaching a threshold;
b) the alternate stable states of moist vegetated and dry desert states of the Sahel region, caused by feedback between vegetation and climate; or
c) desertification through local soil–plant interactions, with reduced vegetation in certain dryland regions leading to reduced water infiltration which, in turn, renders the establishment of new plants more difficult or impossible.

Humans are an integral component of ecosystems. However, anthropogenic (man-made) influences have added increased complexity and are continually altering ecosystems, while natural habitats are declining (MEA, 2005). In 2007, the human ecological footprint, which is an indicator of the ecological capacity necessary to meet human needs, exceeded the earth's actual capacity to produce renewable resources and absorb CO_2 by 50 % (WWF, 2012). Since

1966, humanity's ecological footprint has doubled (WWF, 2012) and humanity is thus living in a so-called "ecological overshoot" (Wackernagel *et al*., 2002).

2.2.2 Ecosystem services defined

Healthy ecosystems have the ability to provide a variety of ecosystem services which are essential to human existence, are complex and not yet fully understood. Most ecosystem services cannot be replaced by technology (Daily, 1997; MEA, 2005). Human health, the economy and security are tied to ecosystem services (MEA, 2005; Adger, 2006). They are understood to be benefits that humans obtain from ecosystems (MEA, 2005), either directly or indirectly (TEEB, 2010). Ecosystem services may be divided into provisioning services (e.g. providing food and water), regulating services (e.g. flood and drought regulation, climate regulation), cultural services (e.g. providing aesthetic, spiritual or educational services), as well as supporting services (e.g. soil formation or water purification) which are needed to maintain the other services (MEA, 2005). Further examples of ecosystem services are provided in Figure 2.2.

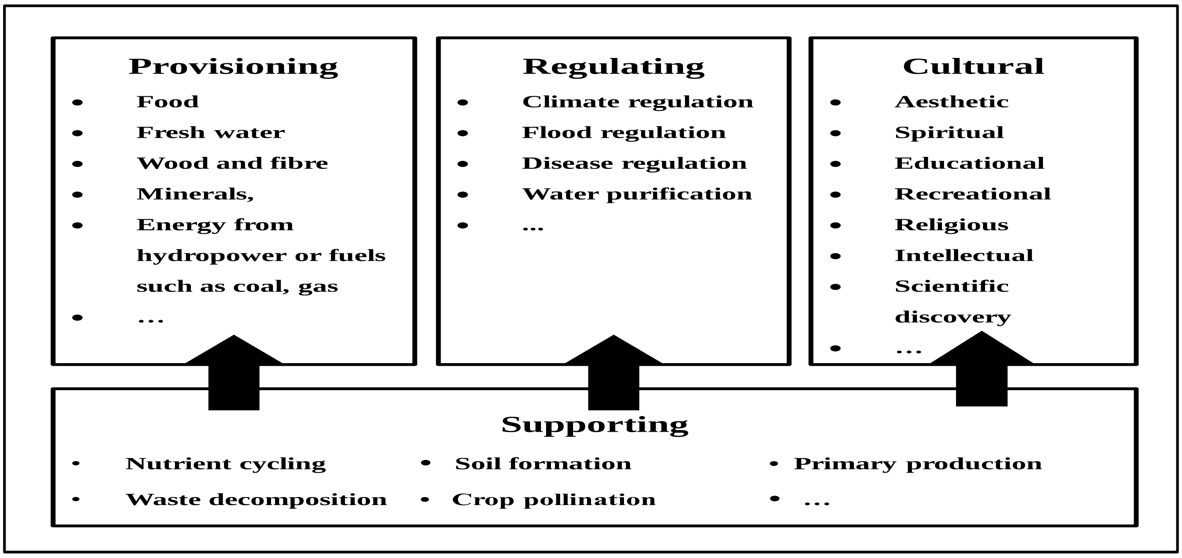

Figure 2.2 Components of ecosystem services (adapted from Millennium Ecosystem Assessment, 2005)

Often ecosystem services have been provided free of charge by nature to society and they can thus be classified as public goods or "commons" (Daily, 1997). Although ecosystem services often do not have "price tags" to them, they have value and might be expensive to replace, if this is at all possible (Turner and Daily, 2008). Valuing ecosystem services, and thereby internalising previously external costs, helps to channel behaviour "toward a future in which nature is no longer seen as a luxury we cannot afford, but as something essential for sustaining and improving human well-being everywhere" (Daily *et al.*, 2009, p. 27).

An ecosystem management approach should allow society to harness ecosystem services sustainably. Ecologists emphasise the importance of conserving natural areas for their ecological processes and functions within a landscape which, next to preserving biodiversity, also give rise to other ecosystem services and, therefore, ensure sustainability (Daily, 1997). However, not only natural areas, but to a certain extent also landscapes with multi-functional uses, give rise to various ecosystem services.

The emerging science of ecosystem services is interdisciplinary, attempting to bring together knowledge from ecology, economics, engineering, earth sciences, landscape architecture and land use planning, for an improved and integrated understanding for decision-making that includes the maintenance of ecosystem services. To translate the benefits of ecosystem services into an economist's language, the term "natural capital" is sometimes used. Natural capital provides benefits, *inter alia*, from soil, climate, topography, flora and fauna and their interaction in a thermodynamically closed system, powered almost exclusively by solar energy (Daly and Farley, 2003). In economists' terms, natural capital is the stock of natural ecosystems that yield a flow of valuable ecosystems goods or services into the future, comparable to the interest of financial capital (Wackernagel and Rees, 1997; Daly and Farley, 2003). It has a relationship with the economic and social capital and is supported by good governance, as shown in Figure 2.3. Natural capital has been identified as increasingly becoming the limiting factor in economic growth, development and well-being (Daly and Farley, 2003; Aronson *et al.*, 2006). Farley and Daly (2006) explicitly distinguish between *economic growth*, which they understand as the physical increase in the rate at which the economy transforms natural resources into economic output and waste, and *economic development*, which is an increase in human welfare for a given level of resource use.

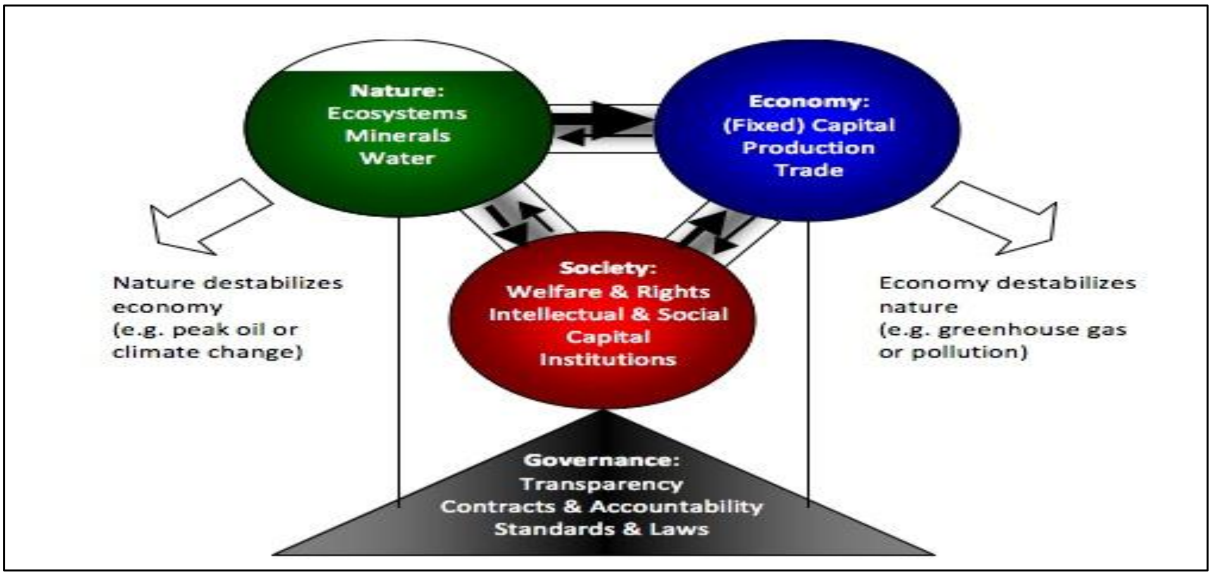

Figure 2.3 Natural capital within a context with the economy and social capital (du Plooy, 2012)

Severe and irreversible declines in ecosystem services and human well-being may occur if not enough emphasis is placed on enhancing natural capital at the same time as human, social and manufactured capital (Carpenter *et al.,* 2006). There are strong arguments for a re-investment into natural capital, either via payment for ecosystem services provision, or via other means (Jewitt, 2002; FAO, 2007; Turner and Daily, 2008). The ecosystem, as a whole, provides multiple associated services. Therefore, there might be multiple benefits to investing in natural capital (de Groot, 2006).

The stock of natural capital has decreased from the pre-industrial era to the present human-dominated era (Aronson *et al*., 2006), with an associated reduction in overall ecosystem services. At the same time, the stock of manufactured capital has increased. The human use of energy, matter and waste material has grown, while the size of the biosphere has stayed the same (Figure 2.4). There were also trade-offs between ecosystem services, e.g. a worldwide increase of food production, but a decrease of other services.

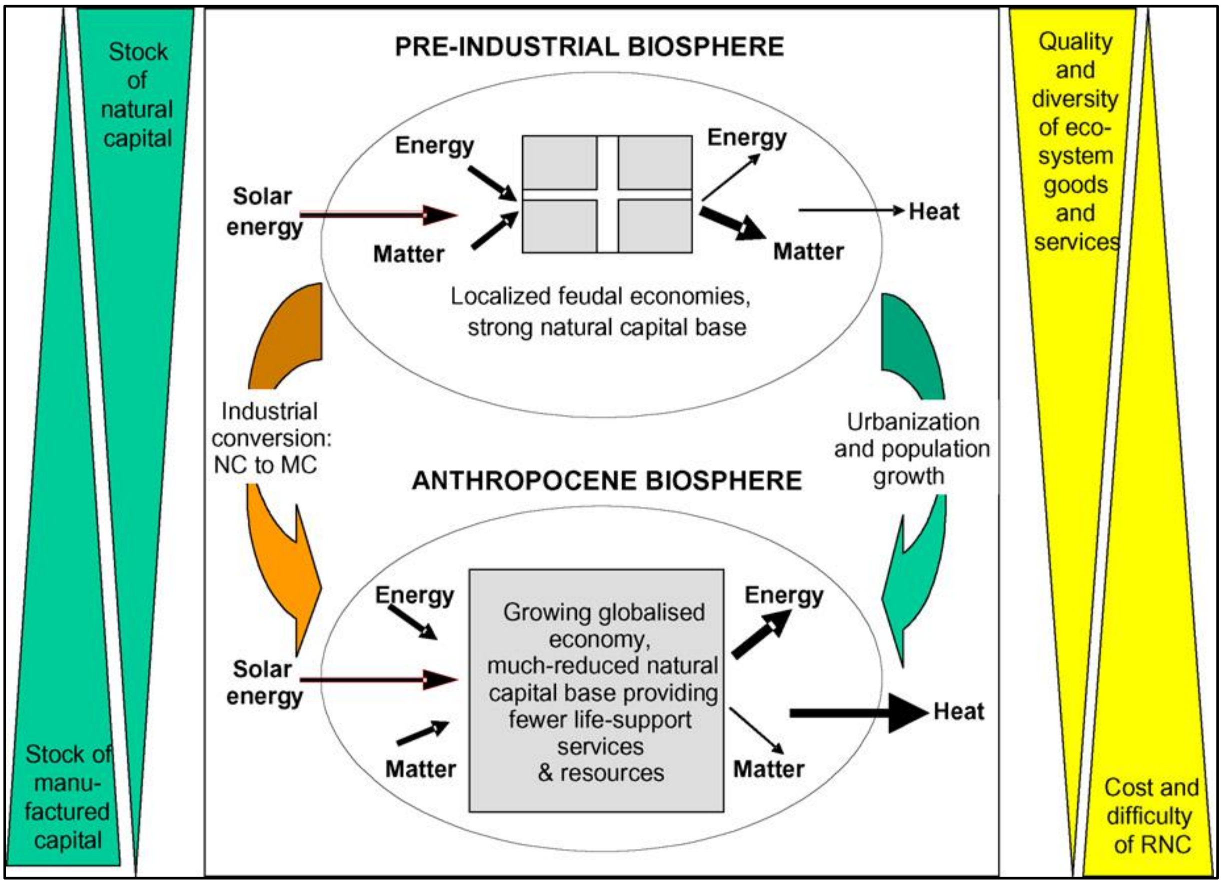

Figure 2.4 A pre-industrial and anthropogenic biosphere diagram (Aronson *et al.*, 2006), in which NC is natural capital, MC is manufactured capital and RNC is restoring natural capital

Owing to the loss of natural capital from past development and the associated deterioration of ecosystem services, there is now a need for any further development to be sustainable. The aim of sustainable development is to meet current needs, while not compromising of future generations' ability to meet their own needs (Brundtland, 1987). Therefore, the development of a resource should be such that the resource's resilience, integrity and characteristics are sustained (Jewitt, 2002). Social and economic development requires the use of natural resources and is thereby impacting on the natural system. A trade-off is likely between certain benefits gained and certain benefits lost, as human influence impacts negatively on some ecosystem services which benefit society (Foley *et al.*, 2005; Brauman *et al.*, 2007). The ideal would be an optimised mix of different ecosystem services and overall maximum benefits from natural and human (artificial) derived services (Figure 2.5). However, there are also views that development cannot be sustainable, if it involves the transformation of natural land (Balmford *et al.*, 2002; Lovelock, 2009). Adopting a sustainability paradigm means rethinking the meaning of development and questioning the adequacy of impact mitigation (Crane and Swilling, 2007).

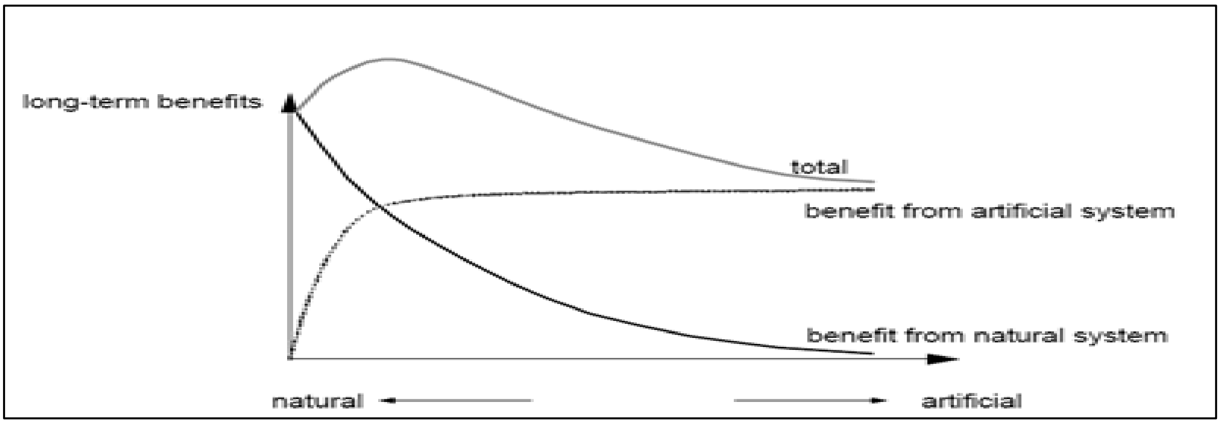

Figure 2.5 Maximising of the provisioning of natural and human-made services (after McCartney *et al*., 2000)

2.2.3 Declining ecosystem services

In the Millennium Ecosystem Assessment (MEA, 2005), compiled from inputs of over 1300 scientists from 95 countries, 15 of the 24 global ecosystem services were found to be declining. When ecosystems are over-utilised, their ability to provide services reduces (Jewitt, 2002). The societal responses to declining ecosystem services may be passive and include falling ill from polluted drinking water or food, famine as a result of land fertility degradation, disputes due to controversies over water and land use, or active responses, for example, when individuals migrate or reduce fallows during crop rotation (Falkenmark *et al.,* 1999). A worst-case scenario of reducing ecosystem services would be that after reaching a threshold the services might be irreversibly lost. Depending on the services lost or reduced, the quality of life for society would then decline, first affecting the poor and resulting in a lowering of average living standards (MEA, 2005). A large-scale reduction in essential ecosystem services would reduce the carrying capacity of a habitat, i.e. the population that can be sustained by that habitat, in this case the earth, leading to increased species extinctions and human mortality (Pimentel *et al.,* 1999). To reduce the chances of this happening, a number of planetary boundaries for a safe operating space for humanity have been suggested (Rockström *et al.,* 2009) for the total amount of land system change, as well as biodiversity loss, climate change, ocean acidification, stratospheric ozone depletion, the nitrogen cycle, the phosphorus cycle, global freshwater use, atmospheric aerosol loading and chemical pollution (Figure 2.6). These planetary boundaries create an environmental ceiling for human well-being, while a social foundation is required on the inside, thus figuratively creating a "doughnut" of a safe and just place for humanity to thrive (Raworth, 2012).

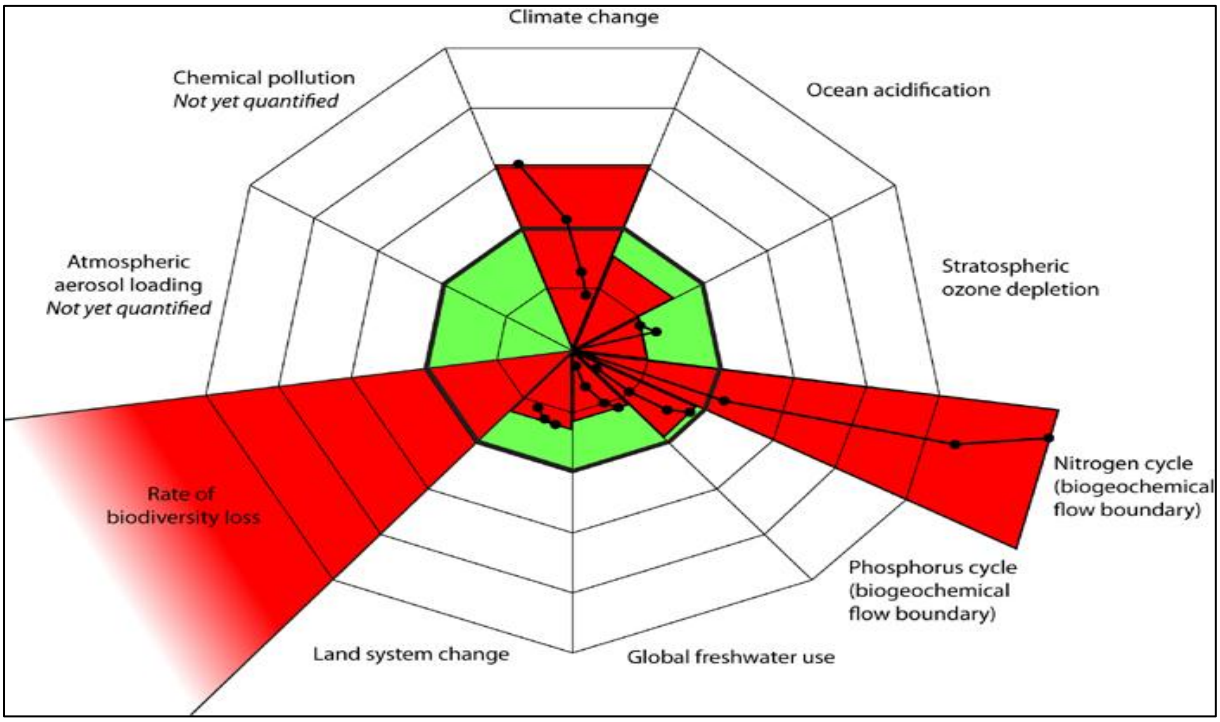

Figure 2.6 Planetary boundaries (after Rockström *et al.*, 2009). The inner (green) shaded area represents the safe operating space, with proposed boundary levels at its outer contour, where the extent of the wedges for each boundary shows the estimate of current (i.e. 2009) position of the control variable and points show the estimated recent time trajectory (1950–present) of each control variable

The question arises why humans nevertheless allow ecosystem and the associated services to decline, especially because it is usually cheaper to avoid degradation than it is to pay for ecological restoration (TEEB, 2010). Explanations for this can be found in the literature and include the following:

a) Intrinsic value alone does not signify the dependence of humans on natural capital (Wackernagel and Rees, 1997);
b) scientific information about ecosystem services and changes to these are not available (Turner and Daily, 2008);

c) decision-makers (governments or individuals) continue to discount inappropriately when deciding between ecosystem conservation and conversion (Pearce, 2007);
d) markets often reward short-term exploitation values of natural capital and greed, to the detriment of sustainable ecological health and associated human welfare (Ostrum, 1990; Balmford *et al.*, 2002; Turner and Daily, 2008);
e) beneficiaries and producers might not be linked (van Jaarsveld *et al.*, 2005);
f) multiple services across a range of competing land uses are not evaluated, so decision-makers have not got all the facts (Balmford *et al.*, 2002);
g) the decision horizon is not long enough (Turner and Daily 2008);
h) the future is discounted for the present (Wackernagel and Rees, 1997);
i) there might be a blocking effect to change through strong stakeholder's interest (Falkenmark *et al.*, 1999);
j) where environmental legislation is in place, there might be lack of enforcement mechanisms or a fragmented administration or bureaucracy (Falkenmark *et al*., 1999);
k) there might be a "global deficit of care" (Pearce, 2007);
l) various psychological barriers exist to environmental action (Wackernagel and Rees, 1997; Gifford, 2011);
m) a consumer-driven, human-controlled world seems to be the goalpost for many (Daly, 1991); and/or
n) the perceptions of environmental baselines keep shifting from generation to generation, thus masking change (Sáenz-Arroyo *et al*., 2005).

2.2.4 Ecosystem services assessments for decision-making

An ecosystem approach is about a new way of thinking and working, by shifting the focus away from looking at natural environmental policies separately e.g. air, water, soil and biodiversity, towards a more integrated approach based on whole ecosystems (DEFRA, 2007). However, measuring and valuing services does not directly lead to an increased use of this knowledge. To see knowledge about multiple ecosystem services generated from a landscape implemented into planning and development tools, communication across ecosystem and sector boundaries is required, including the identification of a range of services, as well as cross- comparison and trade-off analysis (Primmer and Furman, 2012).

Any management approaches to ecosystems require dealing with uncertainty because, as already stated, ecosystems are complex adaptive systems (Jewitt, 2002). Various studies have been undertaken where ecologists and economists have valued the social benefits and costs of conserving biodiversity and ecosystem services (e.g. Balmford *et al*., 2002; Chan *et al*., 2006). Most conclusions were that conserved ecosystems generally generate net benefits. For the purpose of decision-making, it might not be so important to know the total value of specific ecosystem services. Of greater importance, when a certain area is transformed, is often the change or margin to the flow of ecological services. Therefore, a change assessment (also called a marginal assessment) can be used, comparing the changes in ecosystem services before and after a scenario (Daily, 1997). An example is the recent TEEB project, which is a study commissioned by the United Nations to assess the global economic costs of ecosystem degradation and biodiversity loss. The TEEB project concentrates on assessing the consequences of changes resulting from alternative ecosystem management options, including best practice examples from around the world, rather than attempting to estimate the total value of ecosystems (TEEB, 2010).

It is recognised, however, that ecosystems often do not follow linear feedbacks. There might also be sudden consequences, e.g. when a critical threshold has been exceeded, as was explained in Section 2.2.1. A change analysis can be made, as long as the threshold is not exceeded, which means that the lowest functioning point of the specific ecosystem function is not reached. It is acknowledged, however, that this information is often not available and that it is then safer to err on the side of caution.

If only one ecosystem service is taken into the equation of deciding on ecosystem degradation, conservation or restoration, then the benefits might be different to when various ecosystem services are considered simultaneously. There might also be a trade-off between different ecosystem services and their respective value might, in turn, be perceived differently by the various beneficiaries (Lowe *et al.*, 2009). The over-exploitation of provisioning ecosystem services usually leads to a reduction in regulating ecosystem services. This might reduce future yields of provisioning services and it may increase the vulnerability of people to environmental variability (Carpenter *et al.*, 2006).

If in doubt, a complete ecological assessment should be undertaken before ecosystem transformation is allowed. The science of ecosystem services is still evolving, including an integrative framework. Important components for capturing the benefits of ecosystem services are, *inter alia*, property rights (Carpenter *et al*., 2006), as well as stakeholder perceptions and institutional arrangements (Turner and Daily, 2008). Turner and Daily (2008) suggested an 'Ecosystem Services Framework', i.e. an environmental change process which starts with identifying the ecosystem services and the relevant spatial and time scales. Thereafter, suitable models and mapping approaches need to be identified (Turner and Daily, 2008), followed by an environmental change scenario analysis for the relevant different resource uses, policies or choices; an ecosystem services 'benefit capture' via payments; capacity building and monitoring; and lastly, a post-policy appraisal and possible re-evaluation (Turner and Daily, 2008). There is a need for further research to improve the implementation of the ecosystem services concept into decision-making, for example, in landscape planning (Hermann *et al*., 2011).

Various approaches and means of implementing the ecosystem concept have been used, as well as different classifications regarding ecosystem services, values, benefits, functions, processes and indicators (Hermann *et al*., 2011). A widely accepted definition of ecosystem processes is the complex interactions among biotic and abiotic elements of ecosystems (Hermann *et al*., 2011). Most authors agree that goods and services are generated by ecological functions (Hermann *et al*., 2011) and that ecosystem processes, functions and services are interlinked (de Groot, 2006). Lowe *et al.* (2009) emphasise the importance of modelling trade-offs for different scenarios, while Hermann *et al*. (2011) recommend local scale, model-based research activities as significant tools in aiding decision-making. Cowling *et al*. (2008) see the biophysical quantification of ecosystem services as an essential step towards successful implementation actions in order to safeguard them and Egoh *et al.* (2012a) call for a robust biophysical quantification of ecosystem services.

Ecosystem services assessments are, however, not without challenges, including the fact that the assessment of the full range of ecosystem services seems to be impossible (Hermann *et al*., 2011; Primmer and Furman, 2012). Further challenges include the fact that it is still an evolving concept, without universal standards on what to measure and how, and these are important requirements to be able to compare studies (Hermann *et al*, 2011). Various investigations have found that human-induced change to ecosystems might benefit the landowner and individuals, while disadvantaging the community locally and globally. Multi-functionality and sustainability might often not be in the individual owner/manager's interest (Hubacek *et al.,* 2009). Therefore, the total benefit to society needs to be considered in ecosystem services assessments. Furthermore, different scenarios might yield trade-offs between different ecosystem services. Payment for ecosystem services is a possible way of transferring benefits from users to producers and thereby attaining sustainability (Turner and Daily, 2008). The time-frame considered in an assessment might also give different results (a five-year view *vs.* a 50-year view*),* as will the aim. For example, if the aim is the "highest possible quality of life compatible with the conservation of resilient, healthy ecosystems" (Farley, 2012, p. 40) or an increase in total sustainable social welfare or happiness per capita, compared to the current approach of increase in Gross Domestic Product (GDP), the outcomes would be different (Heinberg, 2011). When an ordinary economic approach is used, discount rates to the present are applied, which assumes the possibility of unlimited growth, which is an enigma (Heinberg, 2011). The current economic approach seems to fail to protect ecosystem services and to internalise previous external costs (Daly, 1991; Wackernagel and Rees, 1997; Heinberg, 2011).

2.2.5 Examples of benefits from investments into ecosystem services

Examples abound of successful investments into ecosystem services (e.g. Daily *et al.*, 1997; Balmford *et al.*, 2002; Foley *et al.*, 2005; Turner and Daily, 2008). Some are mentioned below.

a) In the 1990s, New York City officials invested in restoring the natural asset, *viz*. the watershed, rather than building a water filtration plant and saved over $6 billion (National Research Council, 2000; Turner and Daily, 2008).
b) Decision-makers in Napa, California invested in a "living river", which included the restoration of floodplains, rather than building physical concrete barriers. The restoration of wildlife, fish and scenic beauty led to a revitalisation of the town and major private capital investment followed (Turner and Daily, 2008).
c) Costa Rica launched a payment scheme for the provision of a suite of ecosystem services, including water quality and quantity, carbon sequestration, biodiversity and

scenic beauty, funded by a diversity of sources, thereby giving farmers an additional income (Turner and Daily, 2008).

d) South Africa has invested in the "Working for Water" programme, the aim of which is to increase water availability by clearing water-thirsty alien invasive plants and, at the same time, create employment (Mander *et al.*, 2011).

2.2.6 Ecosystem services in the South African context

South Africa is a developing country, with a population of over 50 million (Statistics SA, 2011). An emphasis of the post-apartheid government is on economic growth and the upliftment of previously disadvantaged communities (The Government of South Africa, 2010b). There is a drive for economic development, including the mining of natural resources and industrialisation. The population trends are moving towards an urbanised population. There is a desperate drive to generate economic growth and deliver income, jobs and basic services to poor people, who form the country's majority, which politically means development at all costs (Mander *et al.*, 2011). Biodiversity conservation and environmental protection is perceived as a threat to welfare improvement and an obstacle to development. This simple jobs-versus-the-environment paradigm needs to be changed (Mander *et al.*, 2011). The South African development assumptions largely fail to consider the limits of key ecological resources. When it comes to local government, the development drive is informed by two paradigms: the municipal integrated local area development frameworks (IDPs) and the environmental impact assessments (EIAs), which are 'development-plus-impact-assessment' (Crane and Swilling, 2007).

Enabling laws for the beneficial use of environmental resources are in place in South Africa, in order to serve the public interest and to protect the environment as the peoples' common heritage (NEMA, 1998; Stuart-Hill and Schulze, 2010). However, the link between natural capital and poverty reduction has yet to be made by many with decision-making power (Shackleton *et al.,* 2011).

Ecosystem services are vital for environmental performance. In recent studies, the environmental performance index and South African ecosystem vitality (Yale Center for Environmental Law and Policy, 2012; Standard Chartered, 2013) was extremely poor in absolute terms, amongst the poorest performing countries, out of the assessed, and with a declining trend. The ecosystem effect on water resources showed a very strong decline over the past decade (Yale Center for Environmental Law and Policy, 2012).

With regard to studies about ecosystem services provision, however, South Africa is leading the way in Africa (Egoh *et al.*, 2012b). Water, tourism and grazing are found to be important ecosystem services in Africa and have been included in assessments. A big attraction to tourists in South Africa is the landscape, high biodiversity, flowers and scenery, and Africa remains one of the world's most pristine continents. The role of water flow regulation, as well as water filtration to provide clean water, is found to be important in poverty alleviation in South Africa (Egoh *et al.*, 2012 b).

Rouget *et al*. (2010) conducted a partial sectorial analysis for ecological goods and services in South Africa, specialising in carbon sequestration, surface water supply, water flow retention and soil retention. The study found that it is possible to find economic benefit in restoring or conserving natural capital. The potential market was found to be considerable. The challenge, however, is to create the appropriate institutions to develop such markets (Blignaut and Moolman, 2006; Rouget *et al.*, 2010).

2.3 Hydrological Ecosystem Services

Hydrological ecosystem services cover the benefits to people produced by terrestrial ecosystem effects on freshwater (Brauman *et al*., 2007). Water and associated hydrological ecosystem services are fundamental to life. Constraints in providing sufficient, fresh, good quality water are a limiting factor to development in many parts of the world. This is projected to get worse (FAO, 2000) as a result of rising demand, especially because freshwater comprises only 0.26 % of global water. In the 20th century alone, the freshwater extraction increased seven-fold from that before. The major drivers have been population growth, the rising standards of living, the expansion of irrigated agriculture (Gleick, 1998), as well as increased meat consumption (Hoekstra and Chapagain, 2007; WWF, 2012). Resources are limited, and if more resources are needed to cure past and present ills, then less will be available to prevent future degradation (Falkenmark *et al.,* 1999). Freshwater ecosystems are the focus of this study (Section 3ff) and will be introduced next.

2.3.1 Freshwater ecosystems

Freshwater ecosystems are often understood to consist mainly of rivers and riverine areas. A more inclusive view, which is taken here, and is in line with those of McCartney *et al*. (2000) and Jewitt (2002), is that freshwater ecosystems can be understood as landscape elements that link and affect the passage of water from the land to the sea and water as evapotranspiration from the land to the atmosphere. This definition includes the whole terrestrial catchment area. When examining freshwater ecosystems, the entire hydrological cycle needs to be examined, starting from rainfall over the catchment and not only the water in a river or in other water bodies (NWA, 1998; McCartney *et al*., 2000; Jewitt, 2002; FAO, 2007). The hydrological cycle, therefore, will be examined next.

2.3.2 The hydrological cycle with the partitioning of precipitation into blue, green and white water flows

The total amount of water on earth is unchangeable and finite. This unchangeable amount of water moves within the hydrological cycle, albeit differently in different parts of the world and differently from season to season (L'vovitch, 1979). In the hydrological cycle, precipitation is partitioned into runoff flows, through ground and water bodies, and into water vapour flows back into the atmosphere, through evaporation and transpiration processes. This partitioning of precipitation into the evapotranspiration output (also called total transpiration), is often termed "green water", while "blue water" represents the water flows through ground and water bodies (Falkenmark *et al*., 1999; Falkenmark, 2000; FAO, 2000; Jewitt, 2002; 2006). There is a dynamic interrelationship between evapotranspiration and ''blue'' water (Falkenmark *et al*., 1999; FAO, 2000; Jewitt, 2002). Savenije (2004) and Newman *et al*. (2006) request a further separation of evapotranspiration into evaporation and transpiration, which Savenije (1998) outlined as white and green water flows. For the purpose of this study, the approach of Schulze and Maharaj (2008) is followed, where green water is understood to be the soil water taken up by plants to create biomass and transpired by the vegetation to the atmosphere, excluding evaporation. White water is the portion that is evaporated to the atmosphere from intercepted rainfall by plants or buildings, as well as directly from the soil. Blue water is understood to be water flows through ground and water bodies, in this case streams, rivers, groundwater, wetlands, as well as abstracted water. In other words, it is the runoff coming from the partitioning of precipitation at the land surface, which forms streamflow, and the partitioning of soil water, which forms baseflow and the recharge of groundwater.

The hydrological cycle, showing landscape–hydrological ecosystem–atmosphere interactions, is illustrated in Figure 2.7.

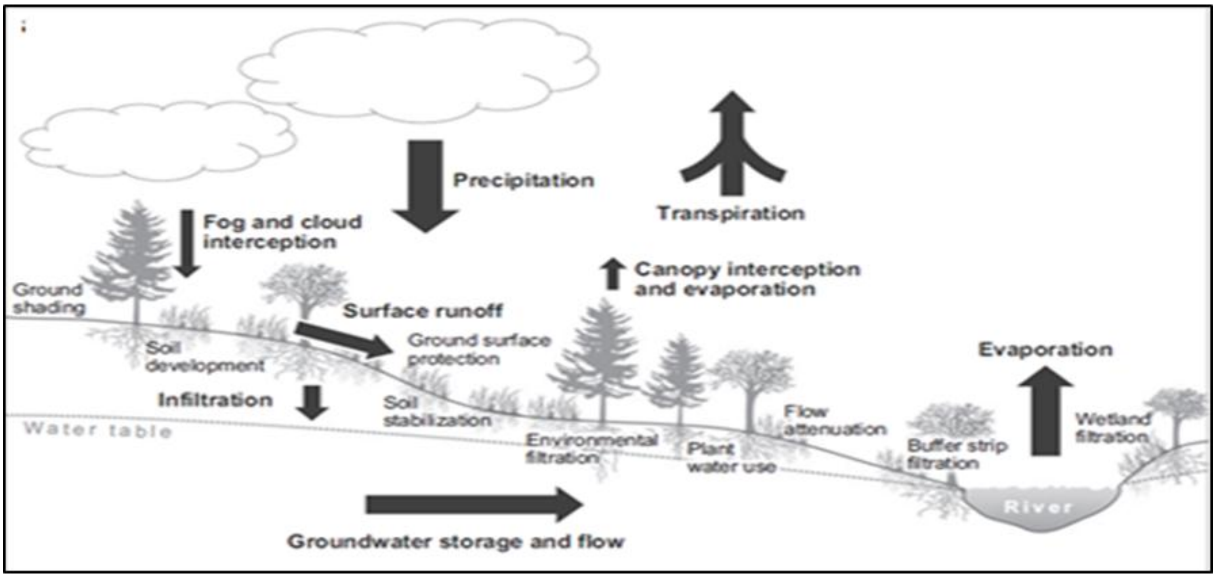

Figure 2.7 The hydrological cycle, showing landscape–hydrological ecosystem–atmosphere interactions (after Brauman *et al.*, 2007)

Humans have influenced the hydrological processes and transformed the landscape to provide freshwater for irrigation, industrial and domestic use. This, in turn, has influenced the hydrological cycle (Foley *et al*., 2003).

2.3.3 Hydrological terminology, processes and responses

Flows through landscape and water stores generally transform high frequency precipitation variability into low frequency modes of hydrological variations (Bounoua *et al*., 2002). These hydrological processes are influenced by climate and land characteristics. The climate influence on hydrological processes are, for example, precipitation and temperature parameters, in as much as they influence evaporative processes and plant growth rates, as well as changes in CO_2 concentrations regarding transpiration feedbacks. Hydrological processes are further influenced by land characteristics such as soil properties, soil water saturation rates, slope, land use, land cover and land management characteristics, which influence soil water evaporation, the infiltration of rainwater and soil erodibility, as well as changes in soil surface properties. While the whole landscape has a role to play in influencing hydrological processes, wetlands and floodplains are often singled out in the literature (e.g. Aylward *et al.*, 2005). They act as natural sponges; expanding by absorbing excess water in times of heavy rain and contracting as they release water slowly throughout the dry season to maintain streamflow (Aylward *et al.*, 2005).

Environmental processes on approximately half of the global land mass are limited by water availability. These so-called water-limited environments include arid, semi-arid and sub-humid regions, and may be understood as areas where the annual precipitation is less than the potential evapotranspiration, with often extreme temporal variability resulting from extended periods with little or no precipitation (Newman *et al.*, 2006). Low flows may be understood as flows of water in a stream during prolonged dry weather and are usually a seasonal phenomenon, while drought is a natural occurrence resulting from less than normal precipitation for an extended period of time (Smakhtin, 2000). The hydrological processes over the catchment control the ability to absorb and store water during precipitation events for later release as low flows, while the processes in the river channel zone are the most relevant for the discharge of stored water into the channel (Smakhtin, 2000). The spatial and temporal components of low flow hydrology are related to physiographic factors, as well as to various man-induced effects (Smakhtin, 2000).

Human demand for water in certain areas might be met the transfer of water from other catchments and within catchments (NWRS, 2004). However, apart from such transfers being expensive, they may also lead to consequences within the receiving, as well as the donating, catchment (WWF, 2009).

Hydrological processes which are relevant for water quantity and pathways through the landscape (Falkenmark, 2000) thus give rise to various hydrological responses e.g. to streamflows, to runoff and its components of stormflow and baseflow, as well as to transpiration, evaporation and sediment yield. The terminology used in this dissertation to describe these hydrological responses is explained next.

a) *Streamflows* have magnitudes, are variable and are spatially distributed. They are made up of runoff accumulated from the entire catchment upstream of a point of interest (Schulze and Maharaj, 2008).

b) *Runoff* is defined here as having been generated from a specific sub-catchment and it may be divided into its components of stormflow and baseflow (Schulze and Maharaj, 2008).

c) *Stormflows* are generated from a specific rainfall event and have unique attributes of magnitudes, rates and carrying capacity of soil particles. They are the main runoff contributors during times of floods (Schulze and Maharaj, 2008).

d) *Baseflows* derive from groundwater storage or other delayed sources and also have unique attributes of magnitudes and rates of release into a stream (Brauman *et al*., 2007; Schulze and Maharaj, 2008) and are typically the biggest contributor to streamflow during dry season low flow conditions (Smakhtin, 2000).

e) *Transpiration* is understood to be the soil water taken up by plants and transpired by the vegetation to the atmosphere, and in the process they create biomass (Schulze and Maharaj, 2008).

f) *Sediment yields* consist of the soil detached from a landscape after a rainfall runoff event. The soil reaches the stream and results from the interaction of slope, vegetation cover and management characteristics, with the peak discharge of an event as the detaching agent and stormflow as the sediment transporting agent. Sediment yields reduce storage capacity in water bodies and slow down streamflows (Schulze, 1995).

Cilliers *et al.* (2013) call for an understanding of land–water interactions based on processes and links between different components, an understanding of their function and structure, as well as the temporal and spatial scales at which they are dominant or dormant. Hydrological processes give rise to hydrological ecosystem services, which will be examined next.

2.3.4 Hydrological ecosystem services and their importance, with examples and categorisations

Hydrological ecosystem services can be understood as the benefits to people produced by terrestrial ecosystem effects on freshwater (Brauman *et al.*, 2007). Precipitation is the ultimate source of water on earth (Mirza and Patwardhan, 2005) and therefore the source of associated hydrological ecosystem services. The understanding is that a certain amount of water can be utilised before the ecosystem loses resilience. However, a level of ecological functioning and integrity is required for maintaining resilience (MacKay, 2000; 2001). It needs to be understood that both ecosystems and the hydrological cycle require adequate multi-level functioning. Failure on one system level will ultimately result in the failure of the entire system. To sustain ecosystem functions, as well as to maintain sustainable water supplies, the amount of water that can be abstracted from a stream system is limited (FAO, 2000; Jewitt, 2002).

Hydrological ecosystem services contain more than just freshwater provisioning services. The hydrological cycle plays many roles in the earth's systems of climate, chemistry and biology and it is difficult to define distinct supporting, regulating, cultural or provisioning service categories (Mirza and Patwardhan, 2005). An attempt to divide hydrological ecosystem services into such provisioning, supporting, cultural and regulating services was compiled by Aylward *et al*. (2005), where provisioning services include sustained quantities and an acceptable quality of water from inland water ecosystems, the variability and seasonality of flows and whether flows are perennial or ephemeral. They make this water available for consumptive uses, e.g. for drinking, domestic, agricultural (dry land and irrigation) and industrial purposes, as well as for non-consumptive uses such as power generation and transportation/navigation. Supporting services include soil water essential for primary production, nutrient cycling and the resilience of the natural hydrological system to extreme events. Cultural services contribute to human well-being through, for example, recreational activities, tourism and scenic values and existence values, such as the satisfaction gained from free-flowing rivers (Aylward *et al.*, 2005). Regulating services include the maintenance of water quality through natural filtration and natural water treatment, the buffering of flood flows and erosion control by floodplains and wetlands. (Aylward *et al.*, 2005; Le Maitre *et al.*, 2014).

Different approaches in classifying hydrological ecosystem services, or trying to link them with functions, processes and attributes, were found in the literature (e.g. Aylward *et al*., 2005; de Groot, 2006; Brauman *et al.*, 2007). These various approaches regarding hydrological ecosystem services, with an emphasis on provisioning, regulating and supporting services relevant for this study, have been combined and are shown in Table 2.1.

This table is not meant to be an exhaustive list of hydrological ecosystem services and the processes that give rise to them, but serves to derive an approach suitable for this dissertation.

Table 2.1 A summary of relevant ecosystem functions, processes, hydrological attributes and services as found in the literature (Sources: Aylward *et al.*, 2005; de Groot, 2006; Brauman *et al.*, 2007)

Ecosystem Functions	**Ecosystem processes and components**	**Hydrological attribute**	**Example of services**	**Author**
Provisioning			Water (quality and quantity) for consumptive use (for drinking, domestic, agricultural or industrial uses)	Aylward *et al.*, (2005)
			Water for non-consumptive use (for generating power and transport/navigation)	
			Aquatic organisms for food and medicines	
Regulation function: Disturbance prevention	Influence of ecosystem structure on dampening environmental disturbances		Flood prevention	de Groot (2006)
Regulation function: Water regulation	Role of land cover in regulating runoff and river discharge		Drainage and natural irrigation	de Groot (2006)
Regulation function: Water supply	Filtering, retention and storage of fresh water		Provisioning of water for consumptive use (e.g. drinking, irrigation, industrial uses)	de Groot (2006)
Regulation	Natural filtration and water treatment		Maintenance of water quality	Aylward *et al.*, (2005)
	Water/land interactions and flood control infrastructures		Buffering of flood flows and erosion control	
Regulation function: Soil retention	Role of vegetation root matrix and soil biota in soil retention		• Maintenance of arable land • Prevention of damage from erosion/siltation	de Groot (2006)
Supporting			• Role in nutrient cycling (role in maintenance of floodplain fertility), primary production • Predator/prey relationships and ecosystem resilience	Aylward *et al.*, 2005)
Habitat functions: Refugium and nursery function	Providing suitable living and reproduction habitat		• Maintenance of biological and genetic diversity (basis of most other functions) • Maintenance of commercially harvested species	de Groot (2006)
Production functions: Food,	Provision of natural resources, Conversion of solar energy into edible plants and animals		• Hunting of fish or game • Small-scale subsistence farming • Aquaculture	de Groot (2006)
Production functions: e.g. Raw materials	Provision of natural resources, Conversion of solar energy into biomass for human construction and other uses		• Building and manufacturing • Fuel and energy • Fodder and fertilizer	de Groot (2006)
Functions supporting cultural services			Cultural services: • Recreation (river rafting, kayaking, hiking, fishing as a sport) • Tourism (river viewing) Existing values (personal satisfaction from free-flowing rivers)	Aylward *et al.*, (2005)
• Local climate interactions • Water use by plants		Quantity (surface and ground water storage and flow)	Diverted water supply: • Water for municipal, agricultural, commercial, industrial, thermoelectric power generation uses In situ water supply: • Water for hydropower, recreation, transportation, supply of fish and other freshwater products Water damage mitigation: • flood damage reduction • dryland salinization • saltwater intrusion • sedimentation	Brauman *et al.*, 2007
• Environmental filtration • Soil stabilisation Chemical and biological additions or subtractions		Quality (pathogens, nutrients, salinity, sediment)		
• Soil development • Ground surface modification • Surface flow path alteration • River bank development		Location (ground/surfaces, up/downstream, in/out of channel		
• Control of flow speed • Short and long-term water storage • Seasonality of water use		Timing (peak flows, baseflows, velocity)		

Hydrological ecosystem services are essential, *inter alia*, for terrestrial production and biological diversity. The availability of hydrological ecosystem services is influenced by the condition of the hydrological ecosystem and the water allocated to sustain its functioning (cf.

Figure 2.6 for hydrological cycle–ecosystem interactions). Water and hydrological ecosystem services are essential to life and have common, or public, goods characteristics. Services that are based on freshwater ecosystems are often taken for granted, because they become available with no, or minimal, investment. It is, therefore, difficult to account for their full economic value, which often becomes evident only once lost (Daily, 1997). One way to place a value on hydrological ecosystem services is to compare them to the cost of new infrastructural projects that are required to replace them, if this is possible (Gleick, 2000).

The serious consequences of reduced hydrological ecosystem services are, *inter alia*, an increase in the occurrence and magnitude of flood and drought events. Drought and flood disasters are statistically the most reported natural disaster events, with millions of people being affected (UN, 2007). To reduce the potential damage from droughts, floods and alterations related to habitat functions, hydrological ecosystem services need to be sustained and invested in. To be able to monitor changes to hydrological ecosystem services, suitable indicators are often required, which will be examined next.

2.3.5 Relevant indicators

Changes to hydrological ecosystem services often cannot be measured directly. This is especially so for case studies with different scenarios, and for some provisioning and many regulating, supporting and cultural services. Frequently, indicators or proxy information are used in practice to measure ecosystem services (Egoh *et al.*, 2012a). Those indicators are a measure of an attribute that can provide the required information. The quantity and quality of water integrates many processes occurring within the catchment. Some of these processes can be measured directly or indirectly by measuring an attribute that can provide information on those processes (Jewitt, 2002).

Streamflow, as well as runoff and its components, are often considered useful indicators of the health of the hydrological ecosystem services (Brauman *et al.*, 2007). Blue water indicators are, however, a delayed response to events within the ecosystem (Jewitt, 2002). Furthermore, the magnitude and duration of low flows and high flows, rather than mean flows, might be more important to ecosystem services in water-limited environments (Nilsson *et al.*, 2003; Jewitt, 2006; Schulze and Horan, 2007). Sediment yield, conversely, is an indicator of water quality, along with *E. coli* bacteria counts and nutrient concentrations, e.g. of nitrates, phosphates, heavy metal.

Owing to the complex processes related to the biophysical sciences behind regulating services, e.g. the regulation of water flows, or erosion prevention and/or the moderation of extreme events, single indicators are often not adequate and process-based modelling often becomes the best option (Egoh *et al.*, 2012a). In their review of 67 scientific papers concerned with practical ecosystem services quantification, Egoh *et al*. (2012a) found that runoff was frequently used as a proxy for surface water availability, followed by land cover (Figure 2.8.). For mapping water regulating services, the main indicators used were nutrient retention, land use and soil characteristics (Figure 2.9), with their definition being that water provisioning services relate to the water that is already available, while regulating services relate to a process through which clean water becomes available. For the ecosystem service of the control of soil erosion, the main indicators used were the type of vegetation cover and the soil erosion potential.

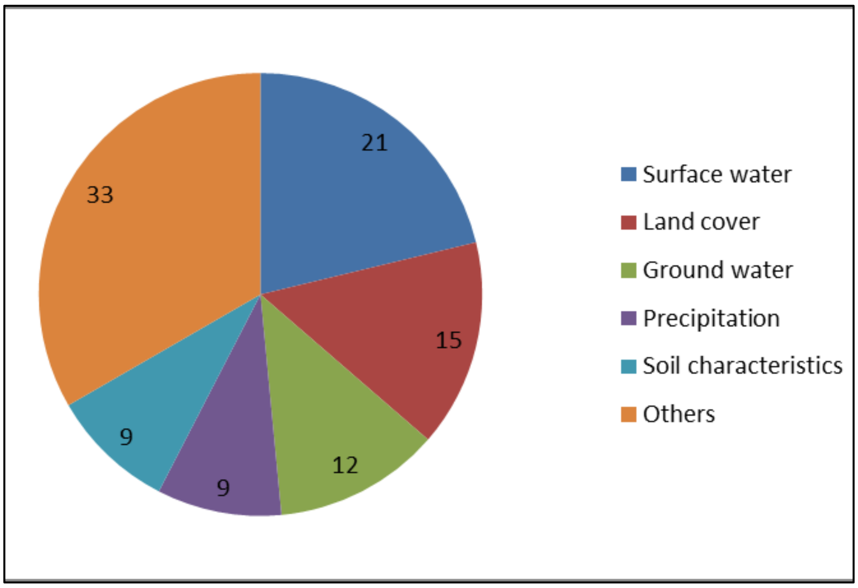

Figure 2.8 Indicators used in practice for mapping the ecosystem service of water provisioning (after Egoh *et al*., 2012a)

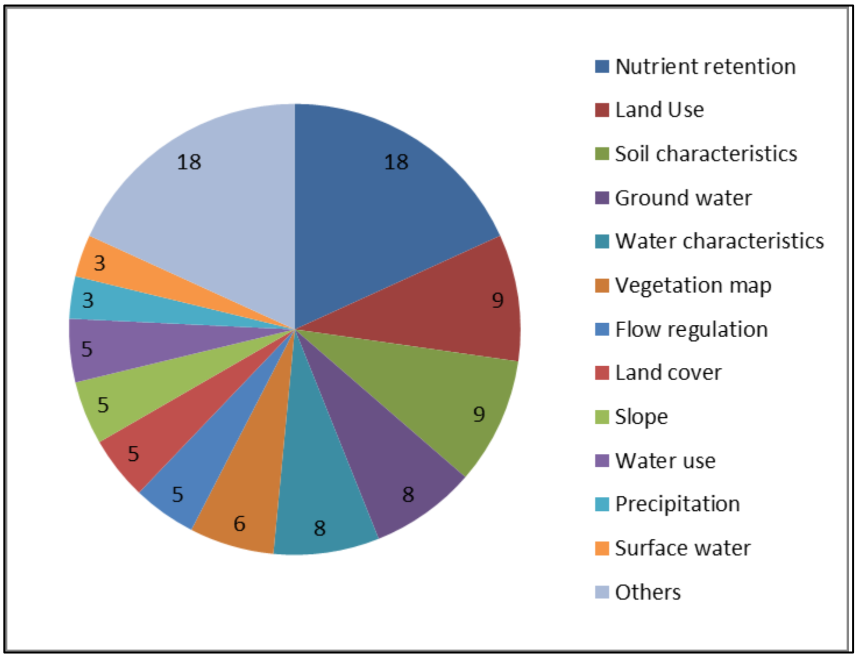

Figure 2.9 Indicators used in practice for mapping the ecosystem service of water regulation (after Egoh *et al*., 2012a)

For the purpose of this study a hydrological process model is used with measured biophysical data as input and hydrological responses, e.g. runoff and its components of stormflow and baseflow, accumulated streamflow, extreme runoff events, sediment yield and transpiration, as modelled outputs. These hydrological responses are seen as proxy information, or indicators, for the ecosystem services of water provision, water regulation (e.g. flood attenuation and erosion control) as well as supporting services (e.g. the supply of green water for primary production), as described in Sections 4.4 and 5.7.

2.3.6 Hydrological ecosystem services in a South African context

Overall, South Africa faces shortages in water and these affect hydrological ecosystem services. South Africa is generally a water-limited country, with major spatial and temporal variations in rainfall and hence runoff. Within semi-arid environments, the green (and white) water flows dominate over blue water flows (Jewitt, 2006).

Its natural hydrology creates a high–risk natural environment (Schulze, 2003). A low mean annual precipitation, as well as a low rainfall-to-runoff rate of conversion is exacerbated by high inter-annual rainfall variability. This inter-annual variability is amplified in the responses of the hydrological system (Schulze, 2003). Over much of South Africa, terrestrial and freshwater ecosystems are not in pristine condition, but rather in a modified and often damaged state, usually through unsustainable human exploitation and often linked with the failure to enforce policy together with a lack of structured and effective governance (Maloti Drakensberg Transfrontier Project, 2007; Lankford *et al.*, 2011).

Many catchments in South Africa are water stressed. Total water availability, including requirements for food production, is expected to decline to below 1700 m^3/person/year, which makes the country vulnerable to serious water shortages by 2030 (Scholes and Biggs, 2004). New big dam infrastructures, inter-basin transfer schemes, high levels of assurance of supply to key sectors of the economy, as well as widespread local reticulation networks, requiring extensive pumping and associated energy use, are expensive and the cost of water provisioning is set to rise (The Government of South Africa, 2010a). Just a 10 % decline in runoff is estimated to double the cost of new water schemes (The Government of South Africa, 2010a). Like most of the rest of the world South Africa has, historically, focused its water resource management approach on controlling part of the hydrological cycle, mainly through building water infrastructures, including dams, to provide sustained water supplies and to reduce threats of water shortages and to thus produce less variable flows. Inevitably, this natural resources management approach resulted in a reduction in the natural diversity of ecosystem functions, associated ecosystem services, as well as ecosystem resilience. In the decision-making process, ecological functioning may have often been ignored, owing to a lack of scientific understanding, as well as the difficulties faced by planners and policy-makers to feature the uncertainties within the ecosystem functions and dynamics (Jewitt, 2002).

2.3.7 South African water legislation related to hydrological ecosystem services

Progressive new water laws came into effect at the end of the 1990s (Water Services Act (WSA), 1997; National Water Act (NWA), 1998). Healthy aquatic ecosystems are considered to be the cornerstone of water resources and are required for equitable access to water as well as for development. The water resource can, therefore, be seen as an ecosystem which includes water, aquatic habitats, as well as the ecological, physical and chemical processes linking habitats, water and all organisms in the given area (MacKay, 2000). Legislation stipulates that a "reserve" will be determined on all river systems. This reserve is defined as the assurance of the quantity and quality of water required to meet basic human needs, as well as to protect aquatic ecosystems, in order to secure sustainable utilisation and development (NWA, 1998).

However, the implementation of laws and policies has been difficult and slow (Schreiner, 2013). At the time of writing this in 2013, 15 years after the NWA came into effect, only few ecological reserves have been determined and implemented. A number of misunderstandings and gaps exist concerning the intention of the law and its implementation (Jewitt, 2002; van Wyk *et al.,* 2006). There are warnings that the land-water link has been neglected and that that ill-considered responses to rising freshwater demands could sever ecological connections within the hydrological cycle (Jewitt, 2002; Gifford, 2011). Van Wyk *et al.* (2006) state that South Africa's water law acknowledges not only water, but the entire ecosystem, as a life support system. This realisation is not widely appreciated because no common understanding exists in South Africa of the reserve being an ecological means to achieving socio-economic ends.

This may be seen in a recent South African policy document (DWAF, 2009) in which it is unclear on the link between water and ecosystem services, yet acknowledging that natural resource management is essential for ensuring water supply for growth and development. The public works natural resource management programmes, e.g. Working for Water, for Wetlands, on Fire, for Woodlands and Working for Energy, are seen as very important to the management of South African water quantity and quality and essential to growth and development (DWAF, 2009). Resource management is understood to yield the best returns on investment for water management, but with the added benefits of other ecosystem services, as well as job creation. On the other hand, the same policy document states, for example, that "developed rivers, such as the uMgeni, are today no more than 'workhorse rivers' and should be managed as such", with no clear indication of what that implies (DWAF, 2009, p. 46).

Based on the above, the implementations of the water laws have been slow and not without problems and misunderstandings, which, amongst other things, lead to reducing hydrological ecosystem services in South Africa. While investigating hydrological ecosystem services in the section above, land use in an ecosystem services context will be examined next.

2.4 Land Use within an Ecosystem Services Context

In this section, land as a physical resource, including the roles of land function, land cover and land uses, will be explored, and followed by a general perspective on the links of land use changes and ecosystem services. Finally, land use in a South African context will be examined.

2.4.1 Land cover and land use

Land may be viewed as a physical resource. Land cover describes the biophysical state of the earth's surface and immediate subsurface in broad classifications, such as grasslands, natural forest, cropland, water bodies or mining (Turner *et al.*, 1995). Land use frequently involves the conversion or modification of natural land cover as a result of human actions, for the primary purpose of agricultural production and settlement (Turner *et al*., 1995). The term land use can be further broken down into land utilisation, land treatment and land management, which include the specific crops, conservation structures (contours, terraces), grazing control, crop rotation or the intensification of production, different modes of tillage practices, burning regimes, as well as the application of fertilizers and herbicides (Schulze, 2004).

Although land has many uses, it is often zoned, based on a single purpose in planning frameworks (Hubacek *et al.*, 2009). The multi-functionality of land provides several potential ecosystem services (Hubacek *et al.*, 2009). There are many studies illustrating the economic, ecological and socio-culturally benefits of multi-functional landscapes, compared to landscapes that only provide few ecosystem services (e.g. Balmford *et al*., 2002; Turner *et al*., 2003; Naidoo and Adamowicz, 2005, Hermann, *et al*., 2011).

Many forms of land uses alter or degrade ecosystems. Ecosystem services thus respond to land use and the changes thereof (Foley *et al.*, 2005).

2.4.2 Land use and ecosystem services

Land use, in an ecosystem services context, is all about coordinating the long-term and the short-term, the small-scale and the large-scale, the public interest and the private interests, the economy and the environment (Lowe *et al.*, 2009). Ecosystem services provided by a landscape, e.g. the availability of water, will often determine the land use and, thereby, influence land use change. For example, agriculture and forestry require a certain level of water availability. Conversely, land uses influence ecosystem services, with property rights often being unclear on the rights or duties of the land user in respect to the ecosystem services that this land provides (Carpenter *et al.*, 2006; Lowe *et al*., 2009).

The effects of land use on ecosystem services are complex and interdependent. Land use change from natural land cover often leads to ecosystem degradation, which may be slow or abrupt (Carpenter *et al.*, 2006). Impacts might not be observable on a larger spatial scale, because of the self-cancelling effects and therefore no action may be taken. Land use impacts depend on the type of use, their intensity and spatial extent (Hobbs, 2000; Schulze, 2004). Land use changes may lead to utilised, replaced or completely removed ecosystems *vs.* conserved ecosystems (Hobbs, 2000).

Human activities, including various uses of land, are driven by several factors, generally placing increasing demands on resources. These factors include a growing population and their basic life support needs, including wants above the level of mere life support needs, and economic growth aspirations, which include both the needs and wants of people (Falkenmark *et al.*, 1999). Winter and Lobley (2009) perceive a strong link between the importance of land and the survival of the human species.

Land use is often changed to satisfy immediate human needs and usually leads to a reduction in ecosystem functions and, therefore, to trade-offs (Foley *et al.*, 2005). When taking trade-offs into account, a scenario of big gains for immediate human needs, but small losses for ecosystem functions, should be aimed at (Foley *et al.*, 2005). Large-scale development schemes that require major changes in land use often turn out to be less profitable than improving the sustainable management of the unaltered ecosystem (de Groot, 2006). Furthermore, modern agricultural land uses may be trading short-term increases in food production for long-term ecosystem services losses, including those that are important for agriculture (Foley *et al.*, 2005). In addition, whilst there is a current worldwide trend towards urbanisation, the resulting land use change is likely to lead to a reduction in the potential local supply of ecosystem services, while the amount available per capita is further decreased through a locally increasing human population (Eigenbrod *et al.*, 2011).

Whilst most environmental problems surface on a regional or global scale, the solutions are at the local and individual levels (Mouratiadou and Moran, 2007; Cowling *et al.*, 2008). Local conservation, land management and stewardship determine local ecosystem responses that make up regional, national and, eventually, global ecosystem responses. Land use planning provides an opportunity for mainstreaming ecosystem services. Land use decisions should be made on the basis of ecological validation studies and the persistence of ecosystem services, including scenarios of alternative futures, with the goal of achieving social and ecological resilience in an uncertain world (Cowling *et al.*, 2008).

2.4.3 Land use and land use change in the South African context

Land use in South Africa is highly varied. In 2010 almost 20 % of the land area had been transformed, with the main land uses being crop cultivation (12.1 %), forestry (1.5 %), urban built up (1.1 %) and land degradation (5 %; DEA, 2010). Only 6 % of land is under formal protection in 1999 (Barnard and Newby, 1999). The recent tendency has been an increased rate of transformation from natural land cover to various land uses (Gbetibouo and Ringler, 2009). Projections in some provinces are that if the current trends are followed, there will be no natural land cover left by 2050 outside of protected areas (Jewitt, 2012). Another development is that South Africa's population is urbanising. Despite many policy statements favouring compact cities, the trend seems to be towards low density urban sprawl along road transportation routes (Crane and Swilling, 2007). To try to reduce the amount of natural land cover lost, the South African conservation authorities have initiated a stewardship programme with landowners to help them manage their land in a sustainable way and thereby also maintain ecosystem services that this land provides. Private landowners can voluntarily be part of stewardship programmes (Egoh *et al.*, 2012b).

From a legislative perspective, recent South African land use classifications aim at unifying land uses and give a broad list of scheduled land use purposes (The Government of South Africa, 2011). The term land use management is further defined to include the regulation of land use changes. Land use changes include the rezoning of a property from residential to commercial use, the regulation of the development of previously undeveloped land, termed 'green fields', as well as the regulation of the consolidation and subdivision of land parcels (The Government of South Africa, 2001). Furthermore, legislation stipulates that every municipality requires a land use management system, with certain minimum requirements having to be met. While land use is varied globally and in South Africa, it is linked to hydrological ecosystem services and *vice versa*. This link will be presented next.

2.5 The Link between Land Use, Hydrological Responses and Hydrological Ecosystem Services

Ecosystem services, which include hydrological ecosystem services, as well as land use and climate, form a complex and interdependent system with feedbacks and linkages (Turner *et al*., 1995. They are further influenced by human population pressures (Figure 2.10).

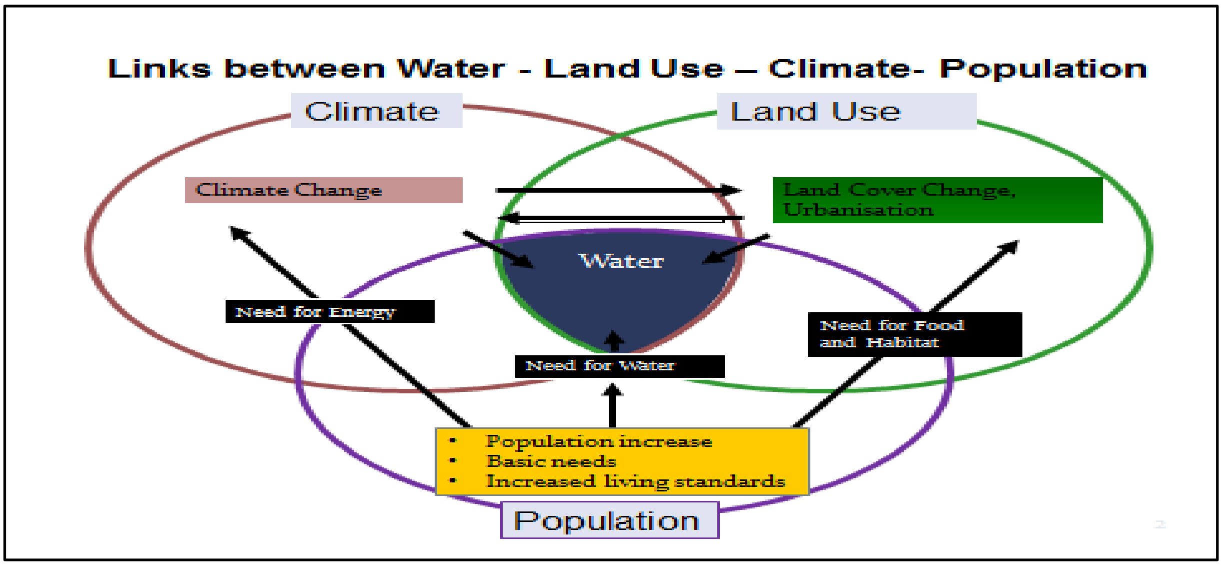

Figure 2.10 A schematic of the climate–land use–population–water interactions (adapted from Schulze, 2007)

Land uses, being water-related, are often dependent on hydrological ecosystem services, while they might, at the same time, impact those (Brauman *et al.*, 2007). This relationship is thus interdependent and, therefore, complex (Falkenmark *et al*., 1999). Forecasting the effects of land use change on stream ecosystems is a challenge, with interdisciplinary approaches being important for future ecosystem management (Nilsson *et al.*, 2003). Especially in water-limited environments, Newman *et al.* (2006) postulate that an interdisciplinary, collaborative approach of ecohydrology is required for the effective management of environmental problems in the critical zone of those environments. It is widely acknowledged that land uses influence hydrological responses, and these influences are discussed next.

2.5.1 Selected land uses and their influence on hydrological responses

Land uses influence hydrological responses of a catchment by influencing the partitioning of rainfall between returns to the atmosphere, as evaporation or transpiration, and flows to rivers and aquifers (Falkenmark *et al.*, 2000; Hope *et al*., 2004, Foley *et al*., 2005). Multiple processes control the quantity, quality and water flow regime. This poses a significant challenge to both management and scientific understanding. The pattern and extent of cities, transport routes, agricultural and natural areas within a catchment influences runoff patterns, infiltration properties and evapotranspiration rates. This, in turn, affects water quantity and quality (Vörösmarty *et al*., 2005). The impact of land use change on hydrological responses is further complicated by changing climates, as well as the changing dominance of different factors at different spatial and temporal scales.

Several effects of relevant land use types on hydrological responses have been identified by various authors and are described next. More examples may be found, for example, in Falkenmark *et al.* (1999). Most rivers today are altered (Ricciardi and Rasmussen, 1999) and so are the low flow regimes and the origin of water in a stream during low flow conditions (Smakhtin (2001). Anthropogenic impacts on low flow generating processes include groundwater abstraction within the sub-surface drainage area, the artificial drainage of valley bottom soils, changes in the vegetation regime, afforestation and deforestation (Smakhtin 2001). Commercial plantation afforestation leads to a reduction of stormflows (up to a point), as well as to reduced groundwater recharge (Gush *et al.*, 2002). Agricultural practices, such as ploughing and tillage, alter the partitioning of rainfall into stormflow and baseflow components, depending on whether conventional or conservation practices are followed (Lumsden *et al.*, 2003). Smakhtin (2001) hypothesises that conservation strategies, including contouring, terracing and mulching, are expected to reduce runoff volumes. Grazing, depending on conditions and management, might increase or decrease stormflows, soil losses and groundwater recharge (Schulze and Horan, 2007). Land use changes resulting in degradation often increase flow variability (Schulze, 2003; Maloti Drakensberg Transfrontier Project, 2007), and are thought to reduce soil water retention, water infiltration and as a result groundwater recharge and increase overland flow, while invasive vegetation, which replaces indigenous vegetation, might increase water use (Le Maitre *et al*., 2007). Land infested by alien invasive plants that spread, often as a result of poor land management, especially in riparian zones, is often associated with reductions in streamflows (Jewitt *et al.*, 2003). Intensive agriculture often increases erosion and hence the sediment load, thereby degrading water quality (Foley *et al.*, 2005). Dams can cause changes in natural flooding regimes, which impact on the various provisioning, regulating, supplying and cultural hydrological services to downstream communities (Lankford *et al.*, 2011) and directly influence low flows (Smakhtin, 2001). Irrigation water use reduces freshwater supplies downstream of the abstraction point and is globally the biggest water user (Gleick, 1998; Foley, *et al.*, 2005). Urbanisation substantially degrades water quality (Foley *et al*., 2005). Urbanisation also leads to a reduction of the ecosystem service of flood mitigation, because reduced permeable areas lead to larger floods and more frequent small floods, while more people are being affected by these floods, because of denser settlements and/or settlements on floodplains (Eigenbrod *et al.*, 2011). Human settlements, with high proportions of impervious areas, are predicted to lead to higher stormflows, higher peak discharges, lower baseflows and frequently to a deterioration of water quality (Schulze, 2004). Nilsson *et al.* (2003) postulate that the urban impervious urban surfaces limit infiltration and should therefore lead to reduced groundwater levels and low flows; however, leaking urban water supply networks and the irrigation of gardens might lead to greater complexity in the system. Falkenmark *et al*. (1999) found increased streamflows as a result of urban growth and an increase of ground water levels, thought to be from leaking water and sewerage pipes, septic tanks and excessive garden irrigation. Smakhtin (2001) found that low flows in urban areas usually decrease as a result of the effects of impervious areas on runoff, infiltration and evapotranspiration, while direct effluent flows into river channels can significantly reduce the water quality and therefore limit its availability for downstream users. The relative quantitative impacts of anthropogenic influences vary substantially in different river catchments (Smakhtin, 2001).

While the above examples mostly refer to the hydrological responses pertaining to the blue water portion of the hydrological cycle, the evaporation or transpiration portion is also of importance. For urban areas, reduced vegetation cover, impervious surface areas and the morphology of buildings contribute to lower cooling through reduced evapotranspiration, compared to surrounding rural areas, which leads to storage of heat and the warming of the surface air, thereby creating urban "heat islands" (Arnfield, 2003; Foley *et al.*, 2005).

Furthermore, the conversion of vegetation cover is an important contributor to climate change, which is a major driver of hydrological responses, not only on a global scale due to release of carbon from the soil, but also regionally (Foley, *et al*., 2005), because changes in vegetation type, reduction in density and increase in albedo can cause changes in the active regulation of water and energy fluxes and might even result in lower local rainfall in certain places (Hutjes *et al*., 1998). Land cover changes (from forest to agriculture) in the tropics have been found to affect local climate through water balance changes, while boreal vegetation changes have been found to have a big effect on local climate through changes in surface radiation balance (Bounoua *et al*., 2002; Foley, *et al*., 2005). The effects of land cover conversion on climate can be seen on a regional scale, rather than on a global scale (Bounoua *et al.,* 2002). The author could not find studies on the influence of land use change on microclimate within the sub-tropics or semi-arid environments, which seems to be a knowledge gap.

The following is a summary of the key influences of various land uses on hydrological responses and effects, as found in the literature:

a) Runoff generally increases when natural vegetation is cleared (Foley *et al*., 2005).
b) Land use change upstream might lead to negative external impacts downstream (Hope *et al*., 2004).
c) The influence of land use change on hydrological ecosystem services can vary from being negligible to being severe, with possible major hydrological changes in respect of total streamflows, the seasonality and responses of flows, e.g. higher peaks and shorter peak lag times, as well as the partitioning of flows into baseflow and/or stormflow (Brauman *et al*., 2007; Schulze and Horan, 2007).
d) The impact of land use often depends on its intensity and may result in a considerable hydrological lag time. Depending on the land use change, a change in annual runoff may be severe and either increase or decrease, with the land use change also influencing total evaporation and water quality (Schulze, 2003; Warburton *et al*, 2012).
e) The evidence of land use change on a small scale is often diminished on a larger scale (Schulze *et al*., 1998).
f) Urban areas were generally found to increase stormflows; however, some authors found increases and others decreases of low flows or baseflows.

In general, the land use in the catchment is critical for hydrological responses and associated ecosystem services (Jewitt, 2002; Schulze, 2003). The impact of land use within a water-limited South Africa is most significant during periods of low flow, when natural land use is often dormant, and it thus has the highest relative impact on streamflow. This is also the time when people and natural systems most require water (Jewitt, 2006). Low flows are, therefore, better indicator of impacts of land use than mean annual flows (Jewitt, 2006).

The integration of land use planning and management with water resources planning and management is crucial (Falkenmark *et al*., 1999; Jewitt, 2006; Warburton *et al*., 2010). Water pathways, flows and quality are determinants of land use practices (Falkenmark *et al*., 1999). The manner and extent to which freshwater ecosystems and their catchments are either well-managed or misused by humans, largely determines the attributes of the water resource over an area. To maintain the water supply in a stressed system, considerations about land use and management, therefore, become critical. Innovative smaller-scale, locally-managed, water-conserving land management methods are often more cost-effective and less disruptive to local communities than major new water infrastructure projects, as has been found internationally (Gleick, 2000) and in South Africa (Maloti Drakensberg Transfrontier Project, 2007). It is critical to encourage and develop water-sensitive, resilient land use planning, including urbanisation, because of the impact of urban areas on their wider hinterland, as well as considering the vulnerability of poor urban communities to land use change. Urban areas should be considered as 'problem sheds' within catchments. Human-transformed systems need to be seen as part of ecosystems and be managed to contribute to ecosystem services (FAO, 2007).

2.5.2 The link between land use and hydrological ecosystem services

This dissertation aims at contributing towards filling knowledge gaps regarding the links between land use and hydrological ecosystem services. The reader is referred to Section 2.3.4 on various links between hydrological ecosystems and functions, processes and attributes as found by different authors.

Case studies in South Africa, using scenario modelling, found that upstream land use change, e.g. the conversion of natural vegetation to commercial afforestation and/or irrigated agriculture, has the potential for increased production and employment, but the apportionment of the catchment water has negative impacts for downstream communities. The rural poor are the most vulnerable because their livelihood is more dependent on local natural resource use, which is a frequently undervalued ecosystem service that might occur in addition to benefits from dryland rangeland agriculture (Hope *et al.*, 2004).

Various findings exist in the literature regarding links between land use and ecosystem services related to freshwater habitat functions. Human activity has been a primary factor in the modification of the eco-hydrological system (Newman *et al.,* 2006), with flow modification, water pollution and habitat degradation being amongst the main drivers of freshwater biodiversity reduction (Dudgeon *et al.,* 2006). Land use change is associated with altered flood regimes and increased sediment channel input, affecting particle size, particle distribution, bed mobility and suspended sediment loads (Nilsson *et al.*, 2006). Increased river sediment loads can lead to habitat alterations, such as the clogging of river bottoms, shoreline erosion, the smothering of shoreline habitats or floodplain degradation (Dudgeon *et al.,* 2006). For example, in some places freshwater fauna extinction was found to be four times as high as terrestrial fauna extinction. The increased extinction rate is linked to extensive habitat deterioration, resulting from sediment loading, pollution and flow regulation resulting from land use activities (Ricciardi and Rasmussen, 1999). River flow is a major determinant of physical habitat in streams, also determining biotic composition (Bunn and Arthington, 2002; Nilsson *et al.*, 2006). Aquatic species have evolved primarily to the local natural flow regime. Catchment land use change and associated water resource development inevitably lead to changes in the flow regime, e.g. to the increased stability of baseflow and reduction of flow variability, erratic patterns in flow below dams and the conversion of flowing stream habitat to standing lake habitat. These influence the habitat function, resulting in an alteration of the biology, a decline in aquatic biodiversity, while there is an increased invasion of alien invasive species (Bunn and Arthington, 2002). Newman *et al.* (2006) call for the potential rapid advance in understanding environmental processes by linking the more reductionist approaches of hydrology, with the more complex approaches of ecology into ‘ecohydrology’, especially in water-limited environments. Richter *et al.* (1997) suggest that near natural flow variation is required to sustain ecological processed and proposed a ‘range of variability approach’ for setting streamflow-based river ecosystem management targets.

A more in depth discussion on the links between the supporting ecosystem services of biodiversity, and river flows can be found e.g. in Baron *et al.* (2002).

2.5.3 Trade-offs within and between ecosystem services resulting from land use change

To be able to support an increased number of people with an accessible, reliable water supply, substantial stabilisation of flows and increased withdrawals over all regions of the world have occurred (Vörösmarty *et al.*, 2005). This has led to trade-offs between human and natural system requirements for services from freshwater. These trade-offs are made both explicitly and inadvertently. The challenge now is to manage fresh water so that the needs of both people and ecosystems are balanced and that ecosystems can continue to provide other services which are essential for human well-being (Mirza and Patwardhan, 2005; Vörösmarty *et al.*, 2005).

Some examples of trade-offs caused by humans include natural flow regime alterations in rivers and waterways, the loss and fragmentation of aquatic habitat, extinction of species, pollution of water, groundwater aquifer depletions, as well as aquatic systems deprived of oxygen (so-called 'dead zones') found in many inland and coastal waters (Mirza and Patwardhan, 2005; Vörösmarty *et al.*, 2005).

Human drivers and their links with ecosystem services (Aylward *et al*., 2005) are presented in Table 2.2, while selected land use change types and their consequences on freshwater provisioning services (Vörösmarty, *et al.*, 2005) are shown in Table 2.3.

Table 2.2 Direct drivers as appearing in the Millennium Assessment (Aylward *et al*., 2005, after Postel and Richter, 2003)

Human Activity (Direct Driver)	Impact on Ecosystems	Services at Risk
Dam construction	alters timing and quantity of river flows. Water temperature, nutrient and sediment transport, delta replenishment, blocks fish migrations	provision of habitat for native species, recreational and commercial fisheries, maintenance of deltas and their economies, productivity of estuarine fisheries
Dike and levee construction	destroys hydrologic connection between river and floodplain habitat	habitat, sport and commercial fisheries, natural floodplain fertility, natural flood control
Diversions	depletes stream flow	habitat, sport and commercial fisheries, recreation, pollution dilution, hydropower, transportation
Draining of wetlands	eliminates key component of aquatic ecosystem	natural flood control, habitat for fish and waterfowl, recreation, natural water purification
Deforestation/land use	alters runoff patterns, inhibits natural recharge, fills water bodies with silt	water supply quality and quantity, fish and wildlife habitat, transportation, flood control
Release of polluted water effluents	diminishes water quality	water supply, habitat, commercial fisheries, recreation
Overharvesting	depletes species populations	sport and commercial fisheries, waterfowl, other biotic populations
Introduction of exotic species	eliminates native species, alters production and nutrient cycling	sport and commercial fisheries, waterfowl, water quality, fish and wildlife habitat, transportation
Release of metals and acid forming pollutants into the atmosphere	alters chemistry of rivers and lakes	habitat, fisheries, recreation, water quality
Emission of climate altering air pollutants	potential for changes in runoff patterns from increase in temperature and changes in rainfall	water supply, hydropower, transportation, fish and wildlife habitat, pollution dilution, recreation, fisheries, flood control

Table 2.3 The type of land use change and its consequences on freshwater provisioning services (Vörösmarty, *et al.*, 2005)

Type of Land Use Change	Consequences on Freshwater Provisioning Service	Confidence Level
Natural forest to managed forest	slight decrease in available freshwater flow and a decrease in temporal reliability (lower long-term groundwater recharge)	likely in most temperate and warm humid climates, but highly dependent on dominant tree species adequate management practices may reduce impacts to a minimum
Forest to pasture/agriculture	strong increase in amount of superficial runoff with associated increase in sediment and nutrient flux decrease in temporal reliability (floods, lower long-term groundwater recharge)	very likely at the global level; impact will depend on percentage of catchment area covered consequences are less severe if conversion is to pasture instead of agriculture most critical for areas with high precipitation during concentrated periods of time (e.g., monsoons)
Forest to urban	very strong increase in runoff with the associated increase in pollution loads strong decrease in temporal reliability (floods, lower long-term groundwater recharge)	very likely at the global level with impact dependent on percent of catchment area converted stronger effects when lower part of catchment is transformed most critical for areas with recurrent strong precipitation events
Invasion by species with higher evapotranspiration rates	strong decrease in runoff strong decrease in temporal reliability (low long-term groundwater recharge)	very likely, although highly dependent on the characteristics of dominant tree species scarcely documented except for South Africa, Australia, and the Colorado River in the United States

In South Africa and elsewhere, it is importance of invest in water, which is a resource which can limit development. An efficient and relatively cheap method of investing in water security is to protect it through prudent land management. In a South African case study, the value accruing from ecosystem services, as a result of the restoration and maintenance of natural capital, was found to be sufficient to be converted into incentives to induce land use management change for the better, for land users and buyers of ecosystem services, e.g. water and carbon (Maloti Drakensberg Transfrontier Project, 2007; Mander *et al*., 2010). Therefore, payment for ecosystem services is seen as a cost savings option for consumers in future water supply augmentation. Payment for water related ecosystem services, especially if it includes other services such as carbon sequestration, was found to be ecologically, hydrologically, economically and institutionally feasible (Maloti Drakensberg Transfrontier Project, 2007; Mander *et al*., 2010).

The above section has showcased several trade-offs in ecosystem services, resulting from actual or proposed land uses. Modelling trade-offs are an important tool and cannot be emphasised enough (Hubacek *et al.*, 2009)

2.5.4 Determining changes in hydrological ecosystem services as a result of land use change, using hydrological models

Some ecosystem services, e.g. water provisioning, may be measured directly by utilising a weir in a river, or dam levels. However, often indicators need to be used, especially when comparing scenarios (cf. Section 2.3.5). Hydrological models may be used to determine hydrological responses as a result of land use change. Models represent a simplified understanding of a system and are especially suitable for what-if analysis. A model is a tool for transferring knowledge from a research plot or catchment to other areas (Schulze, 1995). Process simulation models are suitable for representing complex systems, with interaction between the system's components, and for establishing patterns and trends. Models, however, are limited, as they cannot represent every process in the hydrological cycle explicitly, and thereby also introduce uncertainties. The results thus need to be critically evaluated, to evolve the complex system thinking behind the assumptions and processes within a model (Cilliers *et al.*, 2013).

Hydrological models suitable for the simulation of the interactions between land use and hydrological responses should model the hydrological cycle within the atmosphere-soil-plant-water continuum on the landscape, as well as modelling river flow and its components (Schulze, 2012). The model ideally needs to distinguish between stormflow events, baseflows and sediment yields, generated on an event-by-event basis. Nilsson *et al.* (2003) stress the importance of estimating the magnitude, duration and future changes in flows, including low flows, based on an understanding of the components and processes of the hydrological system, in order to be able to make forecasts of running water ecosystems. Smakhtin (2001) mentions that to model low flow conditions, the model would require regional information for model parameter values which, especially in the case of a daily time step model, is a very difficult task. A model further needs to distinguish explicitly how different land use scenarios are accounted for in their hydrological response (Warburton *et al.*, 2010). The model needs to simulate at appropriately fine time and spatial scales. A daily time step, physical-conceptual hydrological process model such as the *ACRU* model could be considered as suitable for the above (Schulze, 2010). The *ACRU* hydrological model has been verified in South Africa and abroad, and has been used to account for land use change influence on hydrological responses (e.g. Schulze, 1995; Jewitt and Schulze, 1999; Hope *et al*., 2004; Warburton *et al.*, 2010).

While modelling appears a viable option to assess the linkages between hydrological ecosystem services and land use, various uncertainties revolving around land use-related (and other) process representations will be introduced if a modelling approach is used. Further uncertainties include unknown future land use scenarios. However, land use change decisions are continually being made. Therefore, simulations of hydrological responses to plausible scenarios of land use are required (Nilsson *et al.*, 2003). Associated uncertainties should be recognised and, where possible, be constrained (Beven, 2006), rather than used as a reason for not to proceeding with studies of projected future changes (Schulze, 2003; Warburton *et al.*, 2010).

The next section synthesises the above literature review and identifies some knowledge gaps.

2.6 Synthesis and Discussion of the Literature Review, Including Knowledge Gaps

Natural capital and the associated ecosystem services are essential for human existence and need to be sustained and invested in, in order to ensure sustainable development (Daily, 1997; MEA, 2005; Adger, 2006). Because of rapid population growth and higher living standards, resulting in higher resource use, humanity is now at a threshold where future losses may not be able to be compensated for. However, social and economic development, while providing crucial benefits (Foley *et al.*, 2005), results in a trade-off between additional benefits gained from ecosystem services and potential services lost to society (Jewitt, 2002). Trade-offs will always exist and have to be dealt with (Foley *et al.*, 2005). This calls for an in-depth understanding of the value of ecosystem services, their potential benefits and losses, feedbacks and linkages, as well as communication of results to decision-makers. A paradigm shift is required by decision-makers, from considering the environment to be an unlimited resource supplier, to valuing and conserving natural capital for sustainable development. The value of the gross domestic product (GDP) as a measure of development must be looked at critically and discount rates to the present need to be assessed, in order to halt a decline in the services that healthy ecosystems provide. Alternative assessments, such as the ecosystem services approach, need to be considered for decision-making. A schematic of a possible ecosystem services approach, with the links between decision-making, planning and management, ecosystem structure, processes and functions, ecosystem services and values, is shown in Figure 2.11 (de Groot, 2006), with the area of focus within this study highlighted.

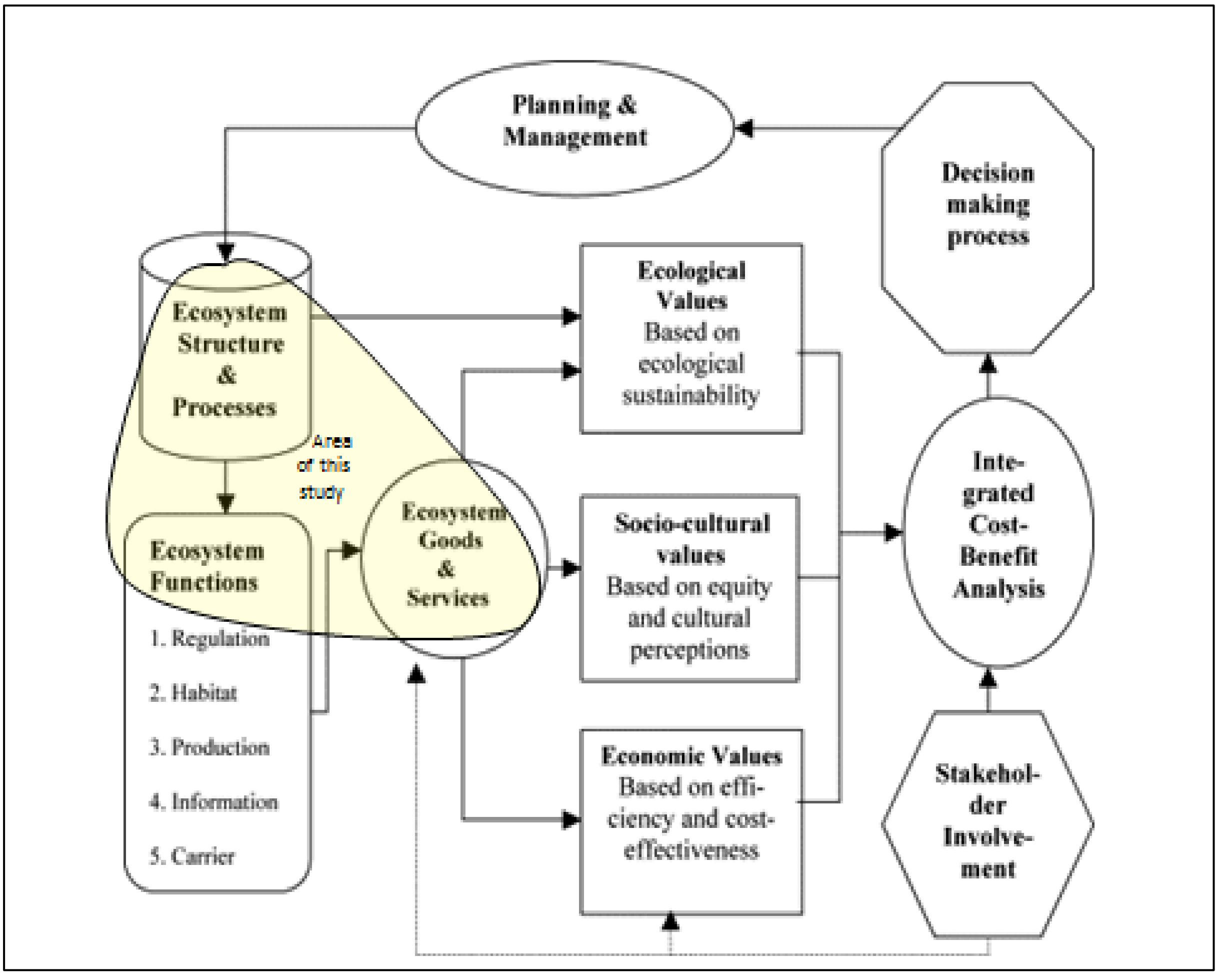

Figure 2.11 A schematic of a possible ecosystem services approach, showing the links between decision-making, planning and management, ecosystem structure, processes and functions, ecosystem services and values (adapted from de Groot, 2006), with the area of focus within this study highlighted

Hydrological ecosystem services form part of services provided by ecosystems. Hydrological ecosystem services were found to be much more than simply freshwater abstraction (Aylward *et al.*, 2005; de Groot, 2006; Brauman *et al.,* 2007). The exact categorisation and naming of hydrological ecosystem services, functions, processes and values varies in the literature. In this study, however, it is not that important in which respective service it is categorised, but rather that a link between land use change, hydrological responses and a beneficial ecosystem service is made, irrelevant of whether it is a direct or indirect ecosystem service to benefit humans.

Changes to hydrological ecosystem services often cannot be measured directly. This is especially valid for case studies with different scenarios as well as for some provisioning and many regulating, supporting and cultural services. Frequently, indicators, i.e. proxy information, are used in practice to quantify ecosystem services, with selected hydrological responses, e.g. runoff, used in practice as indicators for some hydrological ecosystem services (Egoh *et al.*, 2012a). Owing to the complex hydrological processes, modelling often becomes the most adequate option (Egoh *et al.*, 2012a). It needs to be borne in mind that outputs from a model are not absolute representations of reality.

Land cover and land use can have a major influence on hydrological responses (e.g. Falkenmark *et al*., 1999; Brauman *et al.,* 2007). Land cover affects interception, infiltration, overland flow, groundwater recharge and evapotranspiration, all of which affect streamflow. Examples of the land use influencing hydrological flows abound (e.g. Falkenmark *et al*., 1999; Smakhtin, 2001; Gush *et al.*, 2002; Lumsden *et al.*, 2003; Nilsson *et al.*, 2003; Schulze, 2004; Foley *et al*., 2005; Vörösmarty *et al.*, 2005; Eigenbrod *et al.*, 2011, Le Maitre *et. al.*, 2014).

In the South African context, many environmentally sound laws and policies are in place. However, their implementation and enforcement is often slow (Stuart-Hill and Schulze, 2010; Schreiner, 2013). South Africa is experiencing significant land use changes (Gbetibouo and Ringler, 2009; Jewitt, 2012). Environmental considerations seem to be frequently overridden by a drive towards mining and industrial development, based partially on the assumption that this would create jobs and result in the upliftment of the poor. However, a focus on poverty reduction that erodes the supply of ecosystem services can make poverty reduction increasingly difficult (Carpenter *et al.*, 2006). Ecosystem services are vital for environmental performance. In recent studies (Yale Center for Environmental Law and Policy, 2012; Standard Chartered, 2013), the environmental performance index and South African ecosystem vitality were extremely poor in absolute terms, amongst the poorest performing countries out of the countries assessed, and with a declining trend. Unsustainable development will result in expenditure for compensation to lost ecosystem services and it will endanger sustainable development. This may result in an increase of poverty now, as well as for future generations.

Payment for ecosystem services may provide many opportunities in South Africa, given that a large part of the land is currently still in a natural state and/or can be rehabilitated. Conservation, as well as adaptation to adverse conditions, including water stress, needs to be undertaken at a local level.

If land use changes are considered, an assessment should show potential ecosystem services trade-offs, and these should be compared to land use that conserves and rehabilitates natural capital. An individual environmental impact assessment (EIA), often required for an application for land use change, will not take accumulative impacts of other proposed land use changes into account, nor does it consider all ecosystems services.

On the basis of the above literature review and discussion, the aims, objectives and methodology of the proposed case study are outlined in Section 3.

3. BACKGROUND INFORMATION

3.1 Research Overview

The background information on the study catchment fits into the overall research objective and approach adopted as shown in the overview provided in Figure 3.1.

Objective: To evaluate changes to selected hydrological responses and associated selected ecosystem services provided by the study area, as a result of current and proposed land use modifications

Approach: The objective is to be achieved by identifying the scenarios of baseline land cover as well as current and proposed land uses; sub-delineating the study area into land use determined hydrological response units; applying an appropriate hydrological simulation model to assess changes in hydrological responses from baseline land cover as well as current and proposed land uses; and relating these changes in hydrological responses to changes in selected ecosystem services

Sections

Chapter 1 Introduction	Chapter 2 Literature Review	Chapter 3 Background Information	Chapter 4 Methods	Chapter 5 Results	Chapter 6 Discussion Conclusions

Chapter Outline:
- Description of the study area from a biophysical perspective
- Description of land cover and land use related scenarios

Figure 3.1 Background information on the study area, within the context of this dissertation

In this chapter the study area is introduced first, followed by a description of the study catchment from a biophysical perspective. Thereafter, various land cover- and land use-related scenarios will be described, starting with baseline land cover, then current land uses, and finally proposed future land use change scenario.

3.2 Introduction

The area under relatively undisturbed natural land cover in South Africa, which provides the benchmark for hydrological ecosystem services, is reducing. Land use change, including degradation and land transformation, can result in changes to hydrological ecosystem services. Individual smaller catchments by themselves might be seen as having relatively insignificant effects on overall ecosystem services at the exit of a larger catchment. It, however, needs to be understood that changes might have a significant local impact at sub-catchment level and also that total ecosystem services within a larger catchment are made up of the services from the smaller catchments which make up the larger catchment.

Changes in ecosystem services are frequently not taken into consideration during decision-making. This also appears to be the case in the study area of the Mpushini/Mkhondeni Catchments (Figure 3.2) of the already water-stressed uMgeni system in KwaZulu-Natal, South Africa (Figure 3.3).

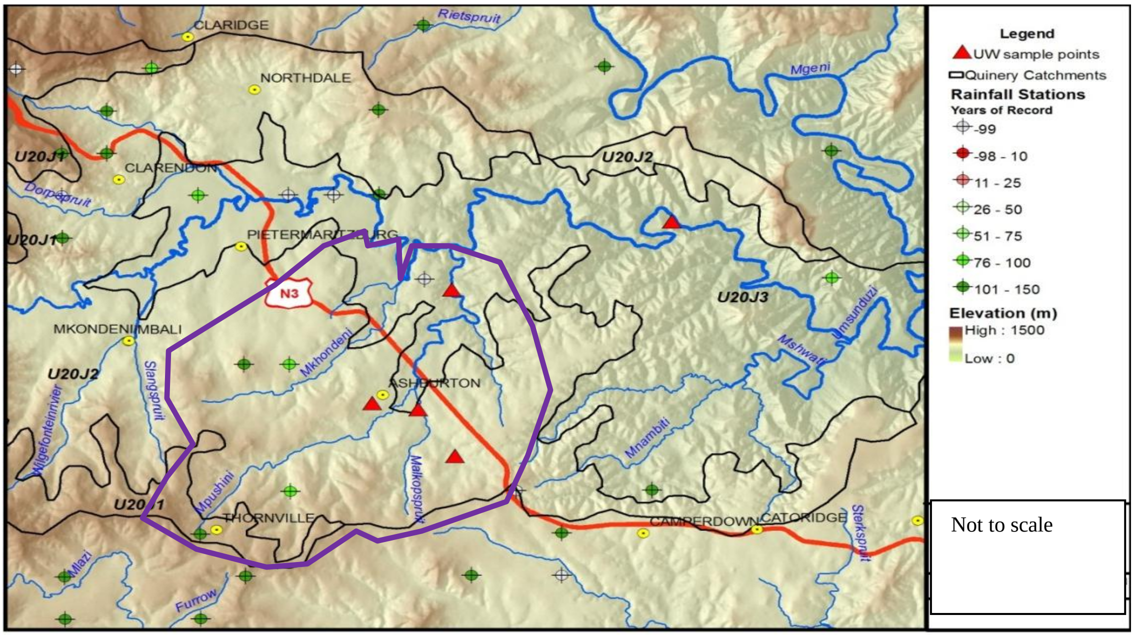

Figure 3.2 The Mpushini/Mkhondeni Catchments and surrounding areas

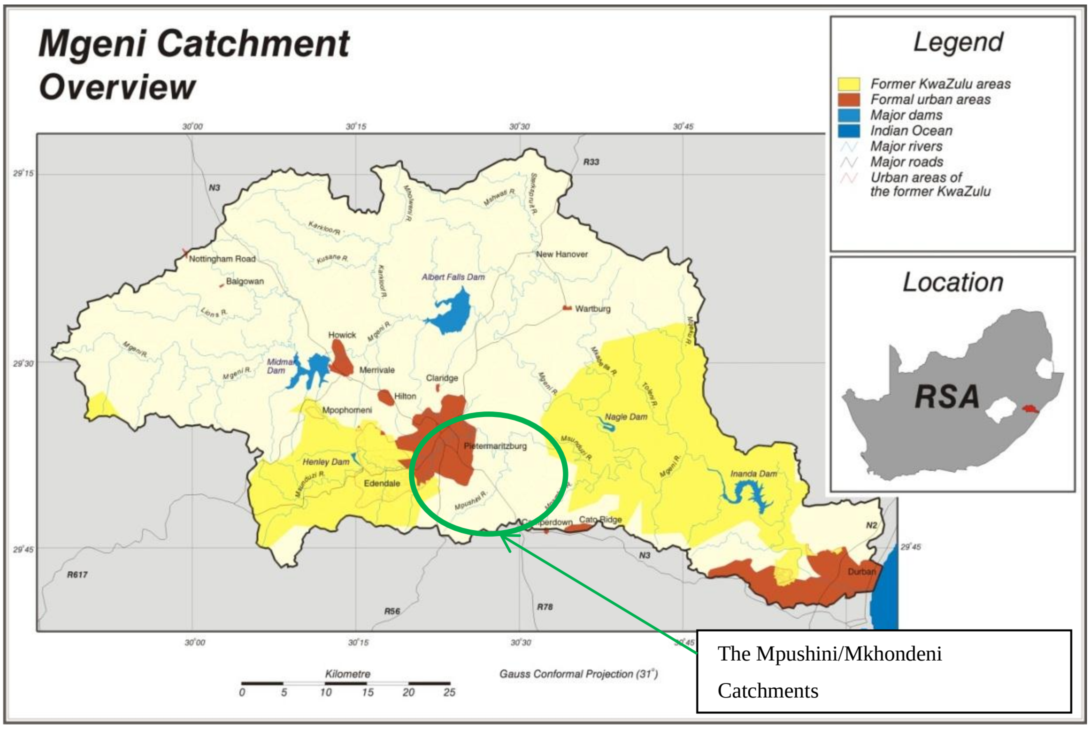

Figure 3.3 The Mpushini/Mkhondeni Catchments and their location within South Africa and the larger uMgeni Catchment

At the time of writing (October 2013) the applications for land use change for the area had reached various stages in the approval process. A local area development plan is currently absent and the effects of proposed land use changes on hydrological services have not been taken into account, especially in an uncertain future which includes projected changes in climate drivers. There is also an initiative by active conservancy associations situated within the area, for a conservation corridor within this generally bio-diverse area, supported by a formal protected environment declaration by the province (Mpushini Protected Environment, 2011). Future land use changes could result in various possible changes in hydrological ecosystem services.

The aim of this study is to better understand the linkages between current land uses, as well as envisaged future land use changes and hydrological responses, and their related hydrological ecosystem services. This, when applied to the Mpushini/Mkhondeni study area, should help to better understand the impacts of potential changes to selected hydrological ecosystem services in order to help make informed, science-based decisions when it comes to land use changes and land management on a local scale. The already water-stressed Mpushini/Mkhondeni Catchments were chosen for this research as this area is presently a relatively undeveloped rural area with limited development and a rich biodiversity, but it is under threat of major changes to current land uses because of the concerted attempt to achieve economic growth and create jobs within the area. This area will be described from a biophysical perspective in the next section, followed by descriptions of the scenarios of baseline land cover, current land uses and proposed land uses.

3.3 The Study Area from a Biophysical Perspective

In order to place the study area in its biophysical context, an overview of its geography is presented. The Mpushini and Mkhondeni Catchments lie within the eastern Msunduzi Local Municipality and the western Mkhambathini Local Municipality, both of which form part of the larger uMgungundlovu District Municipality in KwaZulu-Natal. The two selected catchments are headwater catchments, with no major rivers flowing into them. Both catchments flow into the Msunduzi River which, in turn, is a tributary of the uMgeni River (cf. Figure 3.2). The average altitude is 759 m. The area of the catchments covers 116 km^2, of which the Mpushini Catchment makes up 84 km^2. The two catchments are ungauged. The catchments fall within the Quaternary U20J, with 74 % of the area being in Quinary

Catchment U20J2, 7 % in Quinary Catchment U20J1 and 19 % in U20J3 (Schulze and Horan, 2010). Because the majority of the area lies within U20J2, the climate and soil types of that quinary were used to represent the entire study area. Monthly averages of key climate variables are given in Figure 3.4. The mean annual precipitation for the area is 830 mm, with predominantly summer rainfall. The inter-annual coefficient of variation of rainfall is 22 %. The incidence of frost is low. The considerable monthly and annual differences between the rainfall in 1:10 year dry, median and 1:10 year wet conditions, are shown in Figure 3.5 (cf. Section 4.4.12)

Description	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Monthly means of daily maximum temperatures (◦ C)	26.5	26.8	26.1	24.4	22.5	20.4	20.6	21.8	23	23.6	24.5	26.3	
Monthly means of daily minimum temperatures (◦ C)	16.1	16.2	15.1	12.2	8.8	5.7	5.6	7.5	10.2	11.9	13.6	15.2	
Monthly total of A-pan equiv evap (mm)	176	154	149	120	103	91	99	125	143	157	161	180	
Monthly Mean Precipitation (mm)	122	119	109	50	28	11	13	20	50	88	97	122	830
Precipitation Coefficient of Variation	48	60	64	84	159	138	196	99	151	56	55	54	22

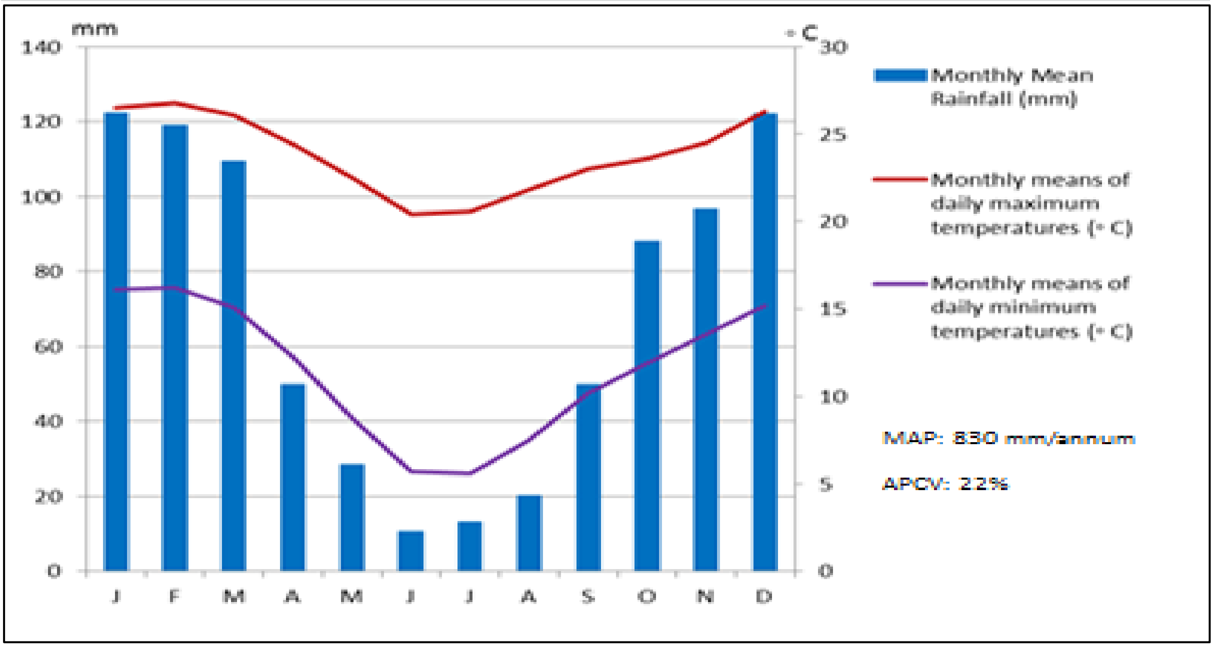

Figure 3.4 Monthly means of key climate variables of the study area, represented by the climate of Quinary Catchment U20J2, with blue bars showing monthly precipitation, red and purple lines showing, respectively, the monthly means of daily maximum and minimum temperature, MAP being the Mean Annual Precipitation and APCV being the Inter-Annual Coefficient of Variation of Precipitation, with data sourced from the Quinary catchment database (Schulze and Horan, 2010)

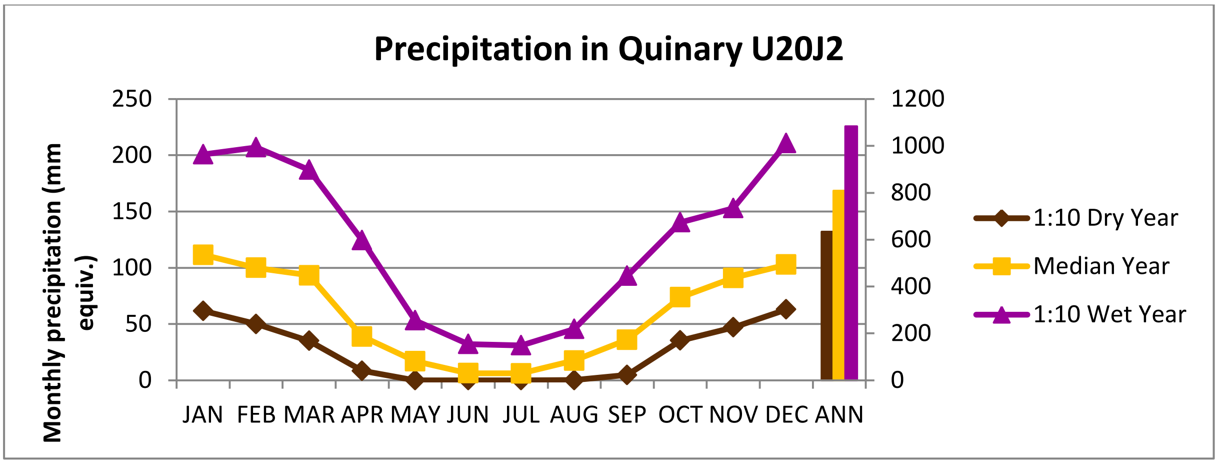

Figure 3.5 Monthly and annual precipitation in Quinary Catchment U20J2 in 1:10 dry, 1:10 wet and median years, with data sourced from the Quinary catchment database (Schulze and Horan, 2010)

3.4 Descriptions of Baseline, Current and Proposed Land Use Scenarios

For the purpose of this study a change in land use is defined as any change in use, including changes in cover, utilisation, treatment or management, for example, from natural to agricultural, or from extensive agricultural to intensive agricultural or to industrial uses.

Four land use scenarios which are important for their differing hydrological ecosystem services are described below. The scenarios to be assessed are the land cover of the area under natural conditions as a baseline, the land uses under current practices, the scenario of rehabilitation of degraded areas and the proposed future land use scenario of increased urbanisation.

Because this dissertation focusses on the impacts of land use within a relatively small catchment, the soil types have been set to remain the same within the study area for all land uses.

3.4.1 Land cover under natural conditions as a baseline

In this scenario, the land cover before human transformation is used as a reference from which baseline hydrological responses and services will be modelled (cf. Chapter 4). Information on baseline land cover was obtained for Ezemvelo KZN Wildlife (Ezemvelo, 2011a), the provincial conservation agency, and land cover classes shown in Figure 3.6.

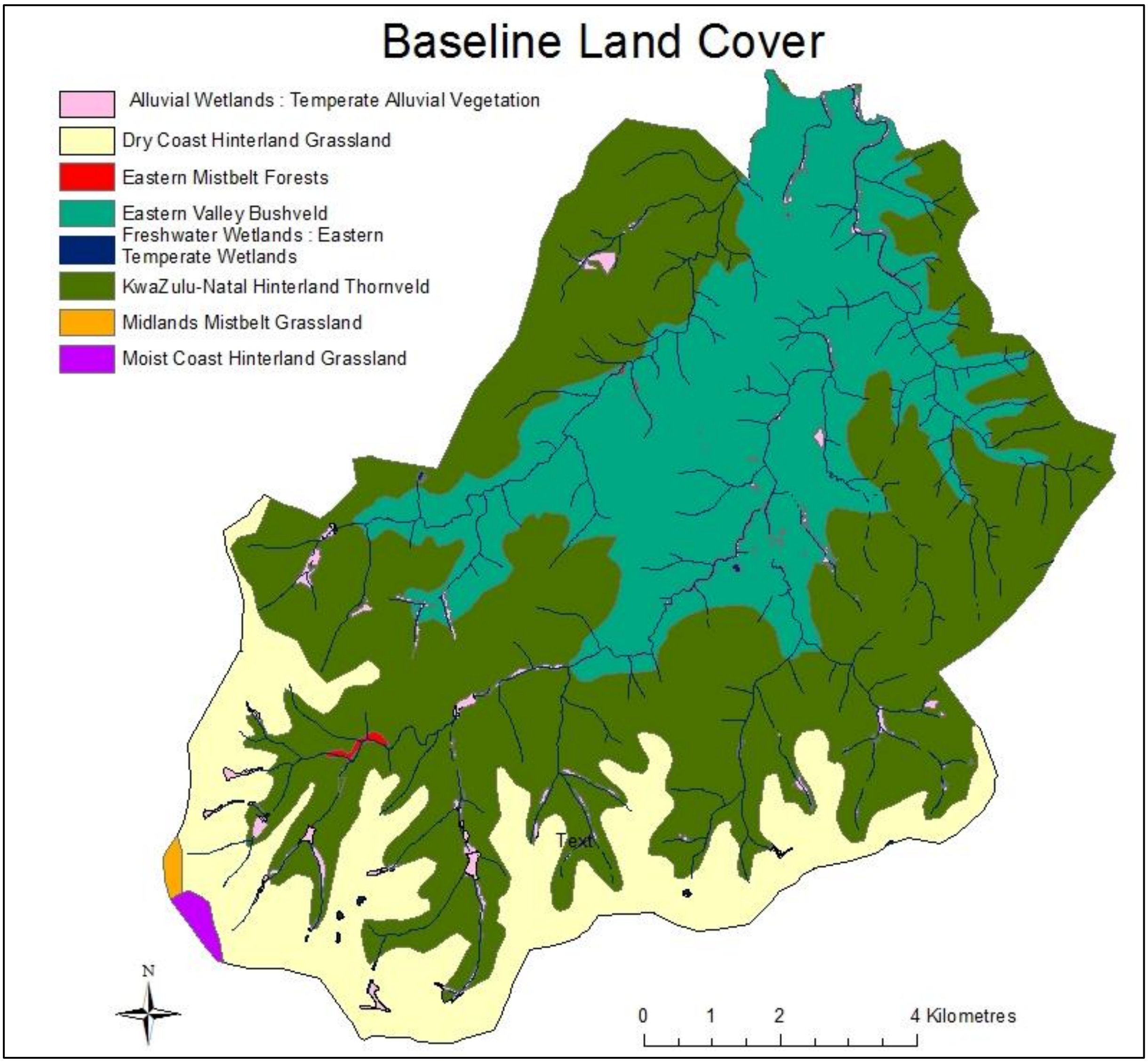

Figure 3.6 The baseline land cover classes within the Mpushini/Mkhondeni Catchments (Ezemvelo, 2011a), with rivers superimposed

The study area lies within the Savanna biome, and more specifically the Sub-Escarpment Savanna Bioregion (Mucina and Rutherford, 2006). The main pre-transformation vegetation types of the study area were found to be “Dry Coast Hinterland Grassland”, “KwaZulu-Natal Hinterland Thornveld” and “Eastern Valley Bushveld”, characteristics of which are described below. In essence, the main vegetation types vary between grasslands which are to a varying degree dominated by *Acacia* thorn trees and shrubs. Ezemvelo KZN Wildlife land cover descriptions are based on those of Mucina and Rutherford (2006), but with some additional information.

- Dry Coast Hinterland Grassland

This is a new classification type (Gs 19) added by Ezemvelo KZN Wildlife (Ezemvelo, 2011a) and is grassland generally dominated by wiry unpalatable Ngongoni grass (*Aristida junciformis),* a mono-dominance associated with low species diversity. However, when in a well-managed condition it can be dominated by palatable red grass *(Themeda triandra)* and trident grass (*Tristachya leucothrix).* Dry Coastal Hinterland Grassland in the study area usually occurs on the ridges between river valleys.

- KwaZulu-Natal Hinterland Thornveld (Mucina and Rutherford classification SVs 3)

This vegetation class is made up of open thornveld dominated by *Acacia* species, and in the study catchments is found on the mid-slopes between river valleys and ridges.

- Eastern Valley Bushveld (Mucina and Rutherford classification SVs 6)

This consists of semi-deciduous savanna woodlands in a mosaic with thickets, which are often succulent and dominated by *Euphobia* and *Aloe* species and usually found in the warmer, lower altitude valley areas of the study area. North-facing slopes receive greater amounts of insolation, sometimes resulting in xerophilous conditions on these slopes.

The delineation of the baseline vegetation will be explained later in Section 4.3.2. The baseline vegetation-related attributes that influence hydrological responses and related ecosystem services will be outlined later in Section 4.4.4. The current land uses will be described next.

3.4.2 Current land uses

The current land uses were identified from the Ezemvelo (2011b) database, using 2008 satellite imagery. The identified land uses are shown in Figure 3.7 and will henceforth be termed current land uses. Of the 46 land use classes identified by Ezemvelo in KwaZulu-Natal, 26 occur within the study area. The largest grouping of current land uses is natural vegetation (Classes #18 to #24 in Figure 3.7), made up of grasslands and bush of varying densities of bush covers. This area is used mainly for cattle, game and horse grazing. More details regarding the delineation will be provided later in Section 4.3.

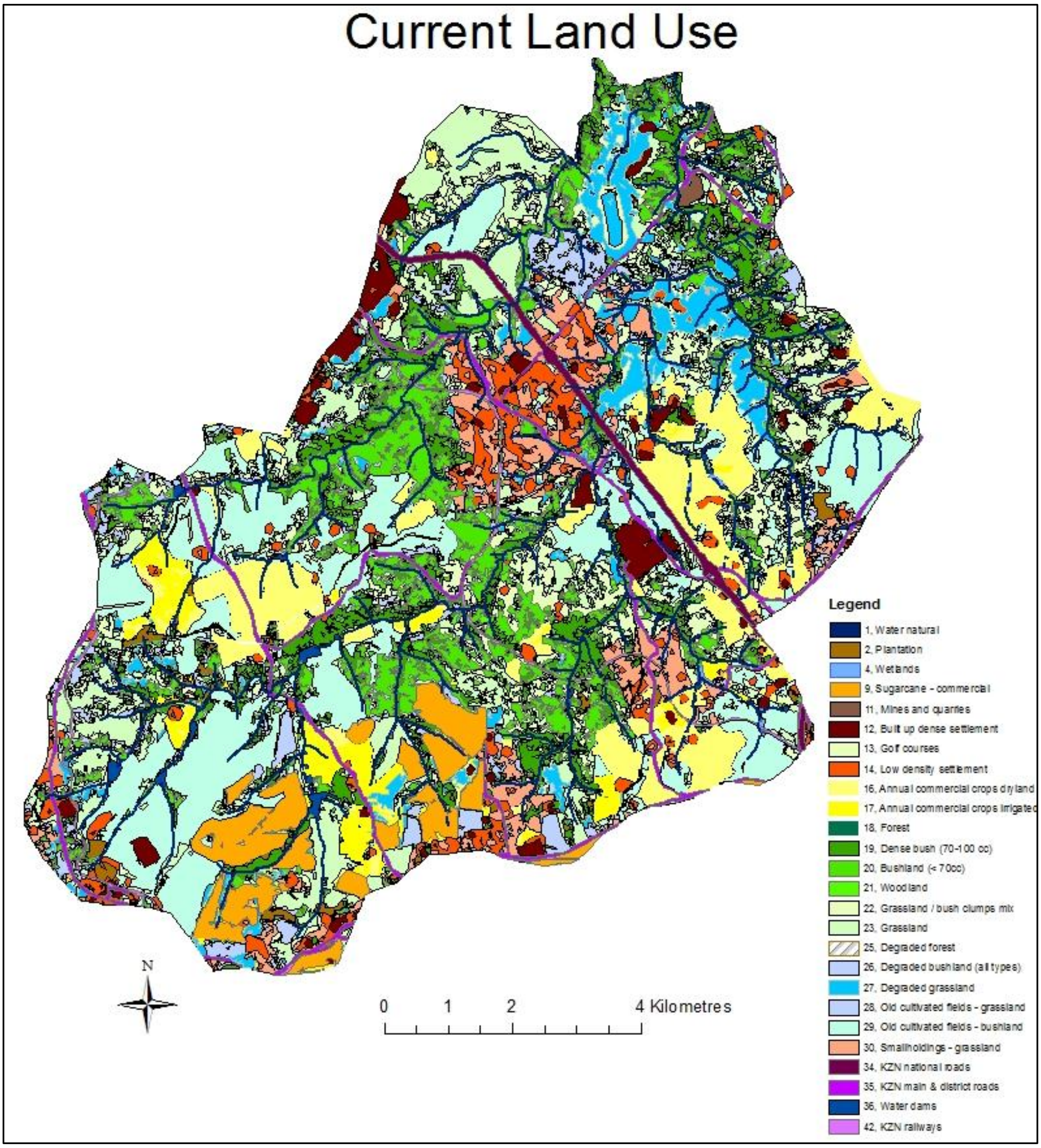

Figure 3.7 Current (2008) land uses within the Mpushini/Mkhondeni Catchments (Ezemvelo, 2011b), with rivers superimposed

Hydrologically important land uses are considered to be those with impervious areas such as urban areas (#12, #14, #30, #34, #35), as well as quarries (#11), dams (#36), land under irrigation (#17), dryland cropland (#18) and degraded areas (#25-29). Their hydrological attributes will be explained later in Section 4.4.

A special emphasis was placed on areas that could be rehabilitated, *viz.* all areas currently classified as being degraded (Figure 3.8), including old fields. This would allow hydrological services to return to a state similar to those under baseline conditions. More hydrologically-related information on degraded areas is given in Section 4.2.4.

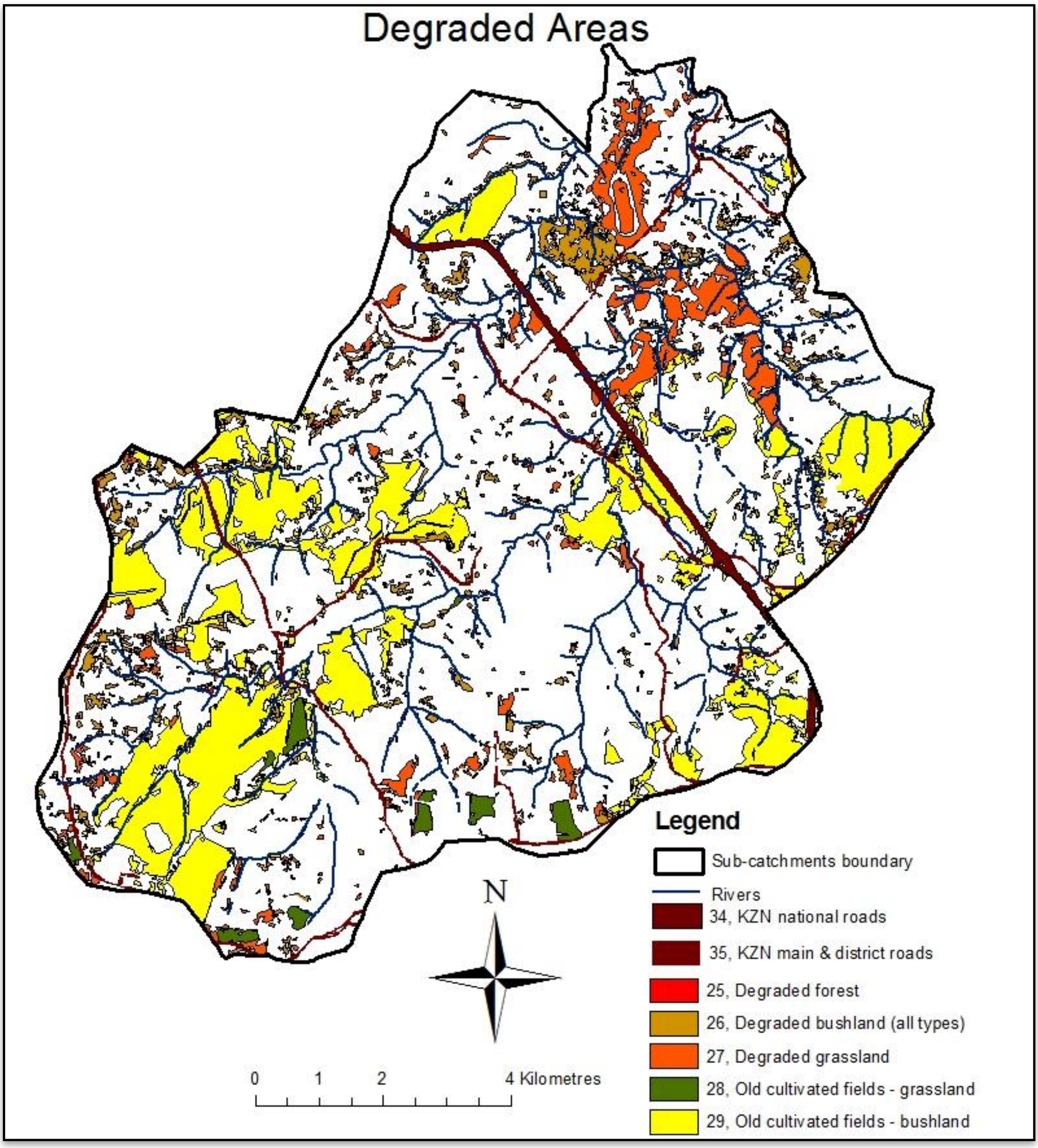

Figure 3.8 Areas within the Mpushini/Mkhondeni Catchments which are degraded (Ezemvelo, 2011b), including roads and rivers superimposed

3.4.3 Proposed future land use change scenario: Increased urbanisation

A significant increase in urbanisation is proposed for the study area (KZN Investor Network. 2011). The information for proposed future land uses was taken from various land use change proposals that in August 2012 were in various stages of completion with regard to the environmental authorisation process and/or the rezoning process. The proposed new land uses included light industrial, residential, commercial and mixed use developments, and they would constitute a significant increase in impervious areas. The proposed developments were superimposed over the study area (Figure 3.9). This scenario will henceforth be termed "proposed land uses". The proposed developments' hydrological attributes will be described in Section 4.4.

After having described the catchment in this chapter, and the scenarios of baseline land cover, current land uses, rehabilitation of degraded areas and proposed future land uses, the methods used in subsequent analyses are described in the next chapter.

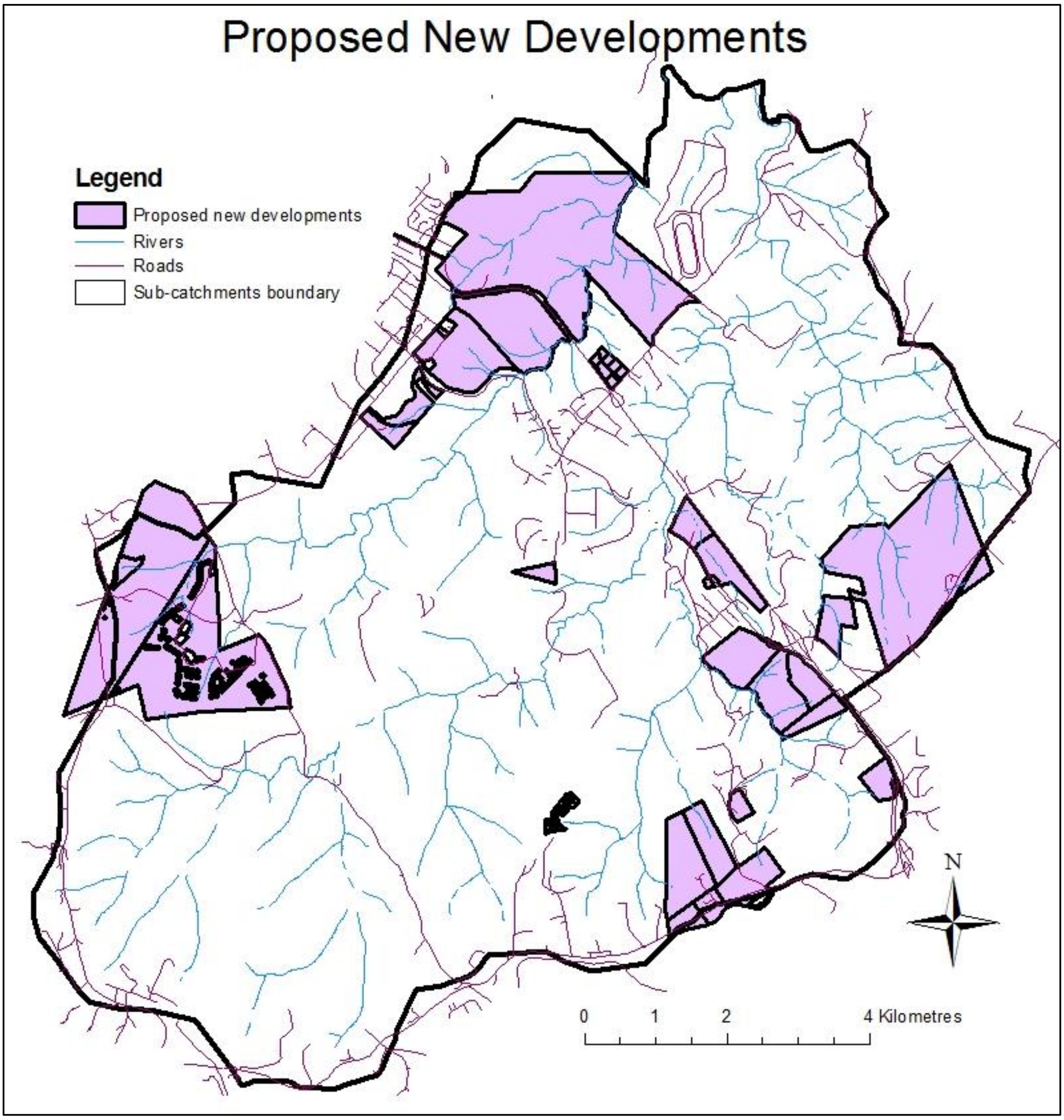

Figure 3.9 Areas demarcated for proposed new developments within the Mpushini/Mkhondeni Catchments, as per August 2012

4. METHODS

In this chapter, following the Literature Review and the Background Information, the methods and approaches used will be described.

4.1 Research Overview and Introduction

This chapter on methods fits into the overall research objective and the approach as shown in the overview provided in Figure 4.1.

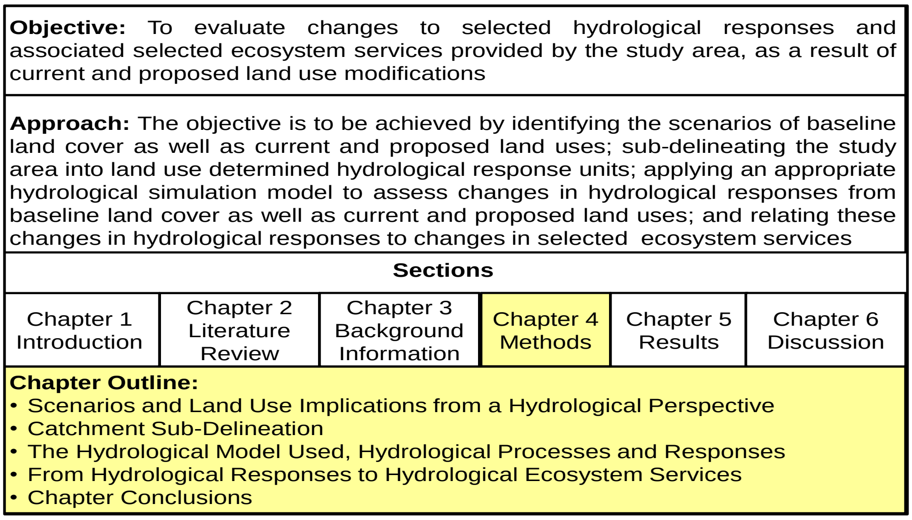

Figure 4.1 Methodology and outline of Chapter 4 within the context of this dissertation

In this chapter, the expected hydrological implications of the land cover and land use scenarios outlined in Section 3.4 are first described. This is followed by a description of the sub-delineation of the study area, based on land uses and the river network, using natural vegetation and present land use databases (Mucina and Rutherford, 2006; Ezemvelo, 2011a, b), as well as added information from proposed land use change applications and site visits. Next, the reasons for selecting the *ACRU* hydrological model are outlined followed by a brief description of the *ACRU* model with the inputs and outputs relevant to this study. Linkages between model outputs and hydrological ecosystem services are then described with a conceptual framework presented, and, finally, conclusions on this chapter are drawn.

4.2 Scenarios and Land Use Implications from a Hydrological Perspective

In this section, qualitative descriptions are given of the influences of baseline land cover, as well as of current and proposed future land use scenarios, from a hydrological perspective. Environmental factors such as climate, geology, soil textures and related properties, the presence of impervious layers, vegetation density, root density and root depth all have an influence on hydrological processes. For the entire study area the soil and climate inputs were taken from Quinary Catchment U20J2 (Schulze and Horan, 2010). It could be argued that more detailed soil and climate information could have been sourced. However, to be able to isolate the land use influences, this was decided against. These hydrological processes include interception, infiltration, soil water redistribution and storage which, in turn, will influence hydrological responses such as stormflow, baseflow, total runoff, sediment yield, evaporation and transpiration. These hydrological responses, in turn, influence the associated hydrological ecosystem services. These hydrological responses will be further explained in Section 4.4.12, while the associated hydrological ecosystem services form part of the results and discussion (Section 5 and 6). In addition to the environmental factors mentioned above, conversions from natural land cover to various land uses also influence hydrological responses and associated hydrological ecosystem services. In order to isolate those land use-related impacts, the influences of the various land use scenarios (cf. Section 3.4) on hydrological processes will be described below.

4.2.1 Baseline land cover from a hydrological perspective

The baseline land cover scenario (cf. Section 3.4.1) serves as a reference for comparing the hydrological changes resulting from different land uses. The climate input variables, especially rainfall, temperature and evaporation, are expected to influence hydrological responses differently during the course of the year. Most rain within the study area falls during the summer months (October to March) and considerably less within the winter months (April to September). Major differences in climate are also expected from year to year and, therefore, hydrological responses for dry, median and wet years need to be examined. The study areas' baseline vegetation cover consists of three main natural vegetation types, *viz*., "Eastern Valley Bushveld", "KwaZulu-Natal Hinterland Thornveld" and "Dry Coast Hinterland Grassland". The higher tree and bush cover and, therefore, a higher biomass and deeper root system of the first vegetation type results in more interception and infiltration compared to the “KwaZulu-Natal Hinterland Thornveld” and even more so compared to “Dry Coast Hinterland Grassland”. This, in turn, is expected to influence hydrological responses, which will be modelled in the next chapter.

4.2.2 Current land uses from a hydrological perspective

Humans have transformed the natural land cover by, for example, dryland cropping, irrigating crops, grazing of livestock, different grassland burning regimes, constructing settlements and roads. These influence hydrological responses further, in addition to the responses from natural climate variability. Land uses that are especially relevant from a hydrological perspective within the study area are certain agricultural and urban land uses. These include dams (cf. Section 4.4.7) and water abstractions for irrigation (cf. Section 4.4.8) or livestock, the types of crops and cropping practices (cf. Section 4.4.6) and land degradation (cf. Section 4.4.5), on which a special emphasis was placed. Rehabilitating degraded areas leads to an increase in basal vegetation cover and therefore has an influence on hydrological processes and responses and this on ecosystem services. It is expected that the enhanced infiltration from rehabilitated areas would increase baseflows and decrease stormflows and sediment yield. Also hydrologically important are land uses that increase impervious areas (cf. Section 4.4.9) and consist of settlements of various densities, roads, as well as quarries. Another important point is that water from outside the catchments is supplied for household, commercial and industrial uses and therefore, in part, adds to the water budget of the study area and thus will be modelled as return flows (cf. Section 4.4.10).

4.2.3 Proposed land uses from a hydrological perspective

The proposed land uses (cf. Section 3.4.3), consisting of substantial increases in residential and industrial areas when compared to current land uses, will have further implications, with expected significant increases in impervious areas adding to stormflow, and the patterns of flows further complicated by externally derived water adding to return flows from urban areas.

4.3 Catchment Delineation and Sub-Delineation

In order to isolate the hydrological effects of different current and proposed land uses and the changes in ecosystem services associated with them, the study area was delineated into catchment units (CUs) with those then further subdivided into smaller land use based hydrological response units (HRUs). The delineation into CUs is described in Section 4.3.1 and the sub-delineation into HRUs is described in Section 4.3.4. The areas of the various land uses areas were obtained by using Geographic Information System (GIS) data bases (e.g. Ezemvelo, 2011 a, b). The relevant areas for baseline land cover for the study area were determined first, followed by the areas for current and proposed land uses, which were simplified into land use clusters by aggregating land uses with similar hydrological responses. This allowed catchment units to then be further broken down into hydrological response unit classes, required for the detailed modelling envisaged.

4.3.1 Catchment units

The study area was first delineated following a catchment delineations approach and informed by river networks and topography derived from 1:10 000 orthophoto maps and GIS information obtained from the Chief Directorate: National Geo-spatial Information (2012). The study area was then delineated into 10 catchment units, based again on the river network and topography, but considering also the location of dams, as well as major current and proposed land uses. These 10 delineated units will henceforth be called “catchment units”, with the abbreviation CU, and they are shown in Figure 4.2. The hydrological flow between the catchment units making up the study area is shown in schematic form in Figure 4.3.

4.3.2 Applications of geographical information and GIS analyses to determine land use areas

Geographical data and maps for the area were utilised and analysed in order to compare past, current and future scenarios. For the baseline scenario, vegetation maps were used (Ezemvelo, 2011a), showing pre-human disturbance natural vegetation land cover in the province of KwaZulu-Natal. This vegetation land cover map is abbreviated as KZN-LC. KZN-LC is based on previous research by Mucina and Rutherford (2006), but with a number of updates by Ezemvelo. The vegetation land cover maps were established on the understanding that natural vegetation properties respond to the dynamic and nature of the environment (Mucina and Rutherford, 2006). Data layers used to obtain the vegetation zones were spatial images, altitude, temperature, rainfall, geology and soil types (Mucina and

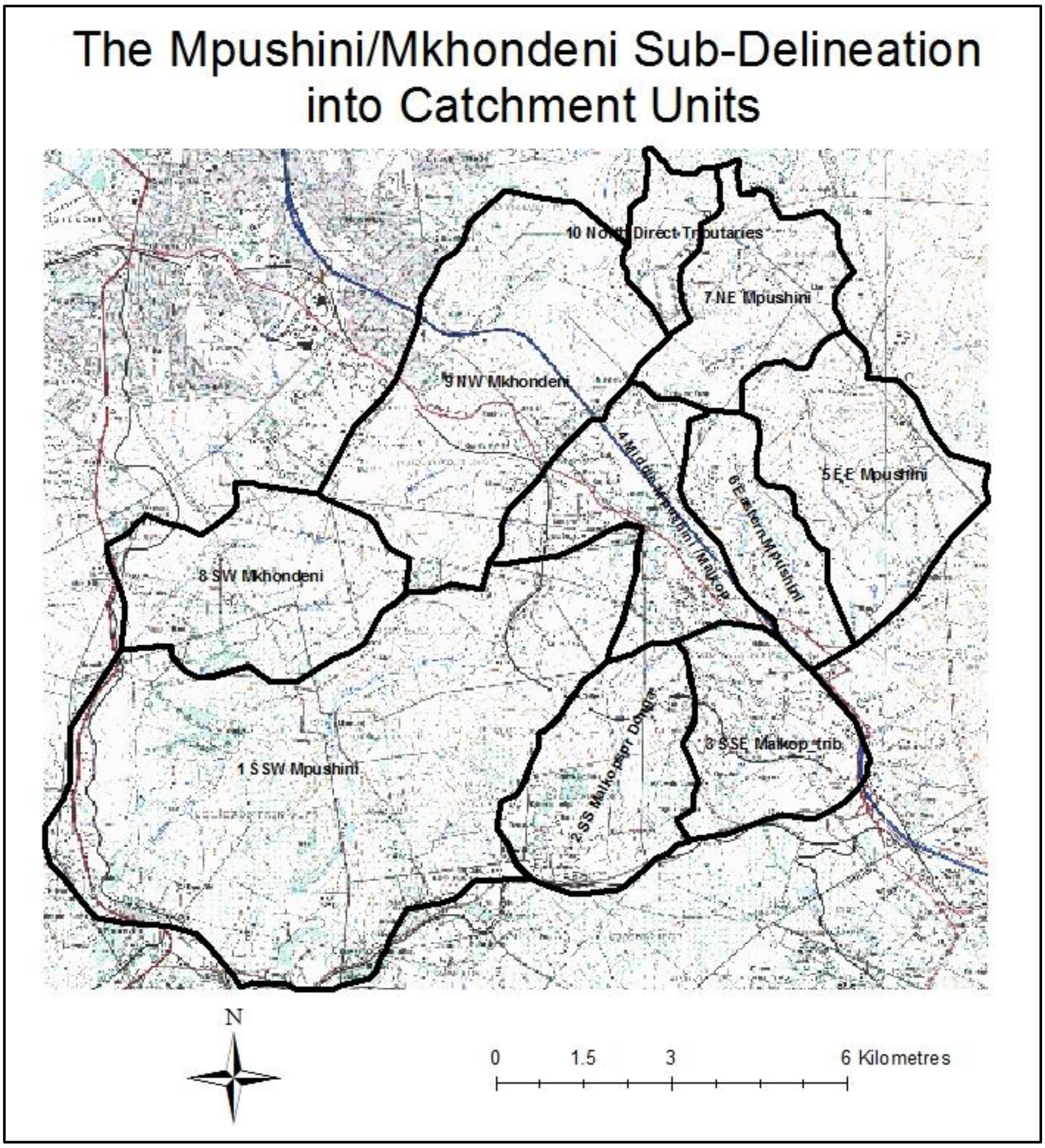

Figure 4.2 Delineation of the Mpushini/Mkhondeni Catchments into 10 catchment units

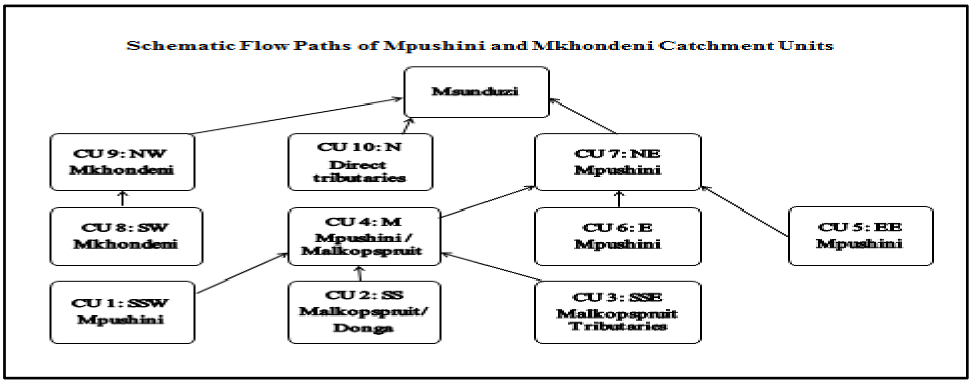

Figure 4.3 Schematic of the hydrological flow paths between the 10 catchment units making up the Mpushini and Mkhondeni Catchments

Rutherford, 2006). Because these factors also influence hydrological responses, vegetation zones can be taken as zones of similar hydrological responses.

The baseline cover was found to consist mainly of the vegetation types Eastern Valley Bushveld, KwaZulu-Natal Hinterland Thornveld and Dry Coast Hinterland Grassland, as explained in Section 3.3.1. The delineated study area was used to clip the vegetation zones from the KZN-LC. This clip (cf. Figure 3.5) is overlaid onto the catchment units and shown in Figure 4.4.

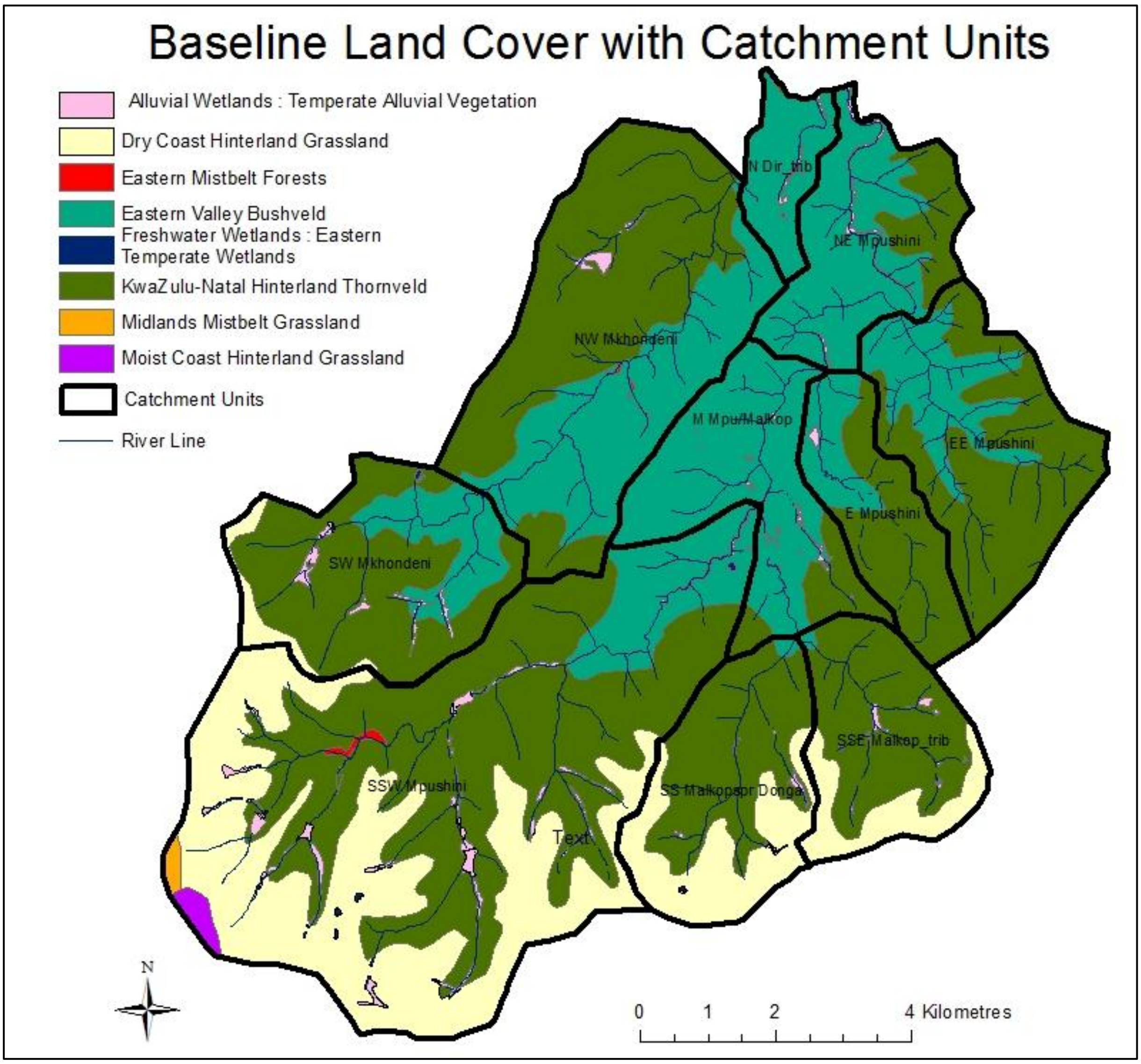

Figure 4.4 The Mpushini/Mkhondeni study area under baseline land cover (Ezemvelo, 2011a), with the 10 catchment units overlaid

The dominant land cover within each catchment unit was selected, following the rules outlined by Schulze (2012). This narrowed the land cover types within the study area down to two, *viz.* KZN Hinterland Thornveld in CUs 1 to 3, 5, 6, 8, 9 and Eastern Valley Bushveld in CUs 4, 7 and 10. The areas of these land cover types within each of the 10 CUs are assigned to equal the size of the CU areas.

For the current land use scenario, land use maps and information from Ezemvelo (2011b) were utilised. This information is based on satellite imagery for the province of KwaZulu-Natal from 2008, as well as previous land use map versions, and is henceforth abbreviated KZN-LU. The KZN-LU provides 47 land use classes, of which 26 are found within the study area. The current land use scenario was evaluated by clipping the study area from KZN-LU (Ezemvelo, 2011b), as was illustrated previously in Figure 3.6. The catchment units were then intersected and the areas per CU and per land use class determined (cf. Chapter 5). It is acknowledged, however, that there are limitations to this approach, as the land use classifications do not specify land management and, for example, conservation agriculture might have different hydrological model inputs, compared to those for conventional agriculture.

For the proposed land use scenario, the delineated study area was clipped from a cadastral map for the region (Chief Directorate: National Geo-spatial Information, 2012) and overlaid with cadastral information for proposed land uses, obtained from various land use change applications (PMMB Trust, 2012; shown previously in Figure 3.9). The delineated catchment units are then overlaid in order to place the proposed developments into the catchment units.

For the rehabilitation scenario (cf. Figure 3.8) the degraded areas, inclusive of old cultivated fields within the study area, need to be analysed. Therefore the relevant degraded land use classes were isolated from the information of current land use, the catchment units were overlaid and the relevant areas per CU determined (cf. Chapter 5).

The KZN-LU land use classification was found to be very detailed. For hydrological modelling purposes, it was therefore necessary to simplify the classification by aggregating land uses with similar hydrological responses.

4.3.3 Aggregating land uses with similar hydrological responses into relatively homogeneous hydrological units

The various land use classes were aggregated into fewer clusters, each of which shows similar hydrological responses for all the scenarios, first for the current land uses, then for the baseline land cover, the proposed land uses and rehabilitation scenario.

- Current land use

The 26 land use classes found within the study area were aggregated into eight hydrological clusters which are later used for hydrological modelling (cf. Section 4.4). All natural vegetation types (Ezemvelo Classes #18-23), including "wetlands" (#4) which however make up less than 0.2 per cent of the overall area, are aggregated into "natural vegetation". The various urban land uses (#12, 14, 34, 35, 42), together with mines and quarries (#11), are aggregated into "Urban land uses". However, more detailed information regarding fractions of impervious areas (cf. 4.5.7) and return flows (cf. 4.5.8) is given later. Various agriculturally-related classes (#13, 16 and 30) are aggregated into "Dryland agriculture, improved pasture". "Natural vegetation, in degraded condition" is aggregated from land use classes #25-29. Land use classes relating to water (dams, #36 and natural, #1) are aggregated into "Open water bodies". The agricultural land uses of sugarcane (#9); (tree) plantations (#2) and cultivated irrigated crops (#17) remain as separate hydrological classes. The aggregation of the land use classes into land use clusters is shown in Table 4.1, with the information in the third column to be used in a later section.

- Baseline land cover

All CUs were further sub-delineated into HRUs (cf. Section 4.3.4), as per current land use, however, all were with the model inputs for baseline land cover, to allow for the comparison of individual HRUs.

- Proposed land use

The proposed urban development falls within the hydrological land use cluster of "Urban land uses". The HRUs were taken from the current land use scenario; however, additional information is required on the fractions of impervious areas (cf. Section 4.4.9) and return flows (cf. Section 4.4.10).

Table 4.1 Aggregation of Ezemvelo land use classes for the study area into land use clusters for hydrological modelling, with cc standing for canopy cover and CU for catchment unit

Ezemvelo Land Cover Class		**Hydrological Cluster**	**Rules for Hydrological Modelling (cf. Section 4.4)**
Land Use Class #	**Land Use Class Description**		
18	Forest (indigenous)	Natural vegetation	Use baseline vegetation of CU
19	Dense thicket & bush (70-100 % cc)	Natural vegetation	Use baseline vegetation of CU
20	Medium bush (< 70cc)	Natural vegetation	Use baseline vegetation of CU
21	Woodland & Wooded Grassland	Natural vegetation	Use baseline vegetation of CU
22	Bush clumps / Grassland	Natural vegetation	Use baseline vegetation of CU
23	Grassland	Natural vegetation	Use baseline vegetation of CU
4	Wetlands	Natural vegetation	Use baseline vegetation of CU
12	Build-up / dense settlement	Urban land uses	Use baseline vegetation of CU, but calculate impervious areas and return flows
14	Low density settlements	Urban land uses	Use baseline vegetation of CU, but calculate impervious areas and return flows
34	KZN national roads	Urban land uses	Use baseline vegetation of CU, but calculate impervious areas
35	KZN main & district roads	Urban land uses	Use baseline vegetation of CU, but calculate impervious areas
42	KZN Railways	Urban land uses	Use baseline vegetation of CU, but calculate impervious areas
11	Mines and quarries	Urban land uses	Use baseline vegetation of CU, but calculate impervious areas
16	Cultivation, commercial, annual crops, dryland	Dryland agriculture, improved pasture	Use the hydrological attributes of the main crop, which was found to be improved pasture
13	Golf courses (Race Course)	Dryland agriculture, improved pasture	Use the hydrological attributes of the main crop, which was found to be improved pasture
30	Smallholdings	Dryland agriculture, improved pasture	Use the hydrological attributes of improved pasture, but also calculate impervious areas
9	Sugarcane	Sugarcane	Use hydrological attributes of inland cane
2	Plantation	Tree plantation	Use hydrological attributes of wattle
25	Degraded forest	Natural vegetation, in degraded condition	Use Baseline vegetation, but adjust hydrological attributes for degradation
26	Degraded bushland (all types)	Natural vegetation, in degraded condition	Use Baseline vegetation, but adjust hydrological attributes for degradation
27	Degraded grassland	Natural vegetation, in degraded condition	Use Baseline vegetation, but adjust hydrological attributes for degradation
28	Old fields - previously grassland	Natural vegetation, in degraded condition	Use Baseline vegetation, but adjust hydrological attributes for degradation
29	Old fields - previously bushland	Natural vegetation, in degraded condition	Use Baseline vegetation, but adjust hydrological attributes for degradation
17	Cultivation, commercial, annual crops, irrigated	Irrigated crops	Choose main crop and obtain irrigation data
36	Water (Dams)	Open water body	Obtain dam data
1	Water (natural)	Open water body	Treat as shallow dam with a height as per river height

4.3.4 Further catchment unit sub-delineations into hydrological response units (HRUs), based on identified hydrologically sensitive land uses

Hydrologically sensitive land uses have different hydrological responses to those of the natural baseline land cover which they replace. The responses can differ by generating either less total runoff than the baseline land cover (e.g. from production tree plantations and in some areas, sugarcane plantations) or by generating more total runoff than the replaced baseline land cover (e.g. from urban land uses with high fractions of impervious areas) or by producing significant changes in the contribution of stormflows vs. baseflows (e.g. from degraded areas or certain types of urban areas) or by generating significantly more sediment yield (e.g. from degraded areas).

In order to account for the hydrological differences of the aggregated land uses (cf. Section 4.3.3) in each catchment unit, each of the 10 catchment units was further sub-divided into a basic configuration of five hydrological response units (HRUs). The soil and climate data were taken from Quinary Catchment U20J2 (Schulze and Horan, 2010), because 74 % of the area falls within that Quinary Catchment and because this study focussed on the effects of different land uses within a relatively small catchment, rather than climate and soil differences within the catchment.

The five, essentially land use determined, HRUs consist of:

a) HRU 1, made up of the CU's natural vegetation, but also including wetlands and urban areas. The reason for two is that the *ACRU* model can distinguish between the effects of all three of the above separately, but in a single simulation (cf. Section 4.4);
b) HRU 2, consisting of the dryland agricultural cluster which, in the case of this study area, is represented by improved pasture (the dominant dryland agricultural land use);
c) HRU 3, which designates so-called "special case land uses", in this study either sugarcane or tree plantations, whichever is dominant in a given CU;
d) HRU 4, which accounts for a second set of special case land uses, in this instance the degraded land use cluster; and
e) HRU 5, in which hydrological effects of natural watercourses, dams and irrigated areas are simulated.

In case HRU 2 to HRU 5 does not exist within a catchment unit, they take on the attributes of the natural vegetation, but require a minimum area to be simulated with the *ACRU* model (cf. Section 4.4.). Note that HRUs are not of equal area, but make up the total area of the CU when added together. Each HRU is modelled individually. The concept of this delineation follows the method developed by Schulze (2012) and is shown in Figure 4.5. The HRUs are then hydrologically interconnected, as shown in Figure 4.6. The above delineation of each of the 10 catchment units into five HRUs, gives a total number of HRUs in the Mpushini/Mkhondeni study area of 50.

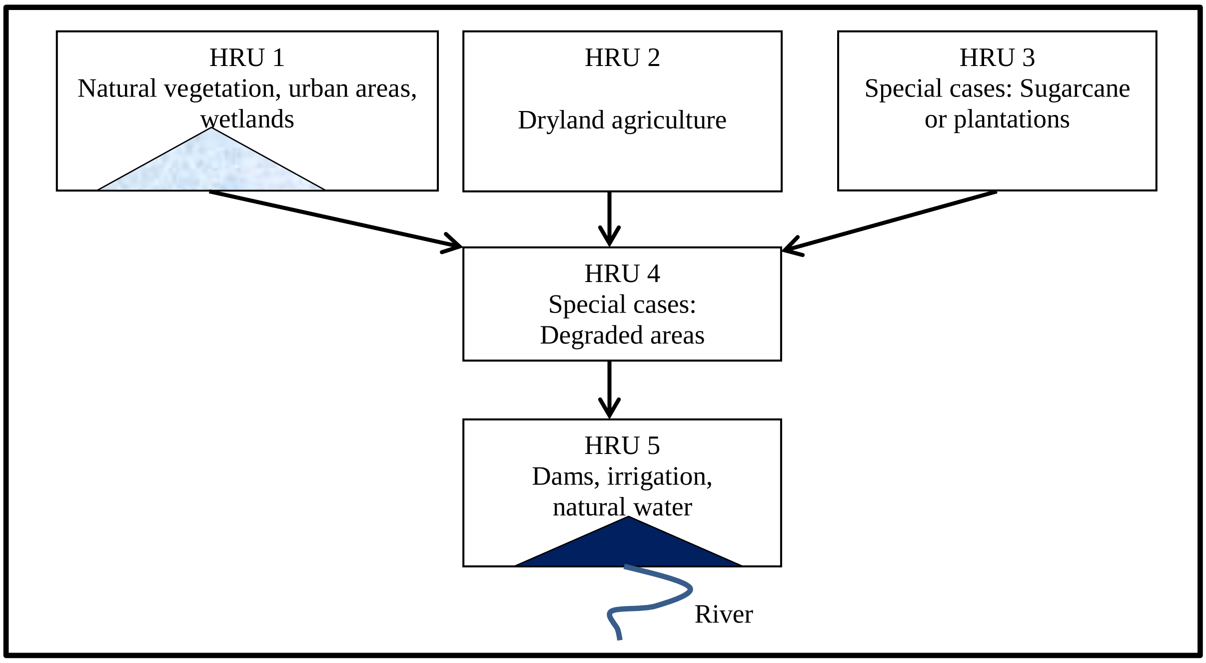

Figure 4.5 Schematic of the sub-delineation of a catchment unit into hydrological response units (HRUs) based on land use (after Schulze, 2012)

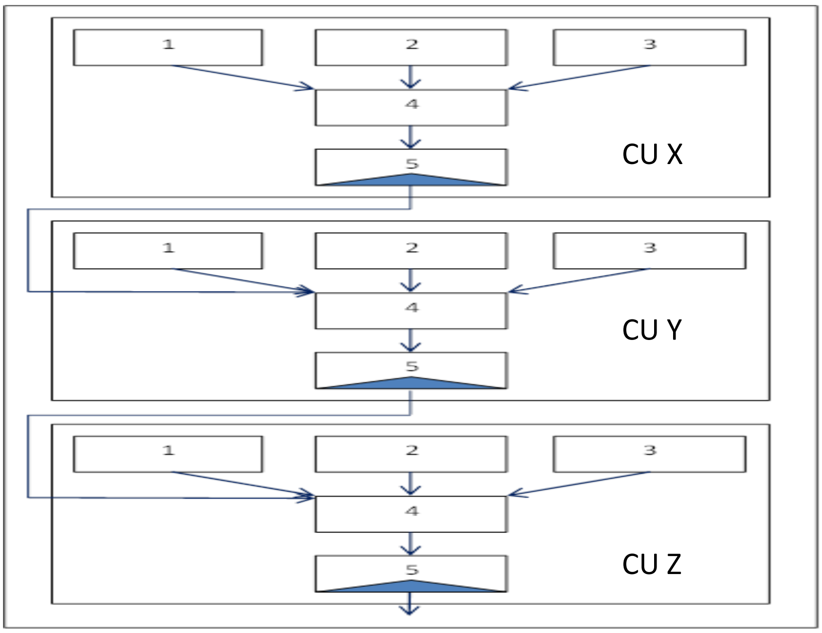

Figure 4.6 Schematic of the flow path between the five hydrological response units of a catchment unit and the flow path between catchment units (after Schulze, 2012)

4.4 The *ACRU* Hydrological Model with Hydrological Processes as Inputs and Hydrological Responses as Outputs

It is not feasible to undertake long-term observations in every catchment of hydrological responses such as stormflow, baseflow, sediment yield, transpiration from plants or evaporation losses from the soil surface. Therefore an appropriately structured and conceptualised hydrological simulation model has to be used when examining changes to hydrological responses and associated hydrological ecosystem services resulting from to land use changes.

4.4.1 Hydrological model selection

The *ACRU* model (Schulze 1995; Smithers and Schulze, 2004; and updates) is a suitable hydrological model as per requirements outlined in Section 2.5.4, in that it takes into account the effects of land uses by modelling the hydrological cycle within the atmosphere-soil-plant-water continuum of the landscape, as well as simulating river flow and its components (Schulze, 2012). This model was chosen over other suitable models, as its output has been widely verified within the uMgeni Catchment (Kienzle *et al.*, 1997; Smithers and Schulze, 1995 and updates; Warburton, *et al*. 2010) and elsewhere (cf. reviews of *ACRU* verification studies by Schulze, 1995; Schulze, 2008). Furthermore, it has existing links to a spatial and temporal hydrological database called the "Quinary Catchments Database", in which 5838 catchments covering the entire South Africa, Lesotho and Swaziland have already been delineated and are linked to climate, soils and other databases (Schulze *et al*., 2010). In addition, expert support on the model is available at the University of KwaZulu-Natal.

4.4.2 A short description of the *ACRU* hydrological model

ACRU is a daily time step, physical-conceptual and multi-purpose model (Figure 4.7) with options to output, *inter alia*, the hydrological responses of daily values of stormflows, baseflows, runoff, total streamflow accumulated from all upstream catchments, transpiration, soil water evaporation, peak discharge, sediment yields, reservoir levels and irrigation water supply at a specific location or for a catchment. The model is designed around multi-layer soil water budgeting (Figure 4.8) and is structured to be hydrologically sensitive to hydrological processes, including those as a result of changes in catchment land uses (Schulze, 1995; 2013).

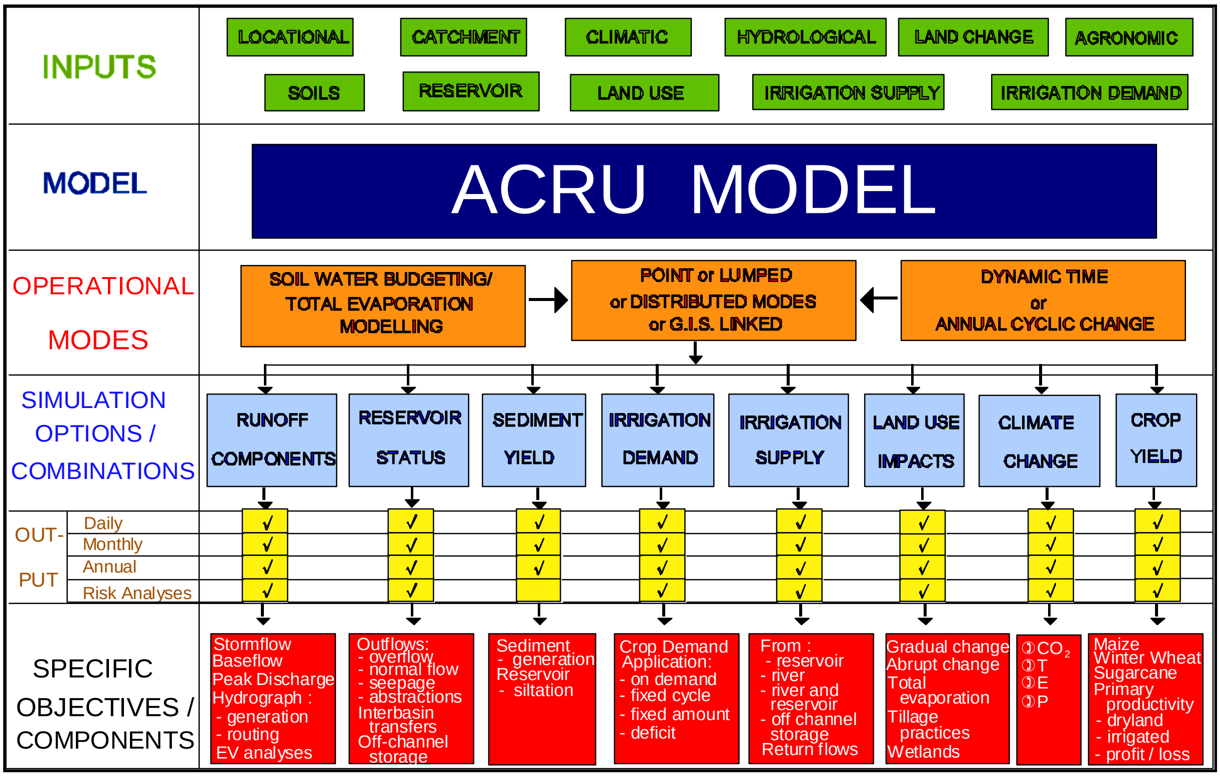

Figure 4.7 Concepts of the *ACRU* modelling system (after Schulze, 1995)

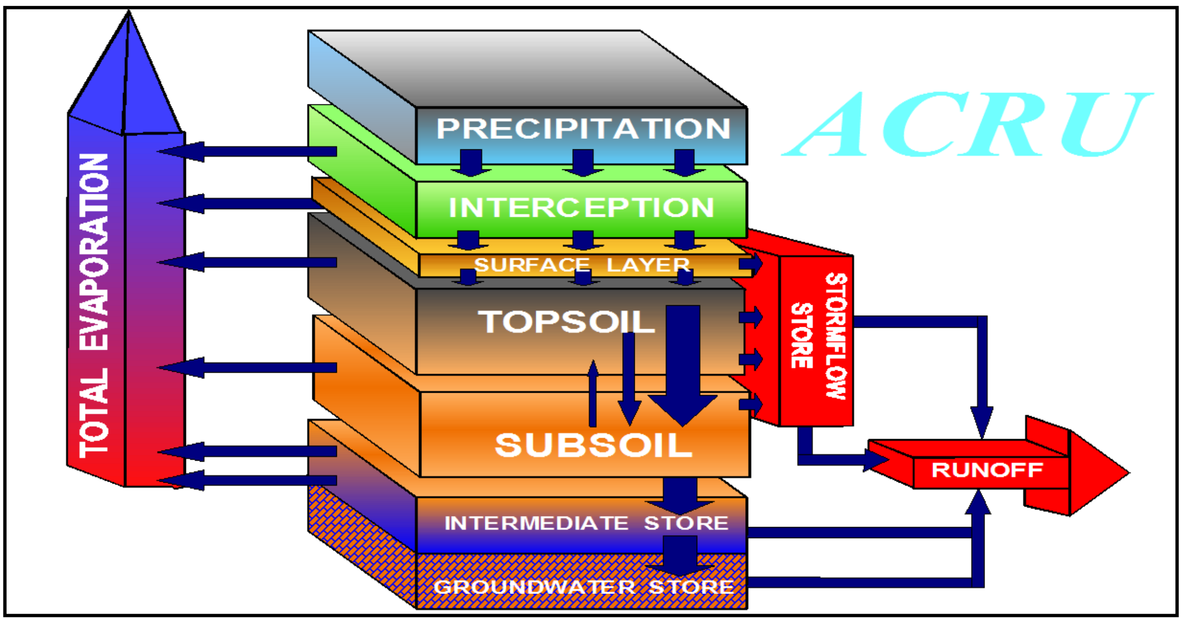

Figure 4.8 Structure of the *ACRU* model (after Schulze, 1995)

The *ACRU* model was run with the relevant land use-related variables for baseline land cover conditions, current land use conditions and proposed future land use change scenarios (cf. Section 3.4). No verification of the current flows was possible, because the streams are ungauged. However previous verifications within the uMgeni Catchment (Kienzle *et al.*, 1997; Schulze, 2008; Warburton, *et al*. 2010) have given highly acceptable results. The selected outputs were the magnitudes and durations of hydrological responses and their variability, broken down into changes to baseflows and stormflows, total runoff, accumulated streamflows, both with and without impacts of dams and irrigation, extreme events, as well as soil water, available to plants (cf. Section 4.4.12). However, the *ACRU* model, like every model, also has limitations. For example, river sediment yield can be simulated, but not bed mobility or particle size distribution of the sediments, which is an important indicator for the stream ecology. It needs to be borne in mind that outputs from a model are not absolute representations of reality, but can rather represent relative changes in hydrological responses if certain inputs, e.g. on land use, are changed.

4.4.3 *ACRU* model inputs

The *ACRU* model requires input of observed or derived data and information on, *inter alia*, climate data (daily rainfall, maximum and minimum temperature and potential evaporation), physiographic data (mean catchment altitude and slope), as well as soil information (thickness of soil horizons, soil water retention constants, drainage rates and soil erodibility). For this study these inputs were derived from existing databases, e.g. climate from the time period 1950 to 1999, soil properties, altitude, slope are all available within the Quinary Catchments Database (Schulze *et al.*, 2010). These inputs remained constant for the various model runs within this study, while the scenario land use-related inputs were changed. The land use-related inputs were vegetation-related (such as vegetation and/or crop attributes), dam-related (e.g. full supply capacities, surface areas, evaporation rates and releases), irrigation-related, impervious area- related, as well as water transfer- related.

4.4.4 Hydrological processes and model inputs related to natural vegetation

The hydrological inputs related to baseline land cover were obtained from previous research with the *ACRU* model (Schulze 2004; 2008). In the *ACRU* model, baseline land covers according to Adcock's' (1988) Veld Types have been assigned a so-called "land use number" (*ACRU* variable CROPNO) and for each land use number the relevant month-by-month *ACRU* input variables have been determined (Schulze and Pike, 2004). Because this study uses the more detailed Ezemvelo classifications of baseline land cover rather than Adcock's' Veld Types *per se*, the Acocks land use number for the Veld Types equivalent to Ezemvelo's classes were selected to represent hydrological inputs for the baseline land cover scenario (Table 4.2).

The baseline land cover-related *ACRU* inputs are month-by-month values of:

a) CAY: the so-called crop coefficient, an index of above ground biomass, which expresses the fraction of water evapotranspired by the vegetation type, compared with a reference potential evaporation, in this case that of the Class A evaporation pan;
b) VEGINT: the canopy interception of rainfall by a plant on a rainday (in mm);
c) ROOTA: the fraction of root mass distribution in the topsoil;
d) COIAM: the coefficient of initial abstraction, which is an index of infiltrability and is dependent on rainfall intensity and above-ground biomass (Schulze, 1995);
e) COVER: the vegetation cover factor, made up of aerial and ground cover, which expresses the fraction of soil loss compared with that from a tilled bare soil;
f) PCSUCO: the per cent surface cover, e.g. of litter or mulch, which affects soil water evaporation;
g) COLON: the percentage of roots colonising the subsoil horizon, which affects soil water extraction rates in that horizon.

Table 4.2 Month-by-month *ACRU* land cover-related inputs for the baseline land cover representing natural vegetation in the Mpushini/Mkhondeni study are (Source: Schulze *et al.*, 2010)

LAND COVER	*ACRU* Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KwaZulu-Natal Hinterland Thornveld, hydrologically represented by Acocks #65: Southern Tall Grassveld *ACRU* CROPNO 2030322	CAY	0.75	0.75	0.75	0.50	0.40	0.20	0.20	0.20	0.55	0.70	0.75	0.75
	VEGINT	1.60	1.60	1.60	1.60	1.50	1.40	1.40	1.40	1.50	1.60	1.60	1.60
	ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	COVER	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
	COLON	70	70	70	70	70	70	70	70	70	70	70	70
Eastern Valley Bushveld, hydrologically represented by Acocks #23: Valley Bushveld *ACRU* CROPNO 2040101	CAY	0.75	0.75	0.75	0.65	0.55	0.20	0.20	0.40	0.60	0.75	0.75	0.75
	VEGINT	2.50	2.50	2.50	2.20	2.00	2.00	1.90	1.90	2.20	2.50	2.50	2.50
	ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	0.95	0.90	0.80	0.80	0.80
	COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.20
	COVER	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
	COLON	80	80	80	80	80	80	80	80	80	80	80	80

The above inputs were also used for the HRU 1 of the current land use scenario. Any subsequent deviations from the baseline land cover through, for example, bush encroachment or alien invasive plant infestation have not been taken into account, as no detailed scientific databases of the respective areas usable at the spatial resolution of this modelling exercise exist, to the author's knowledge.

For land uses other than the baseline land cover, the following inputs were considered for changing in the model: the soil water content at saturation for tilled land; the monthly crop coefficients; the month-by-month canopy interception of rainfall by a plant on a rainday; the fraction of the root mass distribution in the topsoil horizon; the per cent surface cover; the fraction of the catchment occupied by adjunct impervious areas, i.e. areas joined directly to a water course, from which precipitation contributes directly to stormflow, as well as the fraction of a catchment occupied by impervious areas which are not adjacent to a watercourse. Within the current land use scenario, some areas have been degraded, and the processed and inputs of these will be examined next.

4.4.5 Hydrological processes and model inputs related to degraded areas

Some parts of the study area have been identified as degraded within the KZN-LU (Ezemvelo, 2011b) classification. Degraded areas are hypothesised to potentially partition rainfall into higher proportions of stormflow and lower proportions of baseflow, compared to non-degraded conditions. The conditions of degradation may include a reduction of above-ground biomass, which reduces transpiration, canopy interception and the canopy's protective properties. It also may include a reduction to surface litter/mulch, which would increase soil water evaporation and enhance the drying out of the topsoil horizon while also reducing the protective surface layer, which, in turn, increases soil erosion. Degraded conditions are also hypothesised to include a compaction of the soil surface and thereby a reduction in soil infiltration properties.

Following the rules given in Schulze (2013), the following input variables were adjusted, compared to those of the natural vegetation input:

a) CAY (I=1,12): The monthly crop coefficient, an index of above-ground biomass, is divided by 1.4, but in the *ACRU* model may not be less than 0.2 in any month;
b) VEGINT: the interception loss per rainday is reduced by 50 %;
c) COIAM: the coefficient of initial abstraction is reduced to 0.10 for November to March which represents the season of convective rainfall, 0.15 for April, May and October, and 0.20 for June to September, resulting in reduced rates of infiltration;
d) PCSUCO: the percentage litter/mulch is reduced to 10 % as a consequence of reduced surface cover under degraded conditions;
e) COVER: the canopy and surface variable representing soil loss, compared to that of a bare tilled soil, is increased to 0.24; and
f) COLON: the roots colonising the subsoil horizon is reduced to 60 %, because of poor root development.

The *ACRU* model inputs are shown in Table 4.3. Following the above assessment of model inputs for degraded areas, model inputs for agricultural land uses will be examined next.

4.4.6 Hydrological processes and model inputs related to dryland agricultural land uses, inclusive of sugarcane and tree plantations

With the exception of sugarcane and tree plantations, the land use data from Ezemvelo (2011) does not distinguish between different types of annual commercially-grown dryland crops. From field visits, however, improved pasture was found to be by far the dominant crop, although small areas of maize fields were found as well. For the HRU of each catchment unit which represents dryland crops, i.e. HRU 2, the dominant land use was therefore chosen and the land use-related ACRU inputs assigned as in Table 4.4.

Table 4.3 Month-by-month *ACRU* input for degraded areas, obtained by adjusting baseline land cover inputs, as per the rules laid out by Schulze (2013)

LAND USE	*ACRU* Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KZN Hinterland Thornveld - Degraded	CAY	0.54	0.54	0.54	0.36	0.29	0.20	0.20	0.20	0.39	0.50	0.54	0.54
	VEGINT	0.80	0.80	0.80	0.80	0.75	0.70	0.70	0.70	0.75	0.80	0.80	0.80
	ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COIAM	0.10	0.10	0.10	0.15	0.15	0.20	0.20	0.20	0.20	0.15	0.10	0.10
	COVER	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
	PCSUCO	10	10	10	10	10	10	10	10	10	10	10	10
	COLON	60	60	60	60	60	60	60	60	60	60	60	60
Eastern Valley Bushveld - Degraded	CAY	0.54	0.54	0.54	0.46	0.39	0.20	0.20	0.29	0.43	0.54	0.54	0.54
	VEGINT	1.25	1.25	1.25	1.10	1.00	1.00	0.95	0.95	1.10	1.25	1.25	1.25
	ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	0.95	0.90	0.80	0.80	0.80
	COIAM	0.10	0.10	0.10	0.15	0.15	0.20	0.20	0.20	0.20	0.15	0.10	0.10
	COVER	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
	PCSUCO	10	10	10	10	10	10	10	10	10	10	10	10
	COLON	60	60	60	60	60	60	60	60	60	60	60	60

Table 4.4 Month-by-month *ACRU* input variables for improved pastures, representing dryland crops other than sugarcane and tree plantations (Schulze, 2004)

LAND USE	*ACRU* Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dryland agriculture: Improved Pastures hydrologically represented by *ACRU* CROPNO 2030107	CAY	0.65	0.65	0.65	0.55	0.40	0.20	0.20	0.20	0.40	0.50	0.65	0.65
	VEGINT	1.20	1.20	1.20	1.20	1.10	1.00	1.00	1.00	1.00	1.10	1.20	1.20
	ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	COVER	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	PCSUCO	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5
	COLON	60	60	60	60	60	60	60	60	60	60	60	60

The land use class "plantations", which in the Ezemvelo description are production tree plantations, was observed during site visits to consist of unmanaged black wattle (*Acacia mearnsii*) patches, and appear to be partly planted, but mainly self-propagated, as this alien invasive species is known to do. The trees that were found are of varying heights and ages. The inputs related to tree plantations were adjusted, to account for the observed conditions. Should both land uses, sugarcane and tree plantations, be present in a CU, the areas were then added and the land use-related inputs from the dominant one were used (cf. Table 4.5).

Table 4.5 Month-by-month *ACRU* input variables for sugarcane and unmanaged wattle tree plantations (Sources: Schulze, 1995; 2013)

LAND USE	*ACRU* Variable	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Sugarcane: Inland Areas hydrologically represented by *ACRU* CROPNO 5200704	CAY	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	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
	ROOTA	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
	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
	COVER	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
	PCSUCO	90	90	90	90	90	90	90	90	90	90	90	90
	COLON	70	70	70	70	70	70	70	70	70	70	70	70
Wattle Plantations, hydrologically represented by Wattle with no specific site preparation and of intermediate age	CAY	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
	VEGINT	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
	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
	COIAM	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
	COVER	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	PCSUCO	95	95	95	95	95	95	95	95	95	95	95	95
	COLON	60	60	60	60	60	60	60	60	60	60	60	60

Other hydrologically important land uses include dams, the model inputs of which are examined next.

4.4.7 Hydrological processes and model inputs related to dams

The presence of dams influence streamflows by storing water, by abstractions of stored water for agricultural (irrigation or livestock), municipal and industrial uses and by releases (or the absence of releases) for environmental purposes. Dams also have an attenuating effect on floods, as well as reducing downstream flow variability. Evaporation losses occur from dams and they may or may not incur losses as a result of seepage.

Multiple dams within a CU are modelled in *ACRU* by aggregating the dam surface areas at the outlet of the CU. In this study, data for the surface areas at full supply capacity were obtained from KZN-LU (Ezemvelo, 2011) land cover Class # 36 "Water dams", rather than from the DWA's (2013) WARMS database, because that was found not to contain all the dams within the Mpushini/Mkhondeni Catchment. The aggregated dam surface areas of each CU are rounded to the nearest hectare. This is represented by the *ACRU* input variable SURFAR, which is the sum of all dam surfaces at full supply capacity (FSC). The computation of dam volumes at FSC is more complex, however, when multiple dams are considered within a CU and when the volume is not given in DWA databases. In such cases, the volume of each individual dam is first calculated, using the Tarboton and Schulze (1992) formula:

$$V = 0.07702 * A^{1.2987},$$

where

A is the dam surface area at FSC in m^2,

V is the volume of the individual dam at FSA in m^3.

Because of the non-linear form of the above equation, the individual capacities of all dams within each CU are then aggregated to produce the *ACRU* input variable DAMCAP, which is defined as the sum of all dam capacities, in m^3, at FCS. Information on dams is given in Table 4.6. Further relevant model inputs, with the modelled values in brackets, are:

a) ARCAP: an identifier to specify whether or not a relationship between a predetermined surface area to storage volume exists (6 = no area to volume relationship is available);
b) SEEP: seepage (m^3 per day) through the reservoir wall or base (taken to be 1/1500 of full supply capacity for earth walled dams; Smithers and Schulze, 1995);
c) PERDAM, which is the initial reservoir storage at the beginning of the simulation, expressed as a percentage of the full supply capacity (assessed to be 50 %);
d) PANDAM(I), which is the monthly coefficient to adjust A-pan equivalent evaporation losses to those of extensive water bodies, with the monthly values previously determined for Zone 3, which is the zone within South Africa in which the Mpushini/Mkhondeni Catchments are located (0.68 for January, 0.69, 0.71, 0.69, 0.67, 0.65, 0.60, 0.59, 0.60, 0.62, 0.63, 0.63 for December; Smithers and Schulze, 1995).

To account for the influence of dams under current land use conditions, as well as for irrigation, which will be discussed next, a model run can be performed with the relevant inputs either switched off or switched on, and the model outputs can then be compared.

Table 4.6 The number of dams per CU and values of *ACRU* input variables SURFAR and DAMCAP

CU	No. of Dams	SURFAR (ha)	DAMCAP (m^3)
1	23	34	614 366
2	5	3	30 609
3	12	4	38 312
4	12	7	75 519
5	4	2	22 297
6	13	6	64 004
7	0	0	0
8	7	8	109 793
9	5	2	24 569
10	3	2	15 039

4.4.8 Hydrological processes and model inputs for irrigation

Irrigation is a major user of stored water in South Africa and is considered a hydrologically critical land use. Within the KZN-LU coverage (Ezemvelo, 2011b), 386 ha of "#17, annual commercial crops, irrigated" were identified within the study area. However, according to the WARMS database (DWA, 2013), for the same catchment the registered area under irrigation is only 64 ha. This is a significant discrepancy. Neither of the databases is considered entirely accurate. On the one hand, it seems difficult to identify irrigated areas from satellite imagery as used for the KZN-LU because the images are taken at a specific point in time when the irrigation areas might or might not show up. On the other hand, there are numerous smaller-scale irrigated fields that are not identified in the DWA (2013) WARMS database, which only has three registered users within the study area. The dominant irrigated crop registered in the WARMS database is ryegrass. From field visits, ryegrass, along with irrigated kikuyu pasture, was confirmed as the dominant irrigated crop. The main mode of irrigation water application for the study area is by overhead sprinklers (field observations and DWA, 2013). In light of the above uncertainties, the area under irrigation as determined from KZN-LU (Ezemvelo, 2011b) was taken as the more correct one. Ryegrass was chosen as the representative crop. As observed from fieldwork, irrigation was input to take place throughout the year, with application throughout by sprinklers. The irrigation water was abstracted out of a dam and it was found from field visits that the irrigation and the reservoir were situated within the same CU. Based on the above observations and assumptions, the relevant *ACRU* inputs were determined from Schulze (1995), Smithers and Schulze (1995), KZN-LU (Ezemvelo, 2011b) and DWA (2013). Explanations of the irrigation input variables follow, with the inputs used for the model run given in brackets, in the case of default values these being taken from Smithers and Schulze (1995).

a) IRRIGN: switch to specify whether or not an irrigation simulation is to be performed (1 = Yes);
b) IRRMON(I): option to specify those months in which irrigation will be applied (1 = Yes, for every month);
c) HAIRR(I): the area (in ha) to be irrigated in a given month (CU 1 = 49 ha, CU 2 = 34, CU 3 = 24, CU 6 = 7, CU 8 = 15 ha);
d) COIAIR(I): coefficient of initial abstraction for the irrigated area input, on a month-by-month basis (0.3 for every month);
e) IRRPED: option to specify that, in addition to soil textural information, soil water retention values for the drained upper limit, permanent wilting point and saturation are available (1 = Yes);
f) WPIR: soil water content (m/m) at permanent wilting point for the soil being irrigated (0.16 m/m);
g) FCIR: soil water content (m/m) at the drained upper limit for the soil being irrigated (0.26 m/m);
h) POIR: soil water content (m/m) at saturation for the soil being irrigated (0.5 m/m);
i) CAYIRR(I): the area-weighted average monthly crop coefficient for the irrigated crop. CAYIRR is the proportion of water evaporated and transpired by the soil/plant complex under conditions of maximum evaporation in relation to the evaporation by an A-pan for the month under consideration (0.7 for every month);
j) DINTIR(I): the canopy interception loss, either from rain or an irrigation application for the crop under irrigation (1.5 mm);
k) RDMAX: the potential maximum rooting depth (m) of the irrigated crop (0.6 m);
l) RDUP: soil depth (m) to which the majority of soil water extraction takes place for a fully grown irrigated crop (0.3 m);
m) CCOV: the crop coefficient of the irrigated crop when it is at full canopy (0.7);
n) CCMAX: the crop coefficient of the irrigated crop when the rooting depth reaches a maximum (0.7);
o) ISCHED(I): the mode of irrigation scheduling input on a month-by-month basis (1 = Yes, demand irrigation in all months);

p) STPRO(I): the proportion of plant available water at which irrigation water applications are initiated (0.5);
q) CONLOS: the conveyance losses (fraction) between source of water supply and the application point (0.15, assuming highly efficient systems);
r) EVWIN: the spray evaporation and wind drift losses (fraction) after leaving the irrigation nozzle (0.11, a typical value for sprinkler);
s) IRSPLY: variable to specify from which catchment number (ICELLN) irrigation water is supplied (1 = Yes, from the same catchment as that of the dam);
t) IRRAPL: the source of water supply e.g. from a dam or run-of river (1 = Irrigation from dams);
u) INCELL: variable to specify whether irrigation is applied within the CU under consideration (1 = Yes, within the CU); and
v) UPSTIR: the location of the irrigated field relative to the reservoir, i.e. whether the irrigation is upstream or downstream of the dam supplying water (1 = upstream).

In the modelling setup, should irrigation occur within a CU, the area under irrigation is assigned to the fifth HRU (cf. Section 4.3.4). To account for the influence of dams and irrigation, a model run can be undertaken with the relevant inputs either switched off or switched on, and the model outputs then compared.

After having discussed the inputs for irrigation, the inputs relating to hydrologically critical land uses with impervious areas follow.

4.4.9 Hydrological processes, model inputs and calculations related to impervious areas

Urban land uses have various degrees of impervious areas in the form of roofs, roads, parking lots and other hardened surfaces. These result in increases in stormflow, which can discharge directly into receiving streams, while baseflows from those areas are generally depleted through decreased pervious areas (cf. Section 4.4.12; Schulze, 2013). The fractions of impervious surfaces within the area under consideration therefore need to be determined. A distinction has to be made between impervious areas that discharge water directly to a stream, these being classed as *adjunct* impervious areas, with the fraction expressed by the *ACRU* variable ADJIMP, and impervious surfaces that discharge any water into surrounding pervious areas which are not linked directly to a stream, these being classed as *disjunct* impervious areas, with the fraction expressed by the *ACRU* variable DISIMP. A small initial amount of rainfall is abstracted from impervious areas before surface runoff from them commences (*ACRU* variable STOIMP). This is set at 1 mm, following Tarboton and Schulze (1992). KZN-LU Class # 12, "built up - dense settlement" (Ezemvelo, 2011) was assessed within the study area by using Google Earth images and were found to be dense industrial areas, found only in CU 9. For these dense industrial areas, the impervious fractions were set after making a visual assessment from Google Earth and from fieldwork, while for the remainder of Class # 12, as well as for "low density settlements" (Class #14) and for smallholdings grassland (Class #30), the rules determined by Schulze (2013) for urban areas were followed when assigning fractions. Impervious fractions of the transport routes (Classes #34-36) and the quarry (Class #11) within the were assessed from fieldwork. The fractions for impervious areas for the relevant land uses are shown in Table 4.7.

Table 4.7 Fractions of adjunct and disjunct impervious areas for relevant KZN-LU classes, with the sources of fractions from Schulze (1995), Google Earth and from field observations

KZN-LU Class	KZN-LU Description	Observations from Fieldwork	Fraction of Adjunct Impervious Area	Fraction of Disjunct Impervious Area
11	Mines and quarries	Quarry only, near river	0.50	0.30
12	Built up dense settlement (industrial)	High density	0.50	0.30
12	Built up dense settlement (residential)	Formal residential, high density	0.50	0.15
14	Low density settlements	Formal residential, low density	0.00	0.10
30	Smallholdings – Grassland	Very low density	0.00	0.05
34	KZN national roads	With grass strip between lanes	0.10	0.60
35	KZN main & district roads	No grass strip	0.10	0.70
42	KZN railways	Assume all rainfall infiltrates	0.00	0.00

Every HRU for every CU is modelled individually. Therefore, the impervious fractions for every applicable HRU (*i.e.* the first HRU per CU) needed to be calculated separately for adjunct and disjunct impervious areas, by following the steps below:

a) The impervious area of each land use class within HRU 1 of the respective CU is calculated by the product of the impervious fractions of each class in Table 4.7 and the respective area (km^2) of HRU 1.
b) The impervious area (in km^2) of the respective catchment unit (CU) is calculated by the sum of the impervious areas of the various land use classes found in that CU.

c) The area (km^2) under impervious land uses is then assigned to HRU 1 of a CU (cf. Section 4.3.4)

d) Within HRU 1 the impervious fraction is then calculated as the quotient of the impervious area and the total area of the HRU.

Using the rules and assumptions above, the impervious fractions were calculated and are shown in Table 4.8.

Table 4.8 Calculated fractions of adjunct and disjunct impervious areas (*ACRU* variables ADJIMP and DISIMP) within HRU 1 of each catchment unit (CU), for current and proposed land use scenarios, with the CUs affected by proposed land uses shaded

HRU 1 of CU	Current Land Use	Current Land Use	Including Proposed Development	Including Proposed Development
	ADJIMP	DISIMP	ADJIMP	DISIMP
1	0.018	0.045	0.018	0.047
2	0.018	0.043	0.076	0.088
3	0.033	0.130	0.316	0.341
4	0.080	0.167	0.126	0.180
5	0.019	0.032	0.064	0.183
6	0.054	0.093	0.072	0.155
7	0.018	0.049	0.018	0.049
8	0.008	0.048	0.227	0.632
9	0.042	0.051	0.093	0.190
10	0.037	0.015	0.037	0.015

In the section above, the methods of identifying and calculating impervious fractions were described. Another important consideration for modelling is that of return flows of water used for industrial and domestic purposes, where the water used may come from sources either external to the study catchment or from within the catchment. This will be discussed next.

4.4.10 Hydrological processes and model inputs related to return flows

This particular study catchment receives all its treated water for residential and industrial purposes from sources outside of the study area. This water becomes part of the study area's water budget and has to be considered when return flows are calculated, as this adds to downstream streamflow. It needs to be borne in mind that this water is removed from the water budget of another catchment of the uMgeni Catchment, outside of the study area. It is likely that this might have negative effects in the supply catchment, similar to the ones of inter-catchment transfers (WWF, 2009; cf. Section 2.3.3).

The study catchment's treated water is supplied by different municipalities and other service providers. It has proven difficult to obtain figures of the amount of externally sourced water supplied to the study area. For the current land use scenario, the following was therefore assumed:

a) For the dense industrial area of Mkhondeni (situated within CU 9), the effluent and grey water is pumped towards a wastewater works situated outside the study area. Therefore no return flows into the study area are applicable.
b) The bulk of the remaining area operates on septic tank systems or conservancy tank systems. Any water contributing from these sources was disregarded, as the return flows from these are very low and no scientific data on tank systems are available for this area.
c) The only area that has a centralised sewerage treatment system is Lynnfield Park, situated within CU 4. The Lynnfield Park wastewater treatment works currently runs at a capacity of 6000 kl/month, and this figure was used as the return flow for CU 4 (cf. Table 4.10).

The proposed land uses are likely to significantly increase downstream return flows. In order to determine the return flow values, the individual proposed developments are first allocated into the respective catchment units (cf. Section 3.4.3). The return flows per development application were then established, using the following rules:

a) Where the return flows were given in an application, this value was used.
b) Where this was not available, a water supply of 200 l per person per day was assumed, of which 50 % was assumed to become return flows (Schulze, 2013). This equals return flows of 100 l per person per day or 0.3 kl per person per month.
c) For residential developments, four people were assumed to occupy a dwelling. This generates a return flow of 1.2 kl per dwelling per month. This figure was multiplied by the number of proposed dwellings determined from the various development applications.

d) For current industrial/commercial developments, no return flows were found to enter the channels within the study area. For the proposed industrial and commercial developments, return flows of 400 l per 100 m^2 floor space per day are assumed, following the CSIR (2005) guidelines, i.e. 120 000 kl per month per km^2 floor space. This figure was multiplied by the proposed development footprint (in km^2), rather than the size of the property, where the industrial footprint was obtained from the various development applications (PMMB Trust, 2012).

Using the rules and assumptions above, the return flows for each of the development applications were determined and are shown in Table 4.9. The return flows per catchment unit were then aggregated for current, as well as for proposed, land uses (Table 4.10).

Table 4.9 Determination of return flows for the proposed land uses per catchment unit and per development application, either determined (*) directly from the development application, or (**) based on the number of houses and calculated, or (***) based on the development footprint and then calculated, with all information sourced from the development applications

Development Name	CU Location	Application*	Number of Dwellings	Flow from Dwellings**	Development Footprint	Industrial/Commercial ***	Total Return Flow
				kl	km^2	kl/month	kl/month
Ashb_Res_Dev	1		25	300			300
Hutton	2				0.50	60000	60000
Tanglethorn	2		18	216			216
Umlaas Gates	2				0.26	31200	31200
Phoenix	3				0.19	22800	22800
Composting	3				0.10	12000	12000
Hutton	3				0.50	60000	60000
Ibhubezi Industrial Park	3				0.73	87600	87600
Lion	3				0.25	30000	30000
Rita	3				0.19	22800	22800
Mpushini Business Park	4				0.43	51600	51600
Kingthorpe	5		800	9600			9600
Mkhonto	6		20	240			240
	7						0
Foxhill	8		500	6000			6000
Ithaba Ridge	8		200	2400			2400
Ashburton Shopping Centre	9				0.15	18000	18000
Burton Heights	9		490	5880			5880
Hillcove Hills	9	57000			2.53	303600	57000
Shorts Retreat Industrial Zoning	9				0.18	21600	21600
	10						0

Table 4.10 Return flows per CU for current land uses as well as for proposed land uses, in kl/month and in 10^6 kl/month for the *ACRU* variable PUMPIN

CU	Current LU	Proposed LU	Current LU PUMPIN	Proposed LU PUMPIN
	(kl/month)	(kl/month)	(10^6 kl/month)	(10^6 kl/month)
1		300		0.000
2		91416		0.091
3		235200		0.235
4	6000	57600	0.006	0.058
5		9600		0.010
6		240		0.000
7		0		0.000
8		8400		0.008
9		102480		0.102
10		0		0.000

In order to model return flows with the *ACRU* model, a so-called "dummy dam" was created at the outlet of HRU 1 of the required CU, in order to capture the return flow by assuming them to be conveyed to the dummy dam (*ACRU* variable PUMPIN). The model variables relating to dams have been explained previously in Section 4.4.7. The dummy dam was assumed to have a very small surface area (SURFA = 0.1 ha) and a small capacity (DAMCAP = 10000 m^3), in order to constantly spill over return flows. Standard PANDAM values for the dam's surface area, were applied. The dummy dam was assumed to be full at the commencement of a simulation (PERDAM = 100 %). From the return flows (Table 4.10), the *ACRU* input PUMPIN (in 10^6 kl/month) was calculated. On the assumption that return flows from domestic and industrial areas do not vary seasonally, it was assumed that the PUMPIN inputs from January to December remain constant.

In addition to the land use-related *ACRU* model inputs discussed in the previous sections, it is also necessary to configure and interlink the CUs and HRUs within the model, to be able to distinguish between accumulated effects and local effects. This requires model inputs relating to catchment configurations.

4.4.11 Hydrological processes and model inputs related to catchment configurations

Water flows from higher altitude CUs into CUs of lower altitudes, and flows are thus accumulated downstream. The interlinked flow path between upstream and downstream CUs needs to be specified, as shown previously in Figure 4.3, as do the configurations between the HRUs within each CU, as shown previously in Figure 4.5. Within the *ACRU* model, the variable IDSTRM represents the flow path between the HRUs within a CU and flow paths from one CU to the next one downstream. After having discussed inputs relating to various land uses and configurations, the relevant outputs from the *ACRU* model will be examined next.

4.4.12 Hydrological responses, represented by the *ACRU* model outputs

The above established input information is transformed by the *ACRU* model by considering the interactions between climate, soil, vegetative, hydrological and management subsystems. These include thresholds, lag rates and feedbacks. The model then computes the selected outputs, which are simulated, unmeasured hydrological responses. These include "blue water" flows (cf. Section 2.3.2) of daily streamflows (including contributions from upstream HRUs and CUs, runoff from the individual HRU within the CU, and its components of stormflows and baseflows, high and low flows and extreme events). The outputs also include "green water" flows of evaporative losses, made up of plant transpiration, and "white water" flows, made up of soil water evaporation and canopy interception losses. Further to the above, sediment yields are also calculated (Schulze, 1995 and updates; Smithers and Schulze, 1995 and updates; Schulze, 2013). All the above outputs are available as daily, monthly or annual averages and as a frequency analysis. For this study the primary output from the model was on an individual HRU basis, with the ability to then aggregate results to a catchment unit or to the entire catchment, and with the streamflows generated per HRU cascading downstream, according to hydrological flow paths (Figure 4.3) and eventually to the outlets of the Mpushini and Mkhondeni Catchments into the Msunduzi River.

A detailed explanation of the internal computation of the *ACRU* model is beyond the scope of this dissertation and the reader is referred to general *ACRU* literature (e.g. Schulze, 1995 and updates; Smithers and Schulze, 1995 and updates).

The relevant *ACRU* outputs in this study are stormflow, baseflow, runoff, accumulated streamflow, sediment yield and total transpiration, together with extreme runoff events.

Stormflow (*ACRU* output variable QUICKF, in mm equivalent) is defined as water which is generated from a specific rainfall event, either at or near the surface, to contribute to flows in the channel of the HRU. Stormflow is a response to climatic and biophysical inputs, e.g. the magnitude of the rainfall event, how wet the soil is just prior to the rainfall event, slope, soil properties, as well as land cover-related variables affecting infiltration, for example, canopy and soil cover and impervious fractions. Not all the stormflow generated by a specific rainfall event exits the HRU or CU on the same day as the rainfall event, and it can be lagged by a response coefficient QFRESP to yield the stormflow fraction on a specific day. The stormflow exiting a catchment on a specific day is termed "quickflow".

Baseflow (*ACRU* variable RUN, in mm equivalent) is defined as the delayed water from rainfall that has percolated through the soil horizons into the intermediate and groundwater zones and which then contributes as a delayed flow to the streams within a HRU.

Runoff (*ACRU* variable SIMSQ, in mm equivalent) is the water yield from an individual HRU and consists of stormflow plus baseflow. The land use-related variables that influence the partitioning of runoff into stormflow or baseflow are, *inter alia*, the infiltration rate, canopy and soil cover, as well as the fractions of impervious areas.

Streamflow (*ACRU* variable CELRUN, in mm equivalent) consists of runoff from the HRU under consideration plus the runoff contribution from all upstream HRUs.

Sediment yield (ACRU variable SEDYLD, in t) consists of the soil detached from a landscape after a rainfall runoff event, which reaches the stream and results from the interaction of slope, vegetation cover and management characteristics, with the peak discharge of an event as the detaching agent and stormflow as the sediment transporting agent.

Extreme runoff events: In the case of this study, frequency distributions of extreme runoff events were computed by modelling the annual maximum series of daily runoff with the log Pearson Type 3 extreme value distribution, to yield statistically expected maximum runoff and accumulated streamflows for the 2-, 5-, 10-, 20- and 50-year return periods.

Total transpiration: This is water that has actually flowed from the soil via a plant into the atmosphere. This water is used by the plant to produce biomass. The total transpiration is calculated by adding the transpiration from the topsoil horizon *(ACRU* variable ATRAN1, in mm) to the transpiration from the subsoil horizon (ATRAN2 in mm). Note that these *ACRU* outputs are for the pervious areas only. If impervious areas are present, the result needs to be multiplied with the fraction of the pervious area, which is calculated by 1-ADJIMP-DISIMP.

The *ACRU* outputs relevant for this study have been described above. In the analyses which follow in Chapter 5, numerous monthly and annual statistics of these outputs are presented. These statistics might be arithmetic *mean* values, while *median* values, e.g. of flows, sediment yields, rainfall, etc., denote the 50^{th} percentile of a frequency analysis of the variable being analysed, and a median value of a time series will be exceeded as often as it will not be exceeded. A 1:10 high value (e.g. 1:10 high flow year, or 1:10 wet year) denotes the 90^{th} percentile of a time series, and it implies that statistically that value will be exceeded only in 1 year in 10. Similarly, the 1:10 low value (e.g. 1:10 low flow year, or 1:10 dry year) implies that that value is exceeded in 90 % or more of years. Furthermore, in the hydraulic design of, for example, stormwater systems or spillways from dams, the statistically expected runoff for a given recurrence interval, i.e. the return period, is termed design runoff. This is an *ACRU* model output and in this study the 2, 5, 10, 20 and 50 year return periods were evaluated.

4.5 From hydrological responses to hydrological ecosystem services

To be able to evaluate changes to hydrological ecosystem services (cf. Section 2.3), a link has to be established between the hydrological responses (cf. Section 4.4.12) and ecosystem services. Ecosystem services often cannot be measured directly. They can, however, be measured by suitable indicators or by proxy information. In the case of hydrological ecosystem services, frequently modelled process responses are used in practice (Egoh *et al.*, 2012a; Section 2.3.5). Building on the hydrological ecosystem frameworks of Aylward *et al*. (2005), de Groot (2006) and Brauman *et al.* (2007), outlined in Table 2.1, and trying to reduce the identified gap in the literature (Section 2.6), an approach for linking these frameworks to modelled hydrological responses as indicators with the *ACRU* model is shown in the conceptual framework in Table 4.11. The relevant process model outputs relating to hydrological flows, representing the hydrological responses and functions, are used in this study as indicators of relevant ecosystem services. Changes in these indicators, resulting from land use changes, serve as proxy information for changes in associated hydrological ecosystem services. These will be shown in Section 5.7 and discussed in Section 6.3 of this dissertation.

Table 4.11 Links between hydrological ecosystem functions, hydrological responses and *ACRU* model outputs

Hydrological Ecosystem Functions	**Ecosystem Processes and Components**	**Examples of Hydrological Ecosystem Services**	**Hydrological Attributes**	**Suggested Hydrological Indicator**	***ACRU* 3.1. Output**	**Change in Response**
Provisioning function	The role of the landscape to collect and influence precipitation	Water quantity for consumptive use (for drinking, domestic, agricultural or industrial uses) and non-consumptive use (for generating power and transport/navigation)	Quantity (surface and groundwater storage and flow) Low flow periods Timing	Runoff and/or accumulated streamflow	SIMSQ and/or CELRUN	• Annual and monthly magnitudes • Low flow seasonality • Low flow duration
		Water quality for consumptive or non-consumptive use)	Quality (sediment)	Sediment yield	SEDYLD	Magnitude
			Quality (pathogens, nutrients, salinity)	Other indicators required, e.g. chemical analyses of sediments for e.g. nutrient load and bacteria, etc.	N and P outputs	Annual loads
	Provision of natural resources Conversion of solar energy into biomass for food, construction and other uses	Primary production: • Fuel and energy • Fodder • Building and manufacturing	The amount of water flowing through a plant	Transpiration	ATRANS1 + ATRANS2	Magnitudes and low transpiration during dry season
			Others, e.g. soil moisture, harvested yield	Net Above-Ground Primary Production	e.g. STO1, STO2,	Annual Magnitude and Inter-Annual Variability
		• Hunting of fish or game • Small-scale subsistence farming • Aquaculture	Others			
Regulation function: Disturbance prevention: Control of flow speed	Influence of ecological infrastructure in regulating runoff, river discharge and flood control, thereby attenuating environmental disturbances	Flood prevention, buffering of flood flows	High flow periods, peak flow magnitudes, as well as its timing, duration and velocity	One day design runoff (for selected return periods) (extreme value analyses)	EVD	Magnitude
				Stormflow component of runoff	QUICKF	Magnitude
				Runoff and/or accumulated stormflow for high flow periods	SIMSQ and/or CELRUN	Magnitude
		Erosion control		Sediment yield	SEDYLD	Magnitude
Regulation function: Water regulation	Role of land cover and ecological infrastructure in regulating runoff and river discharge	Drainage and natural runoff attenuation	Infiltration and sustained soil moisture	Runoff and/or accumulated streamflow	SIMSQ and/or CELRUN	Changes in annual magnitudes and monthly magnitudes, duration and seasonality of months with low flows
				Baseflow component of runoff	RUN	Changes in annual magnitudes and monthly magnitudes, duration and seasonality of months with low flows
Regulation function: Water supply	Natural filtration and treatment of fresh water	Provisioning of water for consumptive use (e.g. drinking, domestic, agricultural or industrial uses). Maintenance of water quality.	Natural filtration and water treatment to maintain or improve water quality	Sediment yield	SEDYLD	Magnitude
				And other indicators		
	Retention of fresh water		Infiltration and retention of water for slow release	Baseflow component of runoff	RUN	
				Others related to wetlands, groundwater recharge, soil moisture	SUR2, STO1, STO2	
	Short and long term storage of fresh water		Capacity within the natural system and in dams	Sediment yield	SEDYLD	Magnitude
				Others		
Regulation function: Soil retention	Role of vegetation root matrix and soil biota in soil retention	• Maintenance of arable land • Prevention of damage from erosion/siltation	Infiltration	Sediment yield	SEDYLD	Magnitude
				Others		
Supporting function		• Predator/prey relationships and ecosystem resilience		Others		
Supporting function: Habitat functions: Habitat and nursery function	Providing suitable living and reproduction habitat	• Maintenance of biological and genetic diversity (basis of most other functions) • Maintenance of commercially harvested species	Natural flow paradigm and boundary approach (e.g. Richter *et al., 1997)*	Streamflows, peakflows, and others	CELRUN QPEAK	

4.6 Chapter Conclusions

In this chapter, the expected hydrological implications of the various land cover and land use scenarios were described, followed by the method of sub-delineation of the study area. The concept of hydrological modelling was explained, with an account of why the *ACRU* hydrological model was selected. The model inputs were described, with an emphasis on the land use or land cover influenced hydrological variables and processes, followed by an explanation of the relevant hydrological responses, represented by their modelled outputs and their statistics. A conceptual framework was presented to link hydrological responses with hydrological ecosystem services.

5. RESULTS

Following the chapters on the Literature Review, the Background Information and on the Methods, the results of simulations will be described in this chapter.

5.1 Research Overview and Introduction

This chapter on results fits into the overall research objective and approach as shown in the overview provided in Figure 5.1.

Objective: To evaluate changes to selected hydrological responses and associated selected ecosystem services provided by the study area, as a result of current and proposed land use modifications

Approach: The objective is to be achieved by identifying the scenarios of baseline land cover as well as current and proposed land uses; sub-delineating the study area into land use determined hydrological response units; applying an appropriate hydrological simulation model to assess changes in hydrological responses from baseline land cover as well as current and proposed land uses; and relating these changes in hydrological responses to changes in selected ecosystem services

Sections

Chapter 1 Introduction	Chapter 2 Literature Review	Chapter 3 Catchment Description	Chapter 4 Methods	Chapter 5 Results	Chapter 6 Discussion

Chapter Outline:
- Introduction
- Baseline Land Cover Hydrology
- Understanding Impacts of Current Land Uses on Hydrological Responses
- Understanding Impacts of Proposed Land Uses on Hydrological Responses
- Linking Changes of Hydrological Responses and Ecosystem Services

Figure 5.1 Results and outline of Chapter 5 within the context of this dissertation

In this chapter a summary of the catchment's division into CUs and HRUs and a dissection of land uses per CU will be presented first. Thereafter, various hypotheses on hydrological responses are proposed. These hypotheses are tested within the Mpushini/Mkhondeni study area, using the hydrological responses represented by the outputs of the *ACRU* hydrological model for baseline land cover conditions and thereafter for the effects of current land uses and proposed developments on the hydrological responses. Conceptual links between model outputs and hydrological ecosystem services are then discussed and the changes in hydrological responses found for the study catchment are thereafter linked to changes in hydrological ecosystem services.

5.2 The Delineation of the Study Area into Catchment Units (CUs) and Hydrological Response Units (HRUs), Based on Land Use

The areas of the CUs and HRUs were determined, based on the methodology explained in Section 4.3. A summary is shown in Table 5.1 and the detailed breakdown in Table 5.2.

Table 5.1 A summary for the Mpushini/Mkhondeni study area, of the areas per catchment unit (CU), made up of areas of hydrological response units (HRUs)

Area (km^2)	CU 1	CU 2	CU 3	CU 4	CU 5	CU 6	CU 7	CU 8	CU 9	CU 10
Total area HRU 1	18.00	5.23	2.73	4.65	5.01	2.19	5.51	3.30	13.60	1.28
Total area HRU 2	1.84	1.61	2.38	1.75	1.55	2.10	0.30	2.13	1.25	0.14
Total area HRU 3	5.07	0.41	0.05	0.00	0.10	0.00	0.00	0.07	0.03	0.00
Total area HRU 4	10.45	0.96	1.76	1.79	3.56	0.85	1.50	4.28	3.45	1.06
Total area HRU 5	2.21	0.33	0.28	0.07	0.02	0.14	0.00	0.73	0.03	0.05
TOTAL	37.57	8.54	7.21	8.26	10.24	5.28	7.32	10.51	18.36	2.53

Table 5.2 A detailed breakdown of the determined areas per CU, HRU and aggregated land use class, making up the Mpushini/Mkhondeni study area

Ezemvelo Land Use Class		CU 1	CU 2	CU 3	CU 4	CU 5	CU 6	CU 7	CU 8	CU 9	CU 10	CU 1-10
Number	Description											
	HRU 1 Natural vegetation and urban land uses											
	NATURAL VEGETATION											
18	Forest (indigenous)	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.04
19	Dense thicket & bush (70-100 % cc)	2.95	1.41	0.30	0.40	0.90	0.22	1.64	0.55	1.74	0.38	10.49
20	Medium bush (< 70cc)	5.13	1.55	0.44	0.48	0.78	0.31	1.20	1.25	3.73	0.43	15.31
21	Woodland & Wooded Grassland	0.15	0.00	0.01	0.09	0.02	0.02	0.06	0.01	0.03	0.03	0.42
22	Bush clumps / Grassland	2.32	0.88	0.65	0.66	1.50	0.70	0.85	0.60	1.39	0.26	9.82
23	Grassland	4.71	0.55	0.29	0.26	1.32	0.19	1.10	0.43	4.24	0.06	13.14
4	Wetlands	0.00	0.00	0.05	0.00	0.00	0.04	0.00	0.00	0.01	0.00	0.10
	URBAN LAND USES											
12	Build-up / dense settlement	0.47	0.15	0.10	0.60	0.16	0.19	0.02	0.02	1.00	0.09	2.81
14	Low density settlements	1.11	0.44	0.39	1.37	0.19	0.31	0.24	0.21	0.70	0.02	4.99
34	KZN national roads	0.00	0.00	0.08	0.46	0.00	0.15	0.00	0.00	0.38	0.00	1.07
35	KZN main & district roads	0.85	0.16	0.31	0.27	0.14	0.08	0.27	0.19	0.27	0.00	2.54
42	KZN Railways	0.29	0.08	0.09	0.05	0.00	0.00	0.00	0.04	0.09	0.00	0.65
11	Mines and quarries	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.13
	Total area HRU1	**18.00**	**5.23**	**2.73**	**4.65**	**5.01**	**2.19**	**5.51**	**3.30**	**13.60**	**1.28**	**61.50**
	HRU 2 Agriculture, dryland, improved pasture											
16	Cultivation, commercial, annual crops, dryland	1.16	0.66	1.70	0.17	1.19	2.07	0.00	2.09	0.30	0.00	9.32
30	Smallholdings	0.68	0.95	0.68	1.59	0.36	0.03	0.30	0.04	0.94	0.00	5.58
13	Golf courses (Race Course)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.14	0.15
	Total area HRU2	**1.84**	**1.61**	**2.38**	**1.75**	**1.55**	**2.10**	**0.30**	**2.13**	**1.25**	**0.14**	**15.06**
	HRU 3 Special cases: Sugarcane or plantations											
9	Sugarcane, commercial, dryland	4.51	0.31	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.83
2	Plantation	0.56	0.10	0.04	0.00	0.10	0.00	0.00	0.07	0.03	0.00	0.89
	Total area HRU3	**5.07**	**0.41**	**0.05**	**0.00**	**0.10**	**0.00**	**0.00**	**0.07**	**0.03**	**0.00**	**5.72**
	HRU 4 Special cases: Degraded areas											
25	Degraded forest	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
26	Degraded bushland (all types)	1.45	0.23	0.07	0.18	0.64	0.10	0.54	0.54	1.53	0.05	5.34
27	Degraded grassland	1.05	0.29	0.02	0.49	0.95	0.24	0.85	0.06	0.56	1.01	5.52
28	Old fields - previously grassland	0.68	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.95
29	Old fields - previously bushland	7.24	0.17	1.67	1.11	1.97	0.51	0.12	3.69	1.36	0.00	17.84
	Total area HRU4	**10.45**	**0.96**	**1.76**	**1.79**	**3.56**	**0.85**	**1.50**	**4.28**	**3.45**	**1.06**	**29.67**
	HRU 5 Dams and irrigated areas											
17	Cultivation, commercial, annual crops, irrigated	1.87	0.31	0.24	0.00	0.00	0.07	0.00	0.66	0.00	0.00	3.14
36	Water (Dams)	0.34	0.03	0.04	0.07	0.02	0.06	0.00	0.08	0.02	0.02	0.68
1	Water (natural)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.04
	Total area HRU5	**2.21**	**0.33**	**0.28**	**0.07**	**0.02**	**0.14**	**0.00**	**0.73**	**0.03**	**0.05**	**3.82**
	TOTAL AREA	37.57	8.54	7.21	8.26	10.24	5.28	7.32	10.51	18.36	2.53	115.77

5.3 Hydrological Responses under Baseline Land Cover Conditions

In this section the results of hydrological modelling under the baseline land cover conditions (cf. Table 4.4) are presented. Bearing in mind the rainfall and temperature characteristics already discussed in Section 3.3, various hypotheses on hydrological responses are proposed. For each hypothesis, a catchment unit and a component HRU are then selected, to illustrate the localised and/or accumulated effects of the modelled hydrological responses for that particular hypothesis. The findings are then interpreted and the significance of the findings highlighted. The modelled runoff and its components of stormflow and baseflow are examined first. “Green”, “blue” and “white water” flows are then assessed, followed by an examination of sediment yield. Thereafter, relevant higher order hydrological responses, such as wet and dry year runoff, will be compared to equivalent frequencies of rainfall. The section concludes with a summary of the results of hydrological responses, and finally, the significance for linked hydrological ecosystem services will be highlighted.

5.3.1 Understanding the blue water flow responses

The blue water flows of the study area are made up of the runoff of individual HRUs, which are then aggregated into accumulated streamflow. The total runoff from a catchment is dependent on interactions of climatic, bio-geological and land use-related factors. The influence of various factors on runoff and its components of stormflow and baseflow will be explored next, by first stating a hypothesis and then testing it against modelled results.

- Hypothesis: Runoff varies seasonally as well as between years with median and high and low flows

The runoff under baseline land cover conditions was modelled and is shown in Figure 5.2 for a selected catchment unit, in this case HRU 1 of CU 1. The monthly and annual values are shown under conditions of the 1:10 year low flows, median and the 1:10 year high flows.

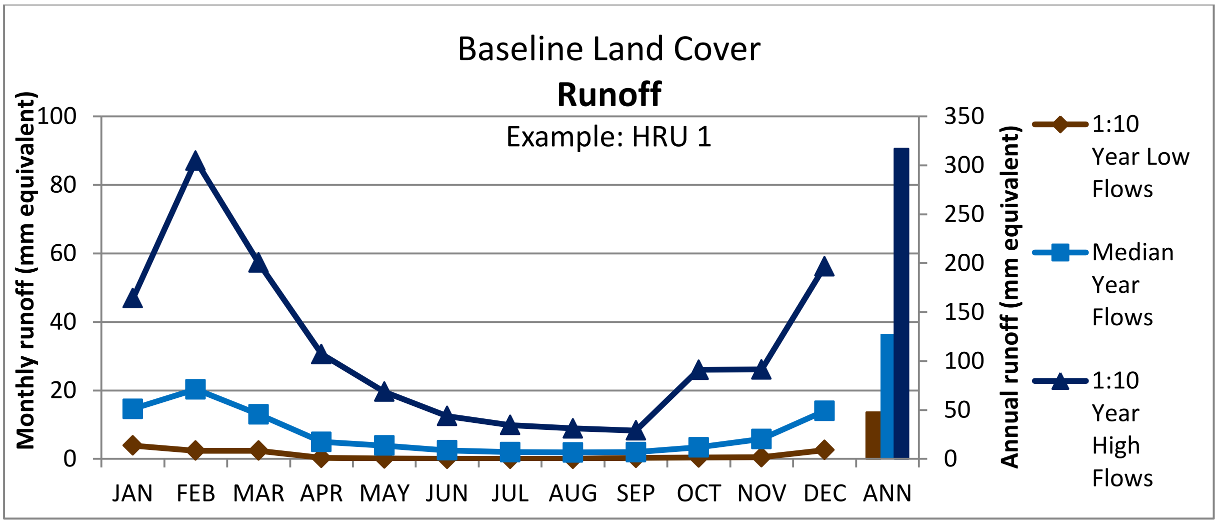

Figure 5.2 Monthly and annual runoff under baseline land cover conditions within HRU 1 of CU 1 of the Mpushini/Mkhondeni study area for years with median and 1:10 high and low flows

Interpretation of Figure 5.2: Most of the runoff occurs during the summer months, which is the wet season (October to March). The runoff can vary significantly from month to month. There are, furthermore, wide discrepancies between the wet and dry years, with a factor difference of 2.5 between years with median flows and 1:10 high flows. Similarly, there are wide discrepancies, by a factor of 2.7, between years with 1:10 low flows and median flows. For individual months, the differences are even greater than for annual statistics, e.g. February displays a factor difference of 4.3 between median and wet years and a factor of 8.5 between low flow and median years. This illustrates that the runoff can be significantly different between months and between years. During a year with 1:10 low flows, especially between April and November, the runoff is very low and can even be zero.

Significance: The above results show that the runoff in this catchment is highly variable within a year and between years, even without any added effects of current land use.

- Hypothesis: Runoff is made up of stormflow and baseflow, but the contributions to runoff are not equal and vary during the year

In order to explore the above hypothesis, the annual and monthly stormflows and baseflows are shown for a year of median flows in Figure 5.3 for HRU 1 of CU 1. The relative contributions of stormflows and baseflows are shown for HRU 1 of CU 1 in Figure 5.4 for a year with mean flows.

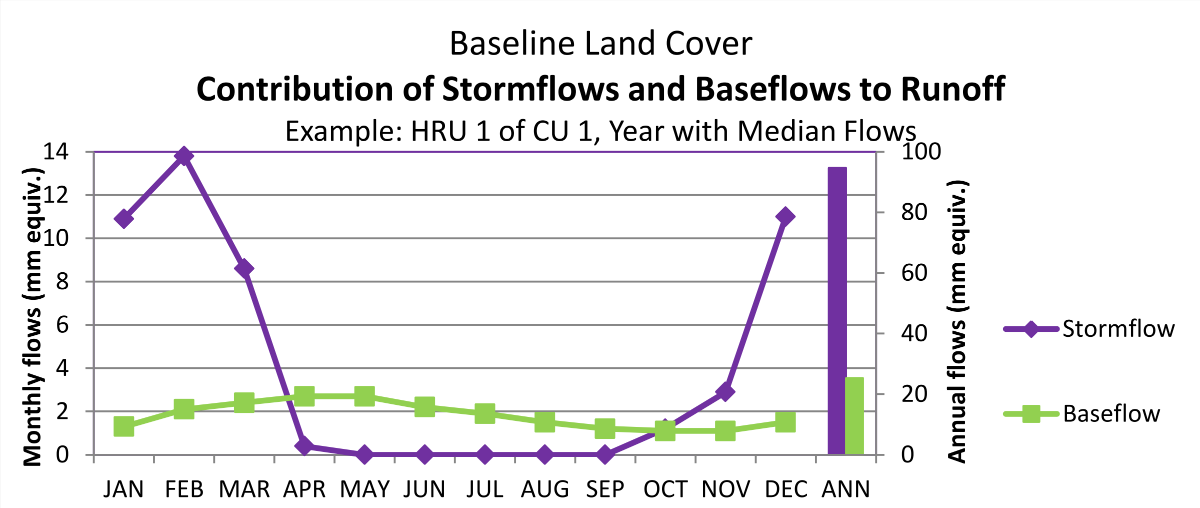

Figure 5.3 Monthly and annual stormflows and baseflows from HRU 1 of CU 1 under baseline land cover conditions, for median monthly and annual flows

Interpretation of Figure 5.3: The annual runoff is dominated by stormflow by a factor of 3.7, when compared with baseflow. While the summer (wet season) runoff is dominated by stormflow, the winter (dry season) runoff is dominated by baseflow. Note a build-up of baseflow in late summer and autumn (February to May), with baseflow recession evident in winter and spring months, thus displaying a lag.

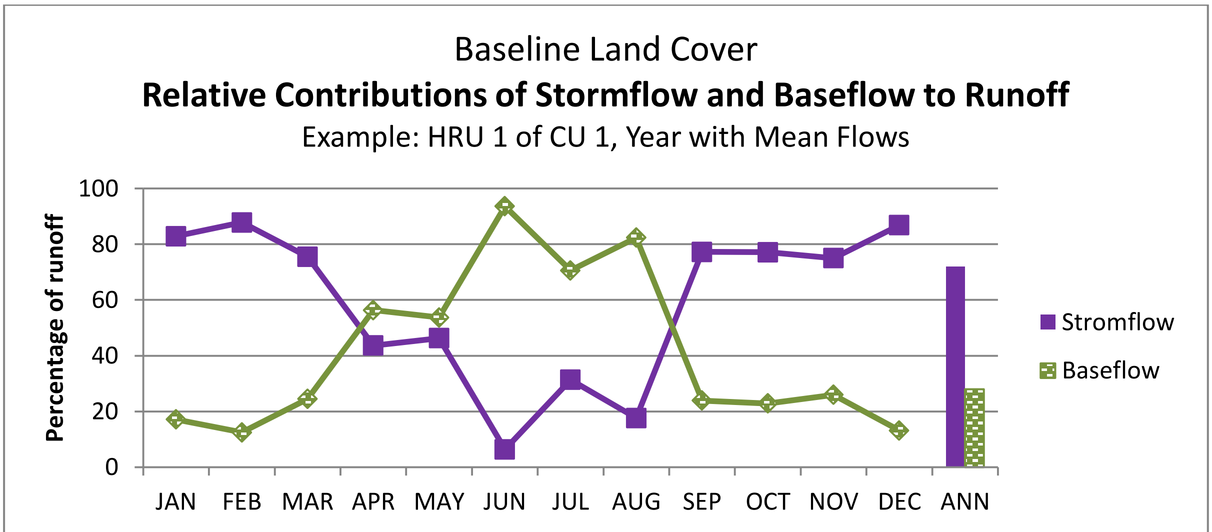

Figure 5.4 Relative contributions of stormflows and baseflows to runoff under baseline land cover conditions, using HRU 1 of CU 1 as an example, with the analysis considering a year with mean flows

Interpretation of Figure 5.4: The annual contribution of stormflows to runoff in a mean year is 72 %, with baseflow contributing 28 %. Stormflow dominates in the higher rainfall months from September to March, while baseflow is dominant during the dry months from June to August. The stormflow in February contributes 88 % of the runoff, compared to only 6 % during June, when baseflow dominates with a 94 % contribution.

Significance: Annually, stormflow contributes more to runoff than baseflow, but baseflow is vital to maintaining some runoff during the dry season and thereby some of the ecosystem services of water provisioning, as well as some supporting services to the ecological functioning of streams.

- Hypothesis: The relative contributions of stormflows and baseflows vary between years with low and high flow

The relative annual contributions of stormflow to runoff for years with median flows, as well as for 1:10 high and low flows, are shown in Figure 5.5.

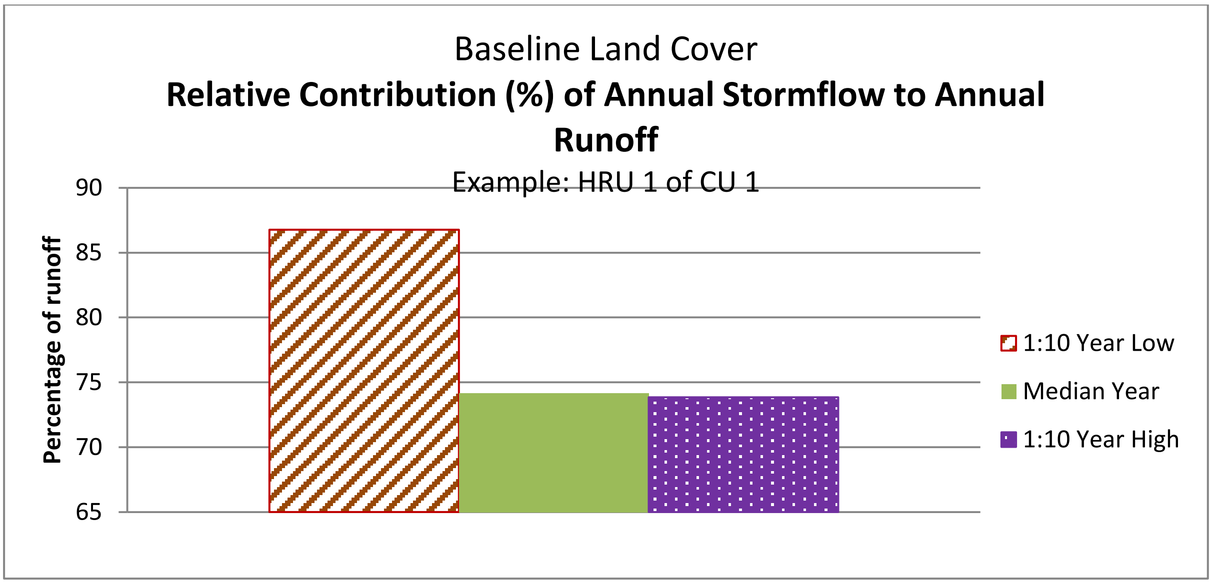

Figure 5.5 The relative contributions of stormflow to runoff during a year of median flows as well as years of 1:10 high and low flows, for HRU 1 of CU 1

Interpretation: The relative annual relative of stormflow to runoff is especially high in years with low flows, at 87.8 % for HRU 1 of CU 1, while years with median and high flows show reductions of the stormflow contribution at 74.2 and 73.8 %.

Significance: The contribution of stormflows to total runoff varies and displays major differences between years with high, median and low flows. During dry years when the contribution of stormflows is higher than in other years, the implication is that baseflows, in situations of already low overall runoff, are markedly reduced. This can have major impacts on provisioning of water to domestic users who are reliant on run-of-river water sources.

In addition to the dependence of runoff and its components to climatic variability, runoff is also affected by different types of baseline land cover. This will be explored in the next section.

- Hypothesis: Different baseline land covers result in different hydrological responses

In order to illustrate the influences of natural land cover types on certain hydrological responses, responses from CUs with different baseline land covers within the Mpushini/Mkhondeni study area will be compared. The stormflow and baseflow responses of two catchment units with different baseline land covers were modelled. Median year stormflows and baseflows from HRU 1 of CU 1, the land cover of which is classified as "KwaZulu-Natal Hinterland Thornveld", and HRU 1 of CU 5, the land cover of which is classified as "Eastern Valley Bushveld", were compared and results are shown in Figure 5.6.

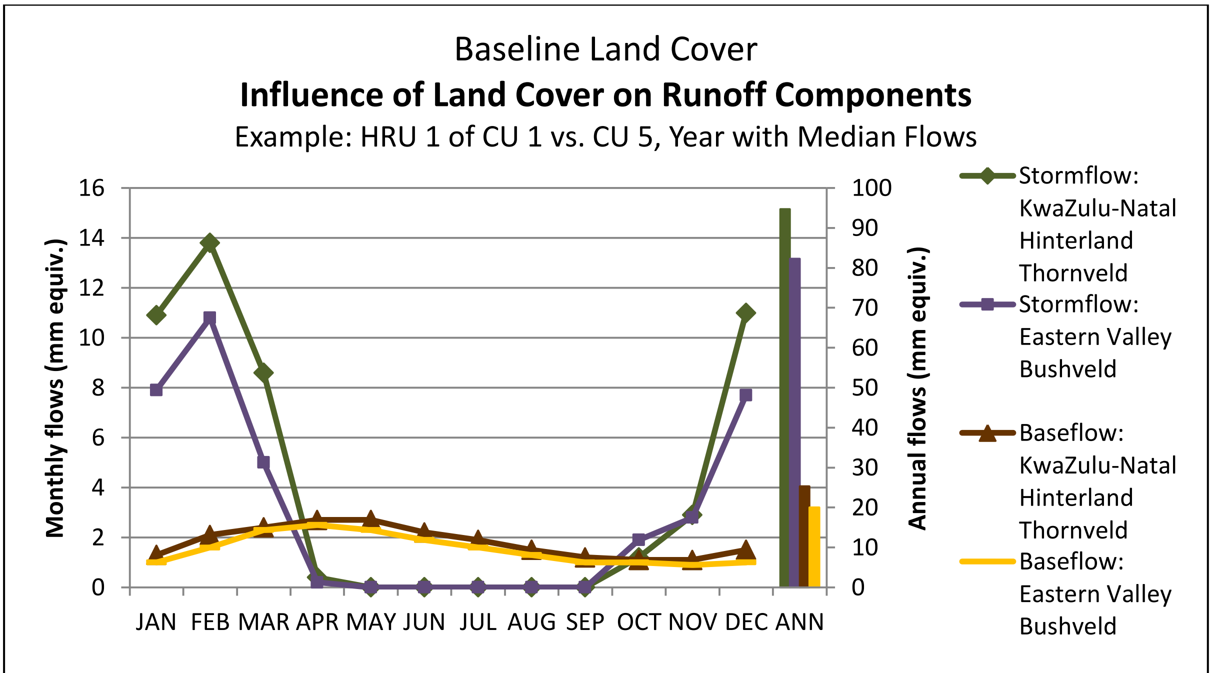

Figure 5.6 Influence of baseline land cover types on the runoff components of stormflows and baseflows for a year with median flows

Interpretation: Baseline land cover can have a significant influence on the partitioning of rainfall into stormflows and baseflows. In this study area, however, the differences are relatively small. The land cover classes “KwaZulu-Natal Hinterland Thornveld” versus “Eastern Valley Bushveld” have above-ground characteristics that are not all that different (cf. Table 4.4, values of CAY), and annual stormflow differences between the two vegetation types are only about 13 %, while baseflow differences are 21 %. The differences are slightly higher in the high flow season, e.g. the differences in February stormflows are about 22 % and in baseflows about 24 %, with the dominant land cover “KwaZulu-Natal Hinterland Thornveld” used as the reference. The two land cover classes of “KwaZulu-Natal Hinterland Thornveld” and “Eastern Valley Bushveld” are relatively similar, with a varied amount of tree cover. The differences are expected to be considerably larger with more distinctly different land cover types, e.g. when hydrological responses are compared between short grassland versus natural forest baseline land covers.

Significance: Baseline land cover impacts on hydrological responses are important and their impacts depend, *inter alia*, on the classes of baseline land cover. Whenever impacts of current land uses on hydrological responses are assessed, they need to be modelled against the baseline land cover as a reference.

Different land cover classes were found to result in different hydrological responses. In the next section, the study area’s water budget will be explored in the light of so-called “green”, “blue” and “white water” flows, assuming baseline land cover.

5.3.2 Green, blue and white water components of the water budget of the study area

A water budget can be partitioned into green, blue and white water (cf. Section 2.3.2). As already mentioned, green water is the soil water taken up by plant to create biomass and is transpired by the vegetation into the atmosphere. White water is defined here as the portion that is evaporated to the atmosphere from the soil, plants or other surfaces. Blue water is water contained in water bodies, in this case, streams, rivers, groundwater, wetlands, as well as abstracted water. In the following section, a hypothesis regarding the relationship between the study area’s green, blue and white water flows will be explored, followed by a further and more detailed evaluation of green water flows.

- Hypothesis: In the catchment's water budget, green water flows dominate over blue and white water flows, but they vary from season to season

The components of the water budget, partitioned for a baseline cover into blue, green and white water flows for a year of mean flows, are shown in Figure 5.7. The relative contributions of the above to the water budget are shown in Figure 5.8.

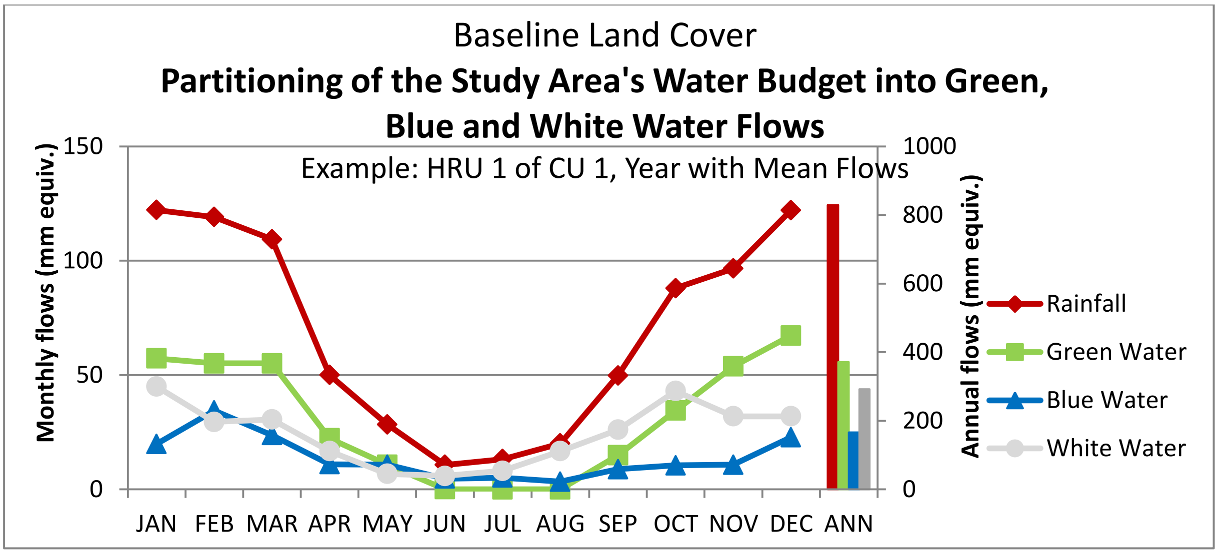

Figure 5.7 Partitioning of the study area's water budget, in a year with mean flows, into green, blue and white water flows under baseline land cover conditions, using HRU 1 of CU 1 as an example

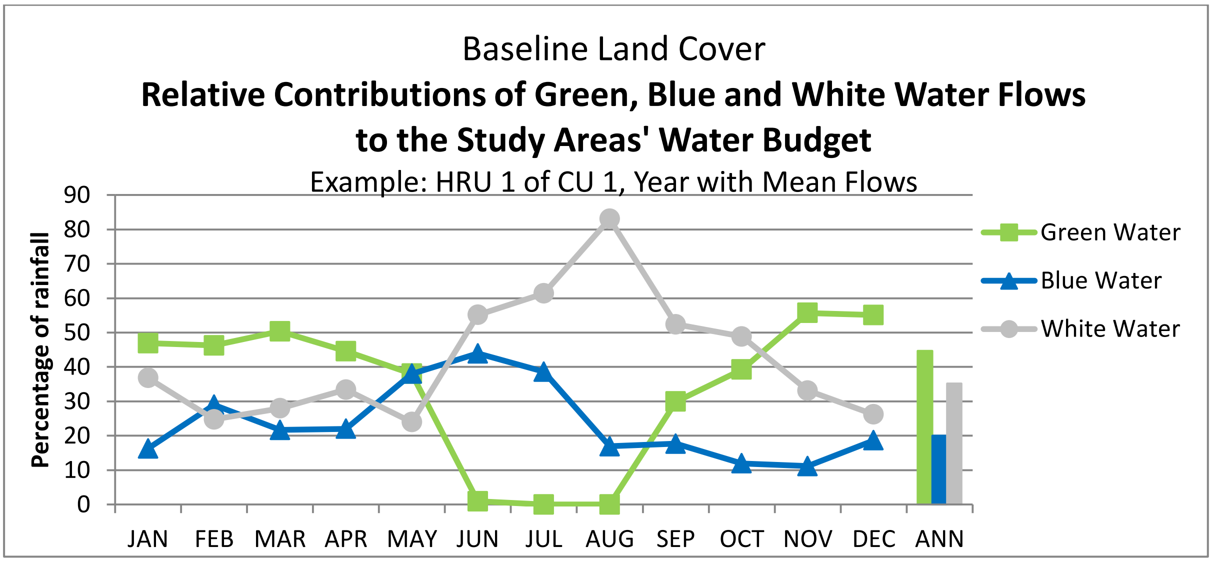

Figure 5.8 Relative contributions of the study area's green, blue and white water flows, using HRU 1 of CU 1 as an example, shown for a year with mean flows and assuming baseline land cover conditions

Interpretation: The green water portion with 45 % has the biggest share in the annual water budget in this example. The white water portion is also significant at 35 %. The blue water portion is only 20 %. Seasonal changes can be seen. Within the dry season, the green water flow contributions are lower, e.g. in July the green water flows are simulated to be zero, the blue water flows make up 39 % and the biggest share is white water, at 61 %.

Significance: Green water makes up a proportionally higher fraction of the water budget than the visible blue water. The white water portion is also fairly high, this being the water not generally put to direct use within the catchment. Therefore only a small portion of the partitioned precipitation contributes to runoff and to services related to blue water flows.

The intra-seasonal variability of green, blue and white water flows are shown above. In the next section the green water flows will be explored further, which was found to be the biggest share in the water budget.

- Hypothesis: Magnitudes of green water flows are influenced by intra- and inter-annual rainfall variability

Green water flows are essential for plant growth and therefore for primary and secondary agricultural production. Green water is the water that is transpired by plants from the topsoil and subsoil horizons. In order to explore the dependency of green water flows on water availability, the aggregated transpiration from the top- and subsoil horizons is shown in Figure 5.9 for a year with median flows and for years with 1:10 high and low flows, with the example taken from HRU 1 of CU 1.

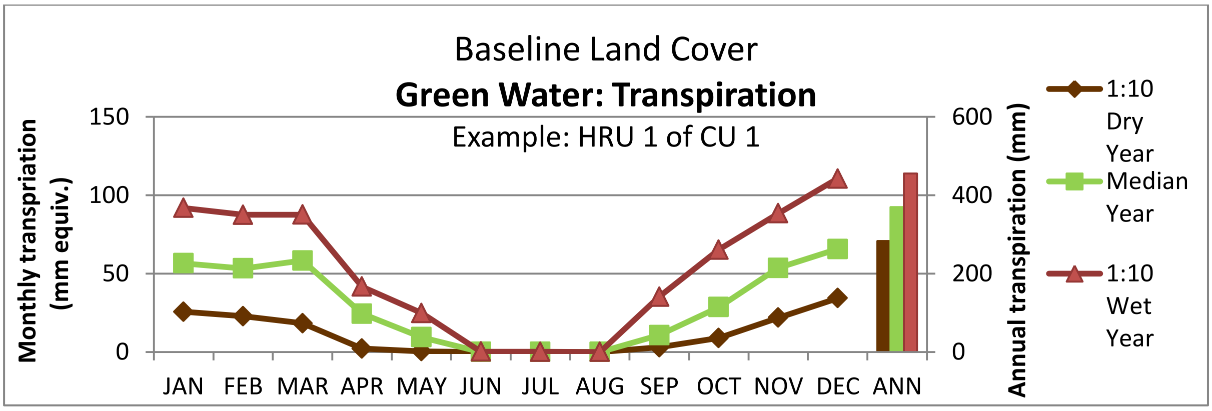

Figure 5.9 Transpiration, i.e. green water flows, within years of median and 1:10 high and low flows, under baseline land cover, using HRU 1 of CU 1 as the example

Interpretation: Compared with year of median flow conditions, from which transpiration is 370 mm, a year with 1:10 low flows for HRU 1 of CU 1 is modelled to have a transpiration component of 283 mm, thus showing 23 % less plant transpiration, while transpiration in a year with 1:10 high flows is 456 mm, i.e. showing 23 % more plant transpiration. Transpiration in the dry season (June to August) is minimal, partially because of senescence of plants and partially because no soil water accessible to plant roots is left in the soil profile. On a monthly basis the differences in transpiration between years with high and low flows are very pronounced during the wet season.

Significance: Differences in green water flows (transpiration) as a result of soil water availability vary seasonally and from year to year, largely depending on rainfall. Furthermore, transpiration ceases during the dry season. Primary production, which is a supporting ecosystem service, is highly dependent on transpiration and hence rainfall availability; alternatively, it is dependent on stored water available for irrigation.

In the above section, variations in green water flows were examined. Another hydrological response from the catchment is the sediment yield, which will be assessed next.

5.3.3 Sediment yield of the study area

Sediments are soil particles that are removed from the surrounding landscape as a result of erosion by rain or wind, and which are then deposited into the water bodies of that landscape. High sediment loads in rivers impact upon physical water quality and reduce the potability of that water, as well as reducing storage capacity in both natural and man-made water bodies and therefore reducing provisioning of water. In summary, high sediment yield therefore reduces the provisioning of clean water, due to its quality and quantity. Sediment yield is the only indicator of water quality that will be assessed in this study.

- Hypothesis: Even under baseline land cover conditions, the catchment's climate results in sediment yields, which are especially high in years of high rainfall.

The annual sediment yield of the entire study area is shown in Figure 5.10.

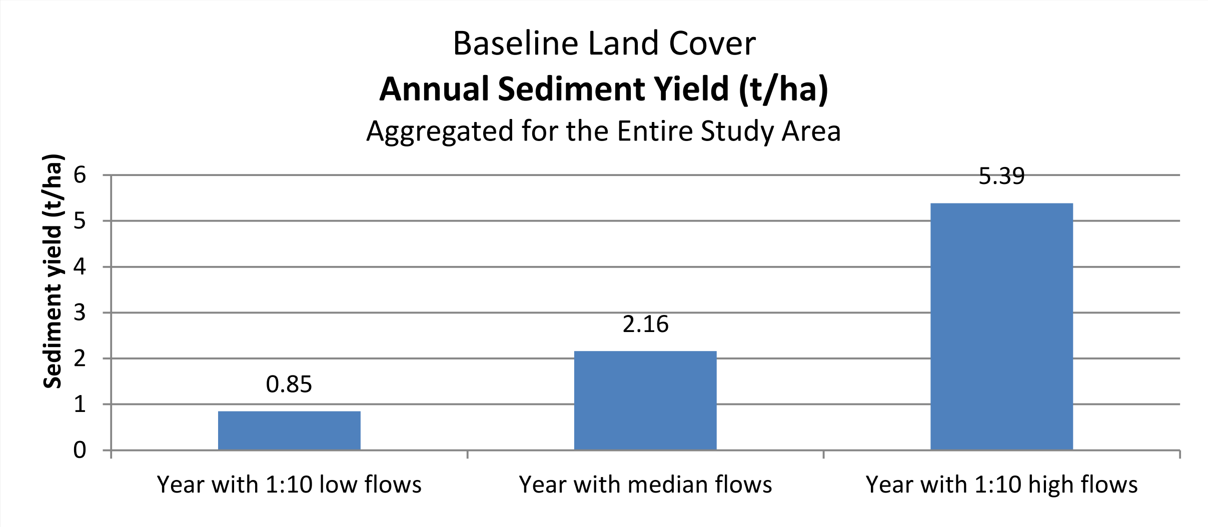

Figure 5.10 Annual sediment yields of the entire study area within a year of median and 1:10 high and low flows, assuming baseline land cover conditions

Interpretation: The modelled annual sediment yields are equivalent to 0.85 t/ha in a dry year, 2.16 t/ha in a median year and 5.39 t//ha in a wet year. The increases in the annual sediment yields of the catchment between years with 1: 10 low and median flows, as well as between years with median flows and 1: 10 high flows, are by a factor of approximately 2.5.

Significance: Sediment yields are especially high during years with high flows. Sediments reduce the storage capacity of impoundments, with the added effect of potentially increasing flood risks, because the attenuating effects of the impoundments are reduced. Sediment yields in rivers are also an indicator of the amount of soil lost from the surrounding land and therefore indicate reduced productivity of that land, also because of carbon released into the atmosphere. From a hydrological ecosystem services perspective, both of the previously mentioned effects are, however, beyond the scope of this study.

The annual sediment yields of the Mpushini/Mkhondeni study area were examined in this section. In the next section, changes to hydrological responses are compared with corresponding changes in rainfall.

5.3.4 Changes in hydrological responses in comparison to corresponding rainfall changes

Hydrological responses include sediment yield, as well as runoff and its components of stormflow and baseflow. One of the main drivers of those responses is rainfall. In this section, the relationships between changes in rainfall and corresponding changes in selected hydrological responses within the Mpushini/Mkhondeni study area, will be examined.

- Hypothesis: Changes in hydrological responses, such as stormflow, baseflow and sediment yield are amplified in both directions in dry and wet years, when compared with corresponding changes in rainfall.

Relative changes of rainfall and corresponding relevant hydrological responses within dry and wet years are compared to responses in median years, with results shown in Figure 5.11.

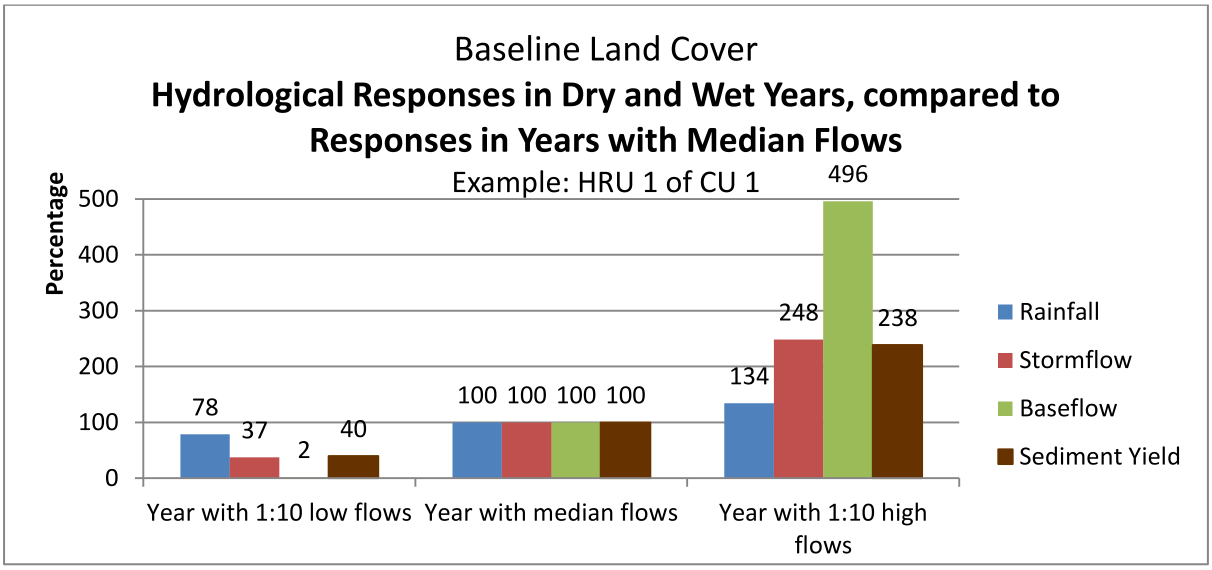

Figure 5.11 Rainfall and hydrological responses of stormflow, baseflow and sediment yield for years of 1: 10 high and low flows, relative to years with median flows, under baseline land cover conditions

Interpretation: Annual rainfall shows a decrease of 22 % in 1:10 dry years and an increase of 34 % in 1:10 wet years. The annual sediment yield shows a decrease of 60 % in years of corresponding low flows and an increase of 138 % in years of high flows. Stormflows show a decrease of 63 % for a year with 1:10 low flows and an increase of 148 % for a year with 1:10 high flows. The biggest change, however, is in the annual baseflows, with a decrease of

98 % in years with low flows and an increase of 247 % in years with high flows. This implies that hydrological responses in years with low and high flows are vastly amplified in both directions, but particularly in high flow years, when compared with corresponding changes in rainfall.

Significance: Hydrological responses such as sediment yields, stormflows and especially baseflows, are highly sensitive to changes in rainfall. This is significant where there is a dependence on sustained baseflows, e.g. in environmental flows, or where the streamflow is the only source of water for poor communities, who are particularly vulnerable to insecure water supplies in the dry years. The amplification also has to be borne in mind for adaptation to climate change, which is projected to result in changes in rainfall patterns. This is, however, beyond the scope of this study.

5.3.5 Summary of the results of the hydrological responses examined under baseline land cover conditions

In assessing various influences under baseline land cover, with no land use factors included yet, the following findings were made for the various hydrological responses within the study area:

a) Both annual and monthly runoff, and therefore the hydrological ecosystem service of water provisioning in this catchment, are highly variable within a year and between years, even without any added effects of land use, with dry season runoff and even annual totals of runoff often extremely low (Figure 5.2)
b) Annually, stormflow contributes more to runoff than baseflow. However, baseflow is vital in maintaining some runoff during the dry season and thereby some of the ecosystem service of water provisioning, as well as some supporting services to the ecological functioning of streams (cf. Figure 5.3 and 5.4)
c) The contributions of stormflows to total runoff display major differences between years of high, median and low flows, adding to the complexities of water provisioning and supporting services from this catchment (cf. Figure 5.5)

d) Differences in baseline land cover can have a significant influence on components of runoff components, although these differences are relative small within this particular study area (cf. Figure 5.6)

e) Of the blue, green and white water flows that make up the water budget, green water constitutes a proportionally higher fraction of the water budget than the other two. The white water fraction is also higher than that of blue water (Figures 5.7 and 5.8).

f) Differences in green water flows, i.e. transpiration, in this study area vary from month to month and from year to year, depending on soil water availability. Transpiration is modelled to cease during the dry season. Plant growth during this time would require either irrigation (Figure 5.9) or unseasonal rains.

g) Sediment yields are especially high during years with high flows. Sediments reduce the storage capacity of impoundments, with the added effect of potentially increasing flood risks because the attenuating effects of the impoundments are reduced. Sediment yields in rivers are also an indicator of the amount of soil lost from the surrounding land and therefore indicate reduced productivity of that land, as well as being an indicator for carbon released into the atmosphere. From a hydrological ecosystem services perspective, further analysis of both of the previously mentioned effects, however, is beyond the scope of this study. In addition, a high sediment yield in rivers impacts upon physical water quality and reduces the potability of that water. High sediment yield therefore reduces the provisioning of clean water (cf. Figure 5.10)

h) Hydrological responses such as sediment yields, stormflows and especially baseflows, are highly sensitive to changes in rainfall (cf. Figure 5.11). This sensitivity is significant where there is a dependence on sustained baseflows, e.g. for environmental flows, or where the streamflow is the only source of water for poor communities which may then become particularly vulnerable to water shortages in the dry season. This amplification of hydrological responses also has to be borne in mind for adaptation measures to climate change, which is projected to result in changes in rainfall patterns. Effects of projected climate change are, however, beyond the scope of this study.

5.4 Understanding Impacts of Current Land Uses on Hydrological Responses

In this section the modelled hydrological responses of certain land uses which are considered to be hydrologically significant in influencing water flows within the hydrological cycle are compared to those hydrological responses under baseline land cover conditions. Dryland agriculture, effects of dams and irrigated agriculture, degraded land, urban areas with impervious surfaces and return flows, all of which can be isolated within a HRU of a selected CU of the Mpushini/Mkhondeni study area, will be examined. This is followed by some hydrological responses modelled for the entire catchment. In each case, the influences on selected hydrological ecosystem services, indicated by the changes of the hydrological responses, will be highlighted.

5.4.1 Effects of dryland agricultural land uses on hydrological responses

The influences of certain dryland agricultural land uses in this study area, *viz.* sugarcane plantations and wattle plantations, will be examined and compared to responses under baseline land cover.

- Hypothesis: Sugarcane and wattle plantations can reduce runoff significantly

The influences of sugarcane and wattle on runoff are modelled (cf. Table 4.7) and are compared to those of the baseline land cover they replace. This is examined for years with low, median and high flows and results are shown in Figure 5.12 for sugarcane and Figure 5.13 for wattle plantations.

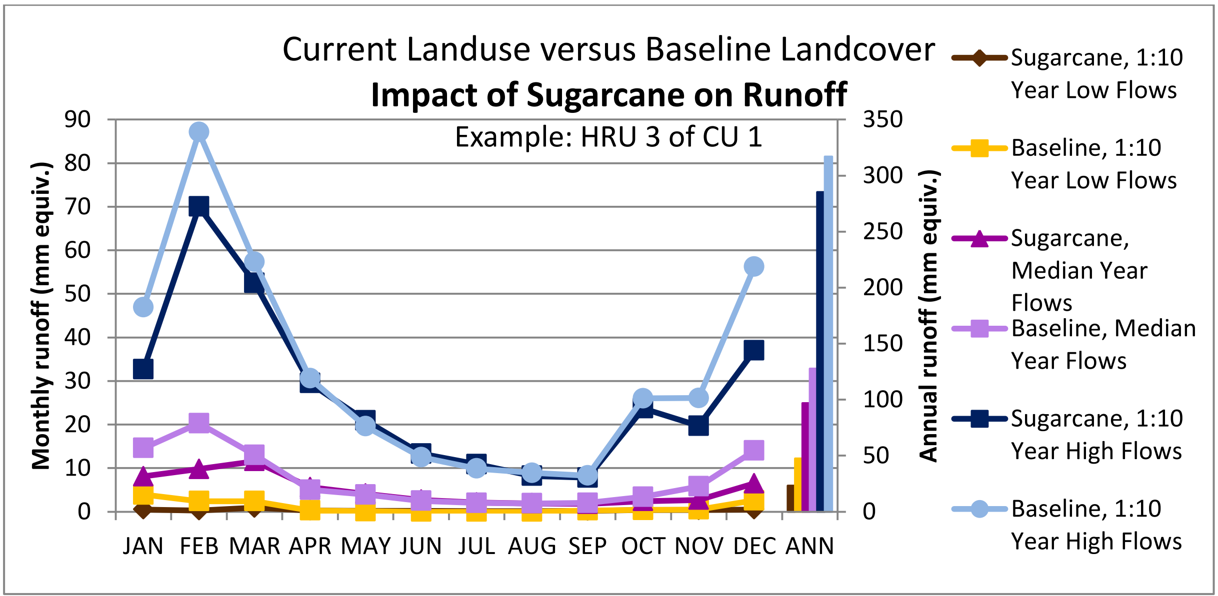

Figure 5.12 Impacts of sugarcane compared to those of baseline land cover during years with median and 1:10 high and 1:10 low flows, using results from HRU 3 of CU 1 as an example

Interpretation of Figure 5.12: Sugarcane plantations have been modelled in HRU 3 of CU 1 to reduce runoff compared to the runoff from baseline land cover. For years with 1:10 low flow conditions the annual runoff was found to be reduced by 24.3 mm, or 51 %. For years with median flows the annual runoff was found to be reduced by 30.8 mm, or 24 % and in years with 1:10 high flows reduced again by 30.8 mm, which is in this case equivalent to 10 %.

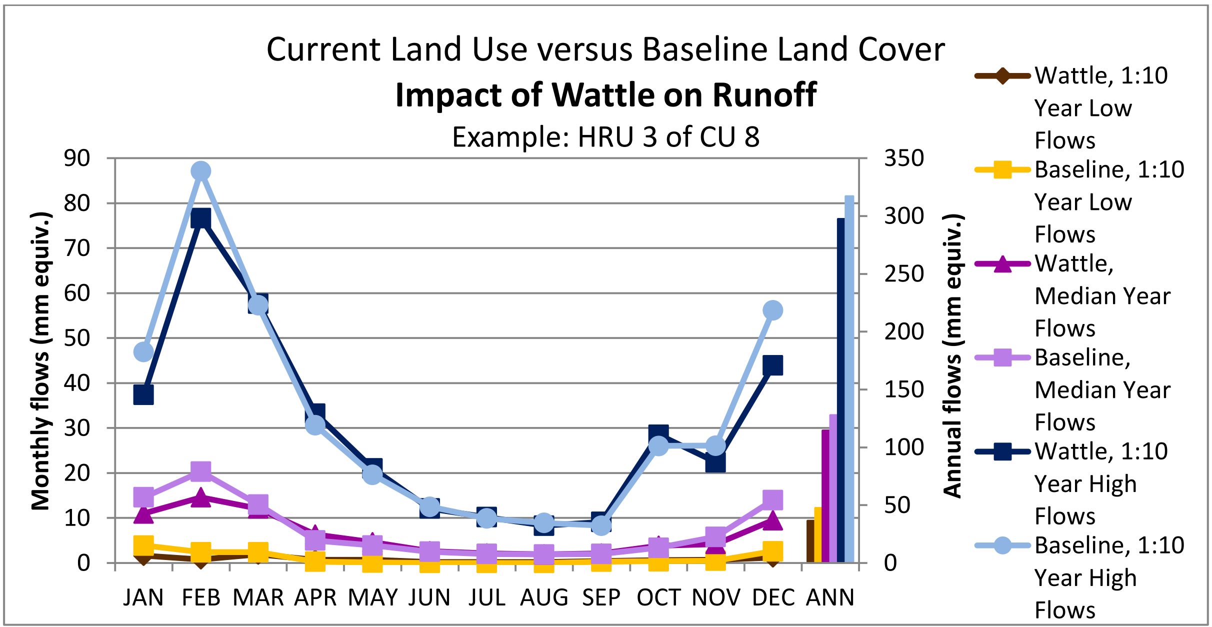

Figure 5.13 Impacts of wattle plantations compared to those of baseline land cover during years with median and 1:10 high and 1:10 low flows, using results from HRU 3 of CU 8 as an example

Interpretation of Figure 5.13: Wattle plantations have been modelled in HRU 3 of CU 8 to reduce runoff compared to the runoff from baseline land cover. For years with low flow conditions the annual runoff was found to be reduced by 11.0 mm, or 23 %. For years with median flows the annual runoff was found to be reduced by 13.3 mm, or 10 % and in years with high flows reduced by 19.6 mm, or 6 %.

Significance: Certain land uses, in this case sugarcane and wattle plantations, are modelled to reduce runoff compared to those from baseline land cover conditions. Those land uses therefore impact upon ecosystem services related to blue water flows. For sugarcane, wattle and other high biomass crops this reduction is particularly high in relative terms during dry years, and relatively less so in wet years. Tree plantations have been recognised as a streamflow reduction activity (SFRA), and, as such, require a water use licence. It is interesting to note that in this catchment the reduction of runoff from the sugarcane plantations exceeds that of wattle plantations. Such a result could possibly prompt a re-look by authorities to have sugarcane classified as a streamflow reduction activity (SFRA). Currently, no SFRAs are registered within the catchment.

5.4.2 Effects of irrigation on hydrological responses

Irrigation from dams is expected to have significant influences on streamflows downstream of such dams.

- Hypothesis: Irrigation from farm dams significantly reduce flows downstream

The comparison of streamflows when irrigation from dams is considered versus not considered was modelled (cf. Sections 4.4.7 and 4.4.8) and results are shown in Figure 5.14.

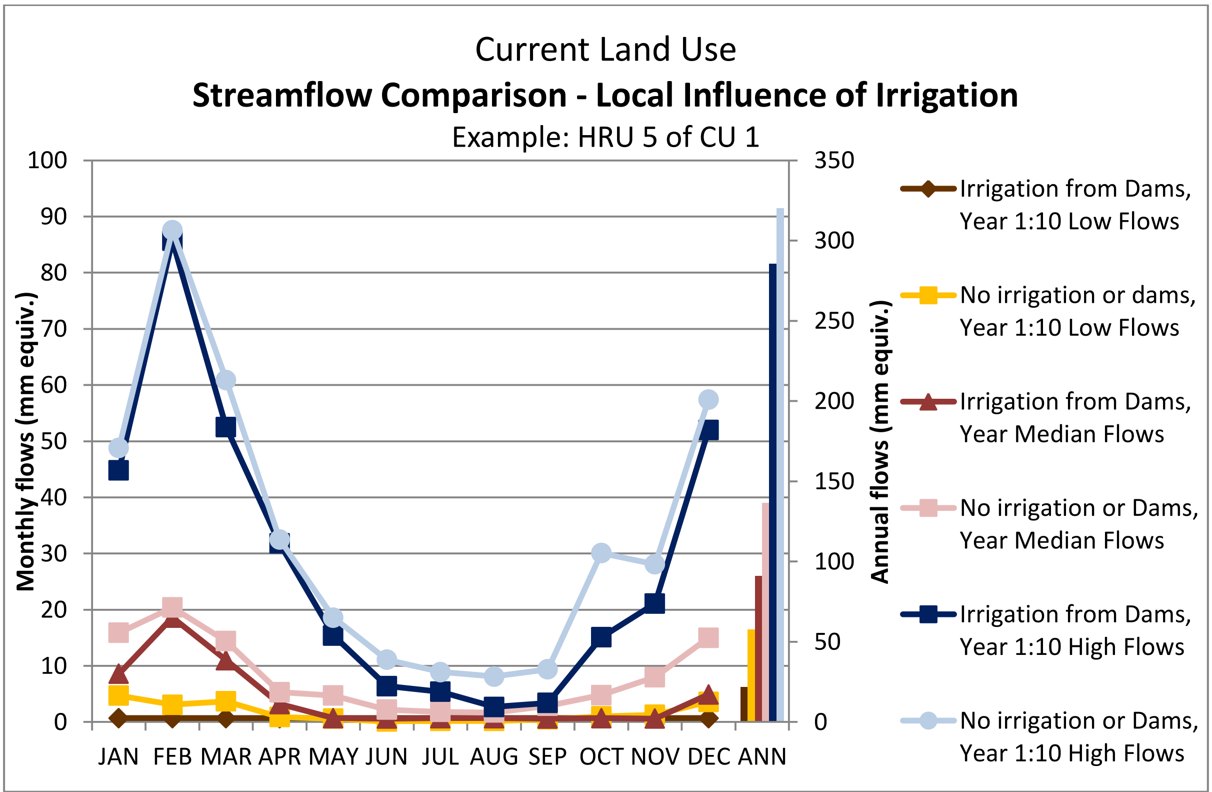

Figure 5.14 Influences of irrigation on streamflows downstream of a dam for years with median as well as 1:10 high and 1:10 low flows, using results from HRU 5 of CU 1 as an example

Interpretation: Irrigation from dams in HRU 5 of CU 1 have decreased downstream streamflows by 63 % from 58 to 22 mm for years with 1:10 low flows, by 33 % from 136 to 91 mm for years with median flows and by 11 % from 320 to 286 mm for years with high flows. The sensitivity of downstream flows to irrigation is thus particularly severe in dry years, and least sensitive in wet years, when irrigation demands are also lower. When the rainy season commences again and dam levels are low because of high dry season irrigation abstractions, there is a lag in the increase of flows downstream because the dam first has to be filled, as is shown from October to December in Figure 5.14.

Significance: Irrigation abstractions from dams can result in significant local decreases in downstream flows, especially in years with low flows. After the dry season (May to September) when dam levels are low, there is a lag in increased streamflow at the start of the wet season, because a depleted dam first has to be filled before overflows commence. This implies that even farm dams which are used for irrigation water supplies should release water for maintaining downstream aquatic ecosystems.

In the above section the localised effects of irrigation on downstream flows were presented. These effects might not be as high if one considers a catchment as a whole.

- Hypothesis: The strong influence of irrigation on local streamflows is reduced on a more regional scale

The effects of all irrigation from all dams within the Mpushini catchment, with its various other land uses, are examined at the outlet of the Mpushini catchment, with results shown in Figure 5.15.

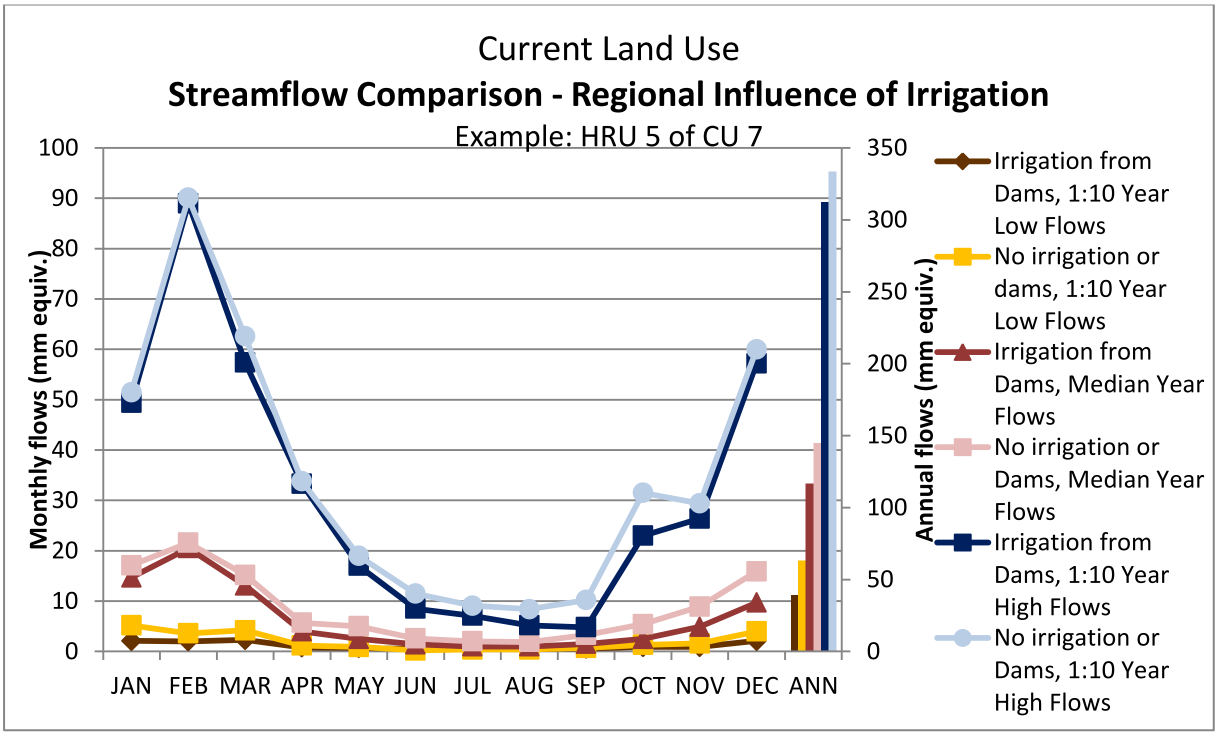

Figure 5.15 Influences of dams and irrigation on streamflows at the Mpushini outlet for years with median as well as 1:10 high and 1:10 low flows

Interpretation: At the outlet of the Mpushini catchment, irrigation has decreased the streamflow by 32 % from 64 to 43 mm in years with low flows (compared with 63 % in Figure 5.14), by 18 % from 146 to 121 mm in years with median flows (compared with 33 % in Figure 5.14), and by 6 % from 334 to 315 mm in years with high flows (compared with 11 % in Figure 5.14).

Significance: Irrigation has reduced the streamflow at the Mpushini outlet significantly, especially during years with low flows. The impact is, however, considerably less than that immediately below an individual dam from which water is abstracted for irrigation. Irrigation results in a decrease in streamflow, which is locally more pronounced, but relatively less so at the outlet of the catchment. The relative decrease is higher in years with low flows.

Hydrological ecosystem significance: Although farm dams have a vital role to play as an engineered water reservoir to provide a reliable local supply of water, the water provisioning and ecological support immediately downstream of dams can be reduced considerably, but less so further downstream. Ecological stream functioning might therefore be critically reduced locally. This study shows that, ideally, even from farm dams, environmental flows should be released especially in times of low flows, in order to better mimic natural flow conditions which might be vital for ecological stream functioning.

5.4.3 Effects of degraded areas on hydrological responses

Degraded areas are expected to have significant influences on hydrological responses, especially on runoff and sediment yield. The impacts of degraded areas are modelled (cf. Table 4.3 for model inputs) and the results are shown in Figures 5.16 and 5.17. It needs to be borne in mind that degraded land can be rehabilitated to a state that would allow hydrological responses to once resemble those under natural conditions.

- Hypothesis: Runoff is expected to increase from degraded areas, when compared to that from baseline land cover

Runoff from degraded areas was modelled and compared to runoff from baseline land cover, using outputs from HRU 4 of CU 7 as an example, with results shown in Figure 5.16.

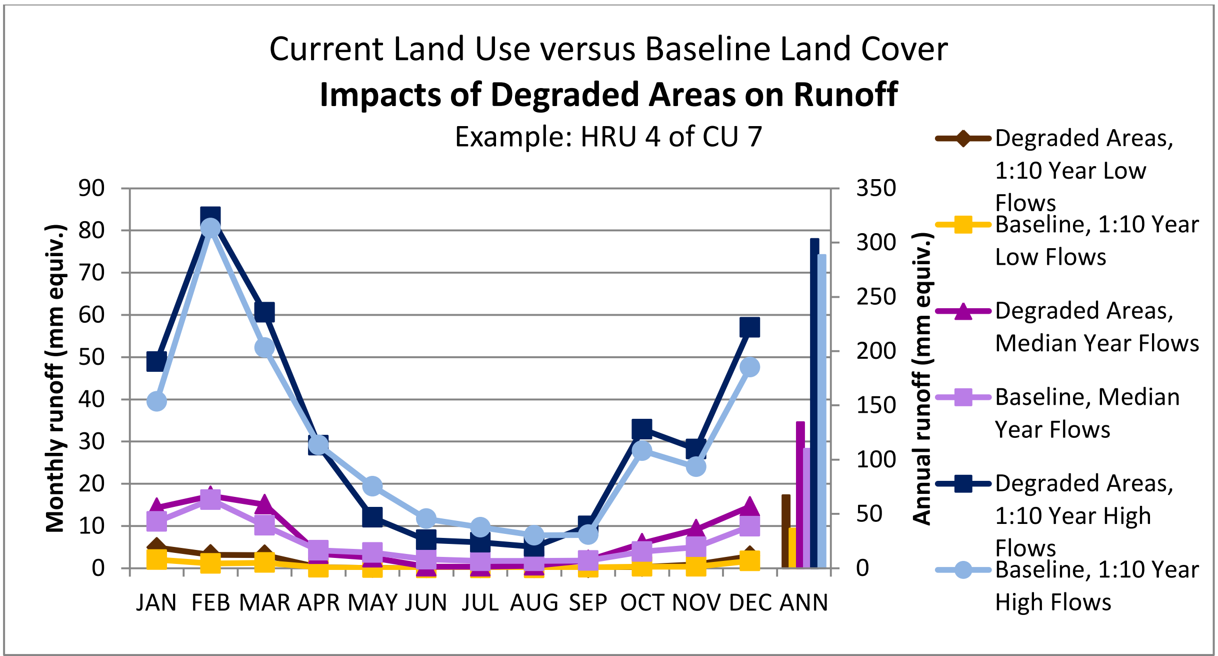

Figure 5.16 Impacts of degraded areas on runoff for years with median and 1:10 high and low flows, using results from HRU 4 of CU 7 as an example

Interpretation of Figure 5.16: Assuming the model inputs in Table 4.3, the degraded areas for this HRU have increased the annual runoff in years with 1:10 low flows by 30.8 mm or 84 %, in years with median flows by 24.5 mm or 22 % and in years with 1:10 high flows by 14.7 mm or 5 %. The significance of the above results is discussed at the end of Section 5.3.4.

- Hypothesis: Baseflows are expected to be reduced from degraded areas, compared to those from baseline land cover

Baseflows, which are a component of runoff, were modelled for degraded areas and compared to those from baseline land cover, again using outputs from HRU 4 of CU 7 as an example, with results shown in Figure 5.17.

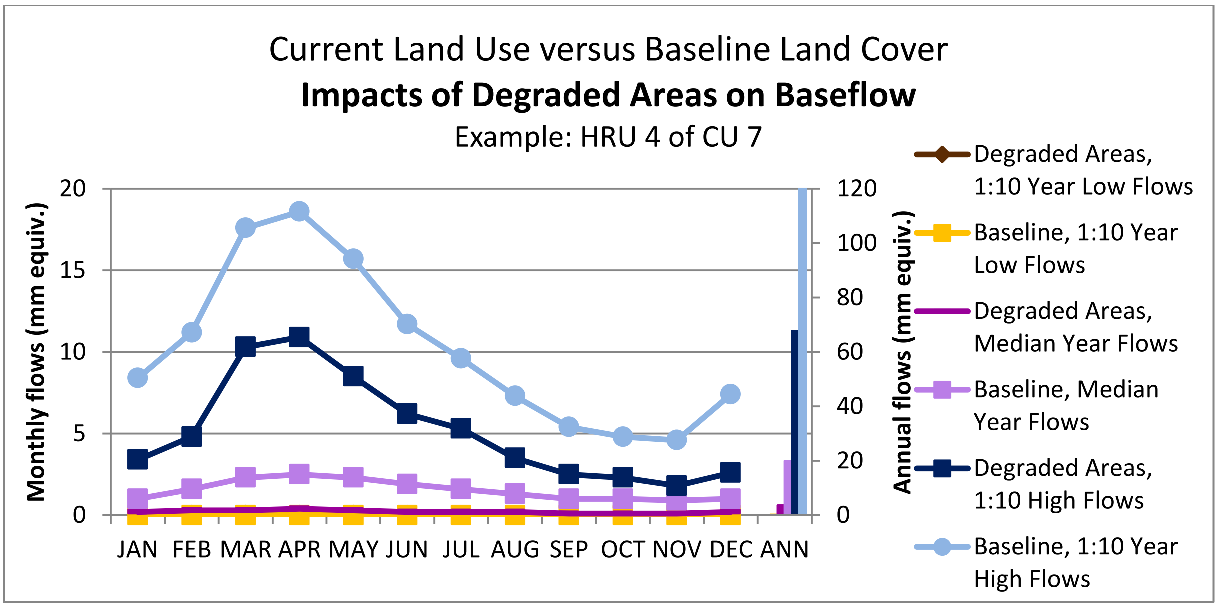

Figure 5.17 Impacts of degraded areas on baseflows for years with median as well as 1:10 high and low flows, using results from HRU 4 of CU 7 as an example

Interpretation of Figure 5.17: For years with 1:10 low flows the annual baseflows of degraded areas were modelled to be 0.0 mm, compared to the annual baseflows from baseline land cover of 0.3 mm. The degraded areas for this HRU have decreased the annual baseflows in years with median flows from 20.0 to 3.7 mm, or by 82 %, and in years with 1:10 high flows from 120.3 to 67.8 mm or 44 %. The significance of the above results is discussed at the end of Section 5.3.4.

- Hypothesis: The magnitudes of one day design runoff for selected return periods are expected to increase from degraded areas, compared to those from baseline land cover

The concept of design runoff has been explained in Section 4.4.12. One day design runoff for selected return periods were modelled for degraded areas and compared to those from baseline land cover, again using outputs from HRU 4 of CU 7 as an example, with results shown in Figure 5.18.

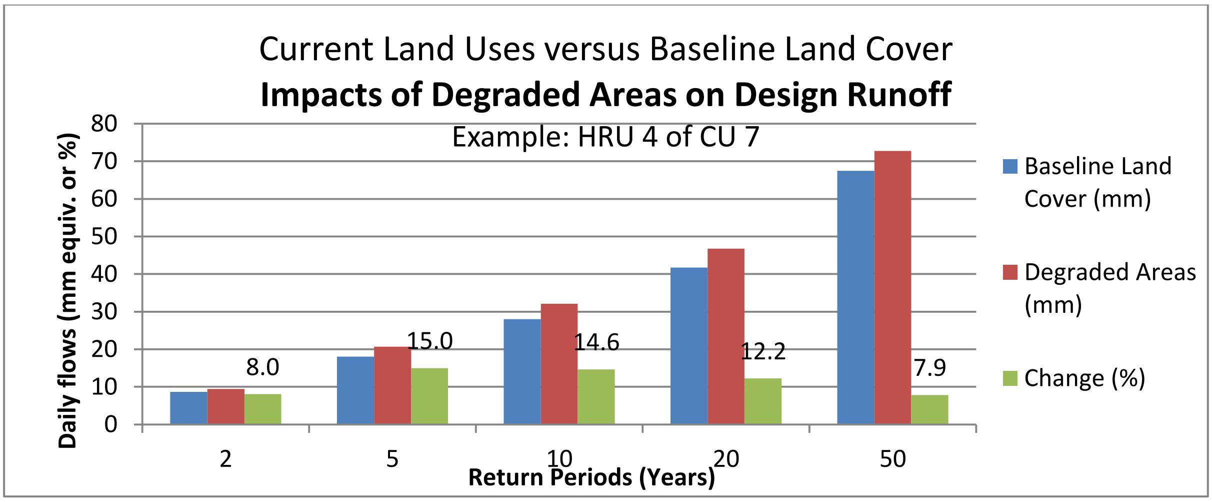

Figure 5.18 Influences of degraded areas on magnitudes of one day design runoffs for selected return periods compared to those from baseline land cover conditions, using results from HRU 4 of CU 7 as an example

Interpretation of Figure 5.18: Degradation has resulted in a general increase in the magnitude of one day design runoff for selected return periods. The one day design runoff for a 2 year return period from degraded land and baseline land cover were modelled to have increased from 8.7 to 9.4 mm, or 8 %. For a 5 year return period the one day design runoff increased from 18.0 to 20.7 mm, i.e. by 15 %, while for a 50 year return period the increase was from 67.5 to 72.8 mm, or 8 %. The significance of the above results is discussed at the end of Section 5.3.4.

- Hypothesis: Sediment yields from degraded areas are expected to increase when compared to those from baseline land cover

Using the *ACRU* model input from Table 4.3, sediment yields were modelled for degraded areas and results compared to those from baseline land cover conditions, again using HRU 4 of CU 7 as an example and with results shown in Figure 5.19, while those from the entire study area are shown in Figure 5.20.

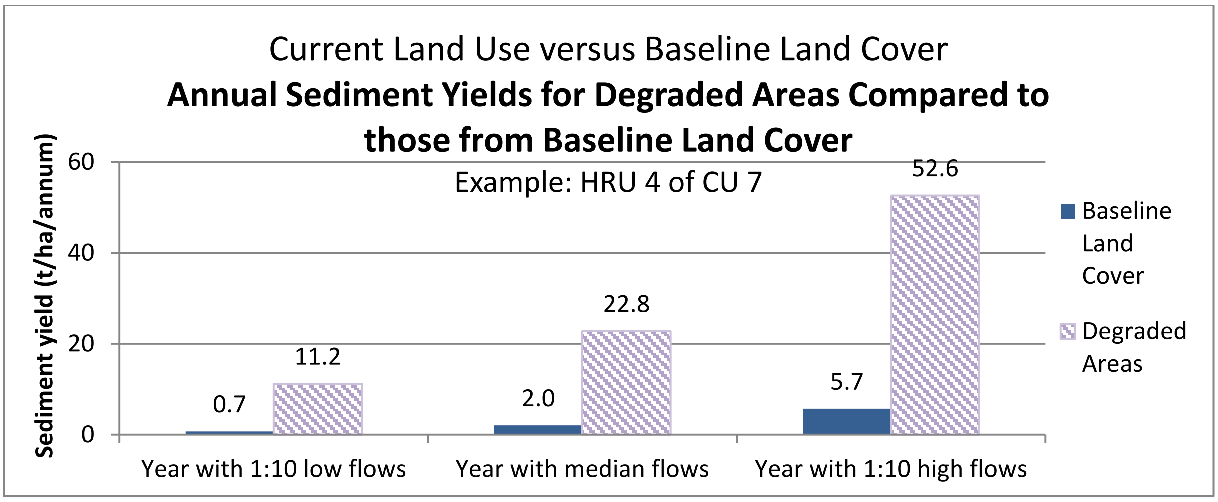

Figure 5.19 Annual sediment yields (in t/ha) from degraded areas and baseline land cover for years of median as well as 1:10 high flows and 1:10 low flows, using results from HRU 4 of CU 7 as an example

Interpretation of Figure 5.19: Sediment yields from degraded areas have increased significantly when compared to those from baseline land cover conditions. For years with 1:10 low flows, the increase has been from 0.7 to 11.2 t/h/annum (i.e. by a factor of 16), in years with median flows from 2.0 to 22.8 t/ha/annum (i.e. a factor of 11.4), and for years with 1:10 high flows from 5.7 to 52.6 t/ha/annum (i.e. a factor of 9.2). The significance of the above results is discussed at the end of Section 5.3.4.

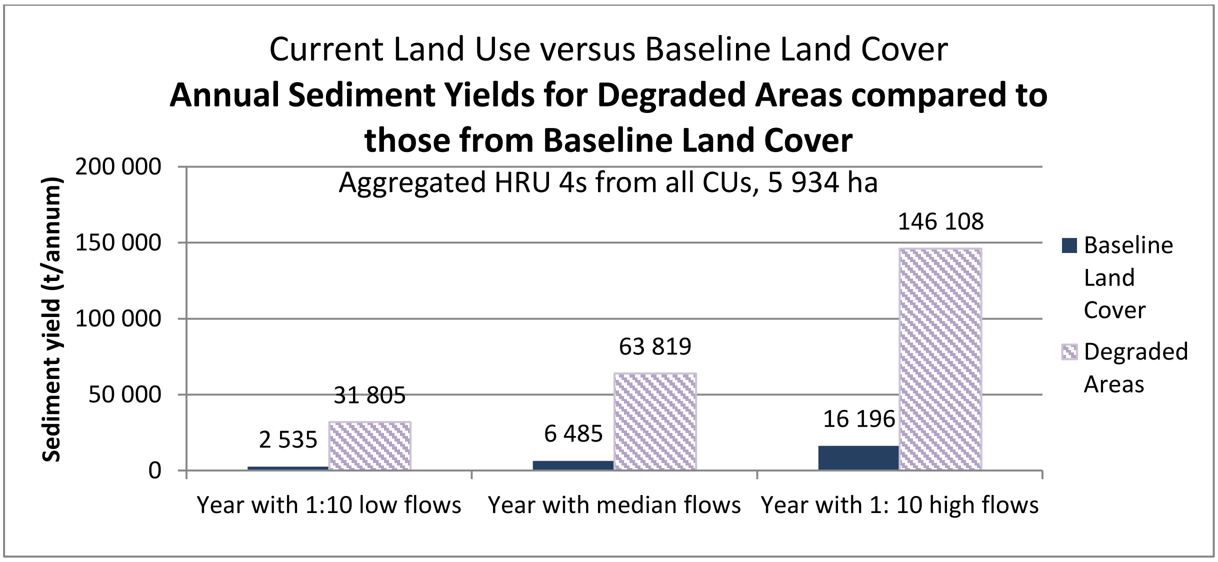

Figure 5.20 Annual sediment yields (in t) from degraded areas and baseline land cover for years of median as well as 1:10 high flows and 1:10 low flows, for the entire study area

Interpretation: Using the inputs from Table 4.3, the degraded areas identified in the entire study area, which total 5 934 ha, have increased the annual sediment yield by 29 Mt, or 12.55-fold, in years with 1:10 low flows, by 57 Mt, or 9.84-fold, in years with median flows and by 130 Mt or 9.02-fold, in years with 1:10 high flows. It is hypothesised that much of this enhanced sediment yield could be reduced to near baseline levels if the degraded area sections within the study area were to be rehabilitated.

Significance of Figures 5.16 to 5.20: As a consequence of assumed reduced above-ground biomass, interception losses, reduced ground surface cover and reduced infiltrability under degraded conditions (cf. Section 4.4.5; Table 4.5), the impacts of degradation were modelled to result in an increase of runoff, but a decrease in baseflow and an increase in the magnitude of one day design runoff for selected return periods, as well as a significant increase in sediment yield, especially in years with high flows. For ecosystem services, this implies that degradation leads to a reduction in the ecosystem service of flow attenuation, a reduction of water provisioning during low flow periods, as well as to a reduction in water quality due to increased sediments in the stream. The land under degraded conditions holds potential to be rehabilitated to a state that would allow hydrological responses to resemble those under natural conditions, reducing sediment yield and stormflows, while increasing baseflows.

5.4.4 Impacts of urban areas on hydrological responses

Urbanisation, because of increases in impervious surfaces, enhances surface runoff and influences the partitioning of runoff into its components of stormflow and baseflow. The return flow from treated water, brought in from sources external to a catchment, is also hypothesised to have an influence on hydrological responses. Increases in runoff are likely to contribute to the incidence of higher flooding and more severe design runoff events.

- Hypothesis: Urban landscapes, because of increased impervious areas, lead to increased surface runoff

The current level of urbanisation in the study area is relatively low. The area with the highest level of urbanisation, HRU 1 of CU 4, is used as an example to illustrate effects of urbanisation. The runoff of current urban areas was modelled and compared to that from baseline land cover conditions for years of 1:10 low flows, median flows and 1:10 high flows, with results shown in Figure 5.21. This HRU consists of natural vegetation and urban, mainly residential areas and covers 4.65 km^2 (cf. Table 5.2). The fractions of impervious surfaces were determined to be 0.08 for disjunct and 0.17 for adjunct impervious areas, thus leaving 75 % of the HRU as pervious areas (cf. Table 4.8).

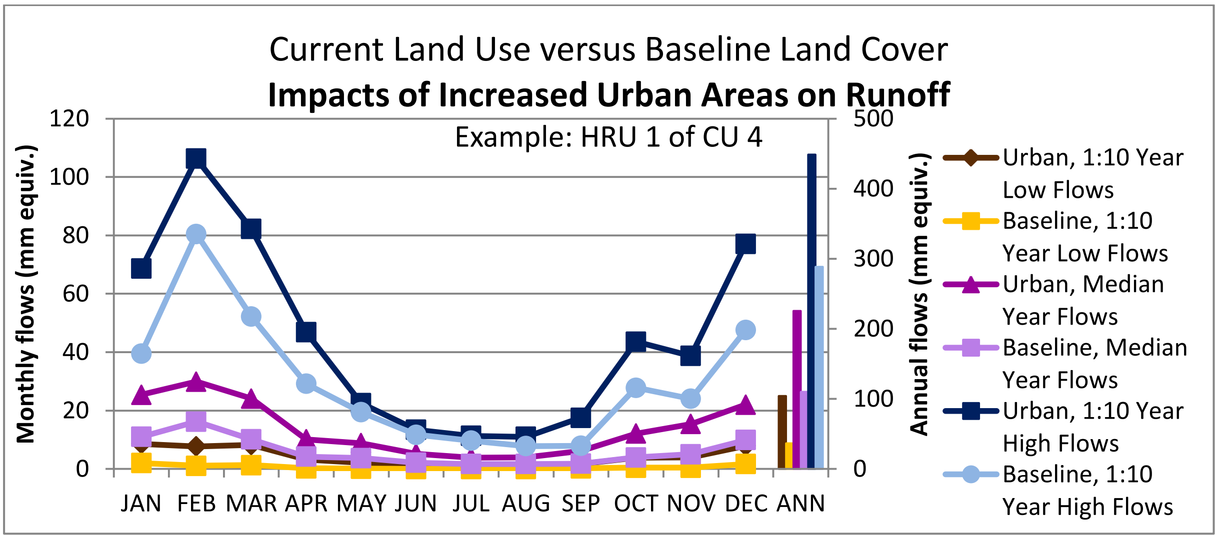

Figure 5.21 Impacts of urbanisation on runoff, for years with median, as well as 1:10 high and low flows, using HRU 1 of CU 4 as an example

Interpretation: The conversion to urban uses, in this example consisting mainly of a conversion to residential areas, increased the annual runoff by a factor of 2.8 in years with low flows, a factor of 2.1 in years with median flows and a factor of 1.6 in years with high flows. The significance of these increases will be discussed later.

- Hypothesis: Urban areas, because of impervious surfaces, have an influence on the partitioning of runoff into stormflow and baseflow

The partitioning of runoff into stormflow and baseflow was modelled, again for HRU 1 of CU 4, and results are shown in Figure 5.22.

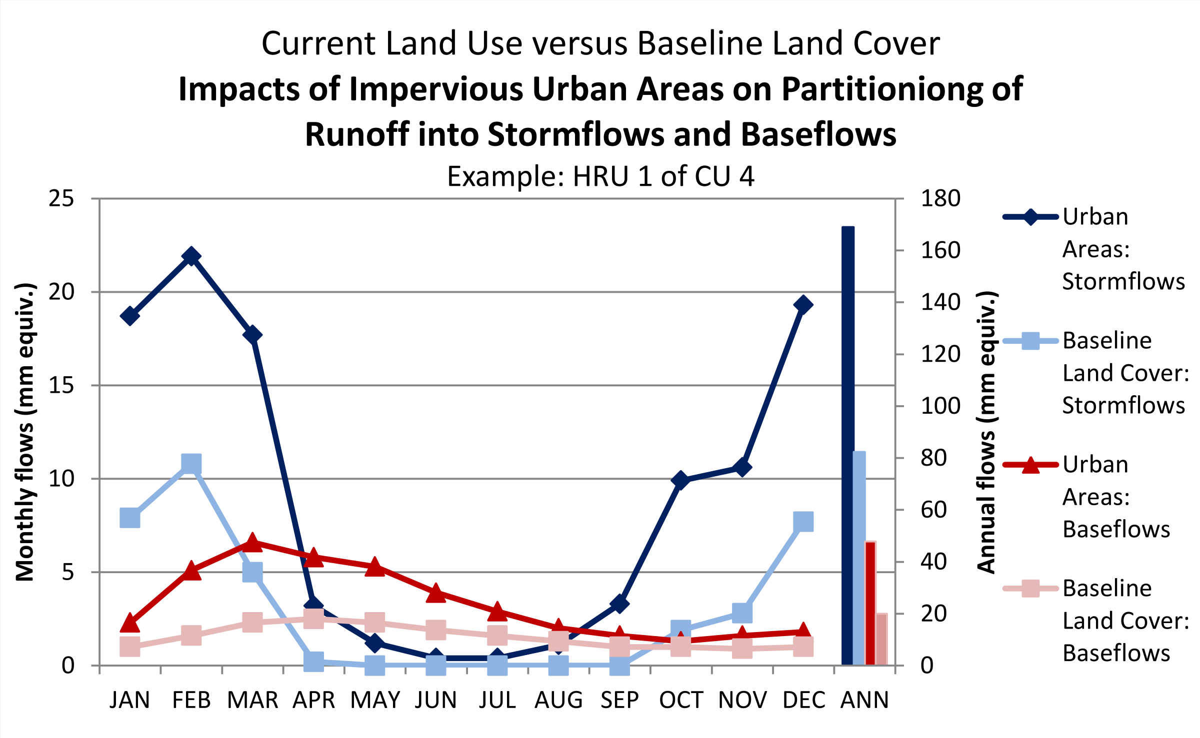

Figure 5.22 Influences of impervious urban areas on the partitioning of runoff into stormflows and baseflows in a year with median flows, using HRU 1 of CU 4 as an example

Interpretation: The impervious portions of the urban areas in HRU 1 of CU 4 have increased the annual stormflows from 82 to 169 mm, i.e. by 87 mm or 106 %, and the baseflows from 20 to 48 mm, i.e. by 140 %. Most of the increased runoff is as a result of increased stormflows. However, even baseflows increased. The increase in stormflows was expected, while the increase in baseflow was unexpected, but in this case is the result of the impervious fraction which is not connected directly to a stormwater system and drains onto the pervious areas (*ACRU* variable DISIMP), wetting those soils and on occasion producing deep percolation and thus baseflow. The significance of these increases will be discussed later.

- Hypothesis: Urban landscapes, because of their increased impervious areas, increase the magnitudes of one day design runoffs for selected return periods

The effects of impervious urban areas on one day design runoffs of selected return periods are compared to those under baseline land cover conditions, with results shown in Figure 5.23.

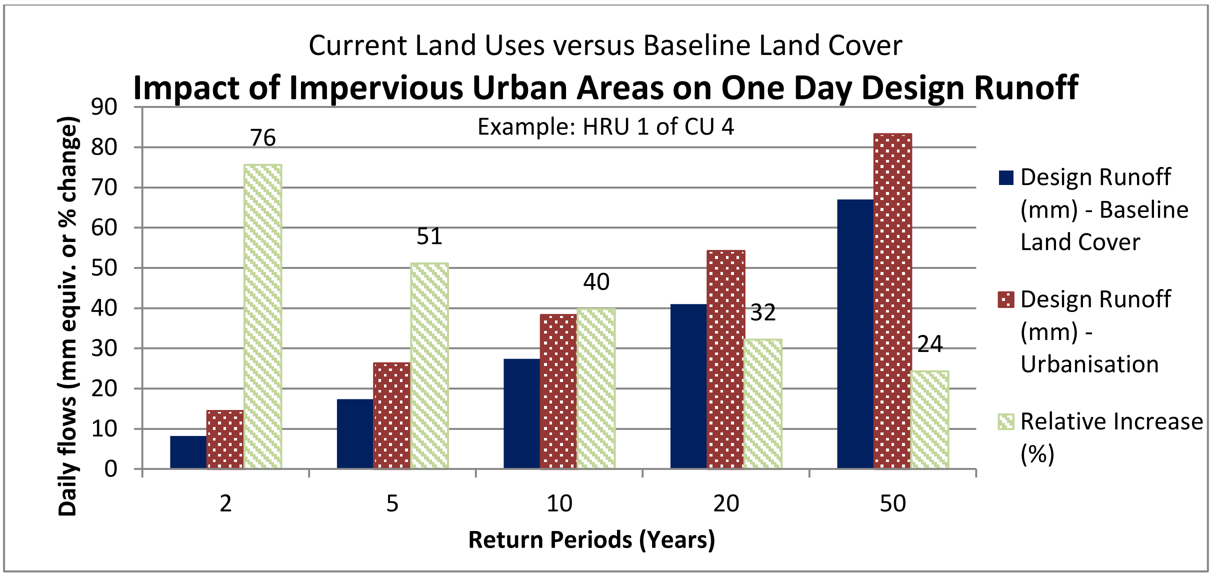

Figure 5.23 Comparison of magnitudes of one day design runoff for selected return periods between current urban land use and baseline land cover, using results from HRU 1 of CU 4 as an example

Interpretation: The impervious urban areas, in this example consisting mainly of residential areas, increased the magnitudes of one day design runoff of selected return periods. For example, for the 2-year return period a runoff increase from 8 to 14 mm is shown, equivalent to a 76 % increase, while for the 50-year return period the increase of 16 mm from 67 to 83 mm was higher than for lower return periods, but was equivalent to only a 24 % relative increase. Thus, while magnitudes of changes increased with return periods, the relative increase declined. The significance of these increases will be discussed later.

- Hypothesis: Urban landscapes, as a consequence of impervious areas, result in increases in blue water flows, but decreases in green and white water flows

Components of the water budget, when partitioned into blue, green and white water flows, are compared between urban land uses and baseline land cover, with results from HRU 1 of CU 4 shown in Figure 5.24.

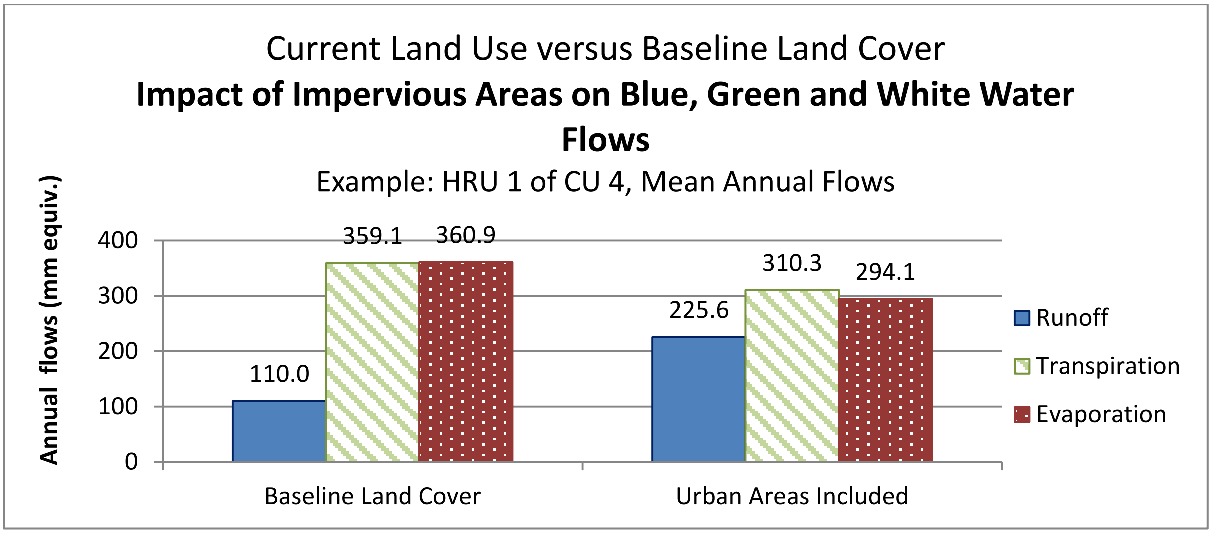

Figure 5.24 Impacts of impervious urban areas on mean annual blue, green and white water flows, using HRU 1 of CU 4 as an example

Interpretation of Figure 5.24: The impervious urban areas resulted in a modelled increase in runoff by 105 % which represents an increase of the portion of blue water flows from 110.0 to 225.6 mm. With a reduction of pervious areas, transpiration (i.e. green water flows), as well as evaporation from surfaces and from intercepted rainfall (i.e. white water flows), decreased. The evaporation from impervious areas is calculated by using the *ACRU* variable STOIMP, with an assigned value of 1 mm according to Tarboton and Schulze (1992).

Significance of findings shown in Figures 5.21 to 5.24: Urban landscapes, because of their increased impervious areas, were modelled to

a) show significantly more monthly and annual runoff than that from baseline land cover (Figure 5.20), implying that blue water flows and, therefore, accumulated streamflows, are increased, with this increase thought to be mainly because of the high frequency of smaller rainfall events which result in runoff from impervious urban areas, where on pervious surfaces less or no runoff would have been generated;
b) increase stormflows, and in this case even baseflows, the latter depending on the disjunct (unconnected) impervious areas from which water spills on adjacent pervious areas;

c) increase magnitudes of one day design runoff for selected return periods, which have a relatively higher effect in smaller flood events, but not such a pronounced effect on less frequent, higher return period flood events; and to

d) correspondingly reduce green water (transpiration) and white water flows (evaporation) with the increase in blue water flows.

Because urban landscapes do not only display an increase in impervious areas, but in the case of this particular study catchments also have the added effects as a result of receiving domestic/industrial water from outside of the study area, this impact is examined next.

- Hypothesis: Because certain urban areas within the study catchment are serviced with domestic/industrial water from external sources, the return flows into streams increase total flows, which is evident especially during the low flow period

The effects of urban return flows from external water sources (cf. Table 4.10) on the streamflow contribution were modelled and the results are shown in Figures 5.25 and 5.26.

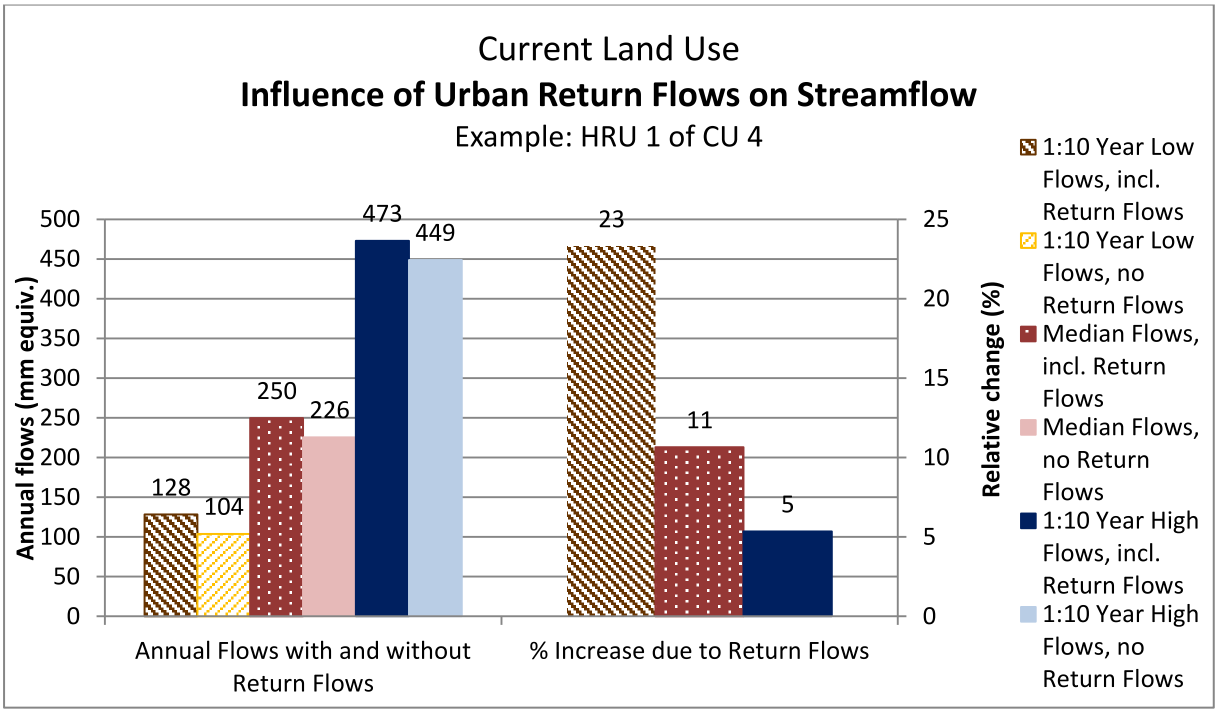

Figure 5.25 Influences of urban return flows on streamflow contribution during years with median and 1: 10 high and low flows, using results from HRU 1 of CU 4 as an example

Interpretation: The streamflow contributions increase as a result of urban return flows. The current return flows in this particular HRU have increased the streamflow contribution in years with low flows by 23 %, from 104 mm to 128 mm, in years with median flows by 11 % from 226 to 250 mm, and in years with high flows by 5 % from 449 to 473 mm. The impact is therefore particularly high in years with low flows. However, irrespective of wet or dry years, the additional urban return flows remain constant, in this particular HRU the equivalent of 24 mm per annum.

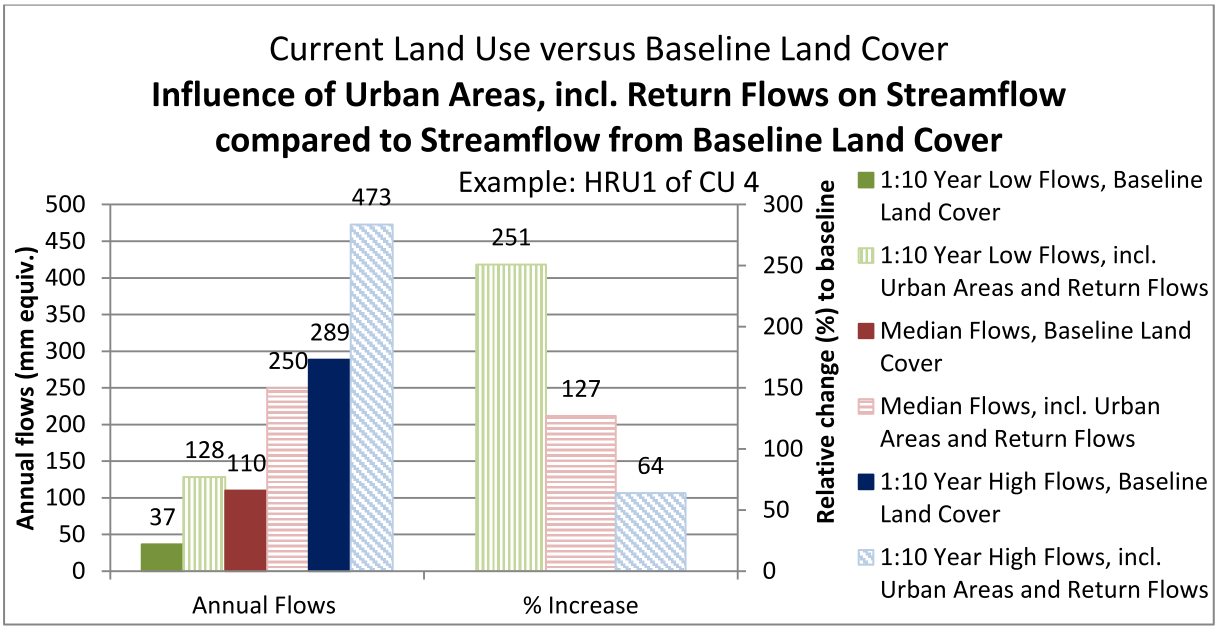

Figure 5.26 Influences of impervious areas and return flows of a more highly urbanised area on the streamflow contribution (excluding upstream contributions) in a year with median flows, as well as in years with 1:10 high and low flows, using results from HRU 1 of CU 4 as the example

Interpretation: The streamflow contributions increase as a result of impervious urban areas and urban return flows. In this particular HRU, the combined influences of impervious urban areas and urban return flows have increased the streamflow contribution in years with low flows by 91 mm, or 251 %, from 37 mm to 128 mm, in years with median flows by 140 mm, i.e. by 127 %, from 110 to 250 mm and in years with high flows by 84 mm, i.e. by 64 %, from 289 to 473 mm. The impact in relative terms is therefore particularly high in years with low flows, but in absolute terms is highest in years with high flows.

Significance: Based on the assumptions made on modelling urban return flows, they contribute to a consistent increase in flows, irrespective of the month of the year or whether years are wet or dry. Return flows of water from external sources increase the streamflow, and they are relatively more significant in dry periods. This increase in low flows contributes to maintaining flows above a minimum threshold, which may be important for certain aquatic species and processes, while on the other hand this may possibly have negative consequences for certain species which require low flow periods. It is expected that the much higher increases in return flow for the proposed land uses scenario will show greater effects. Furthermore, return flows are likely to be of lower water quality than natural flows. Additional to the above ecosystem effects from return flows, the increase in annual blue water flows from impervious areas also possibly change the ecological functioning of streams, as explained above. However, owing to a likely reduced water quality generated from urban areas (which does not form part of this study), any positive effects might be negated. While the biomass production on the pervious areas increases where there is a spill-over from impervious onto pervious areas (when *ACRU* variable DISIMP is > 0), the overall biomass production of an urbanised area may decrease (as in the case of HRU 1 of CU 4), because the pervious areas have been reduced.

The influences of urban land uses on various hydrological responses have been examined in the above section. The combined influences of the mosaic of current land uses on hydrological responses will be examined next.

5.4.5 Combined effects of current land uses on hydrological responses

The effects of individual current land uses described in the previous sections can either accentuate or attenuate hydrological impacts, both locally and on an entire catchment basis, when the entire 'land use mosaic' of the Mpushini/Mkhondeni study area is considered. In this section, the combined effects of current land uses on two relevant hydrological responses, *viz.* streamflow and sediment yields, will be examined with regard to the larger area of the study catchment.

- Hypothesis: To a certain extent, the influence of the combined effects of current land uses on streamflow cancel each other out

The total streamflow at the Mpushini Catchment outlet, as well as the total streamflow of the entire Mpushini/Mkhondeni study area outlet into the Msunduzi River, were examined to assess the combined effects of current land uses, compared to streamflows from baseline land cover conditions. The results are shown in Figure 5.27 for the Mpushini catchment outlet and in Figure 5.28 for the entire Mpushini/Mkhondeni study area.

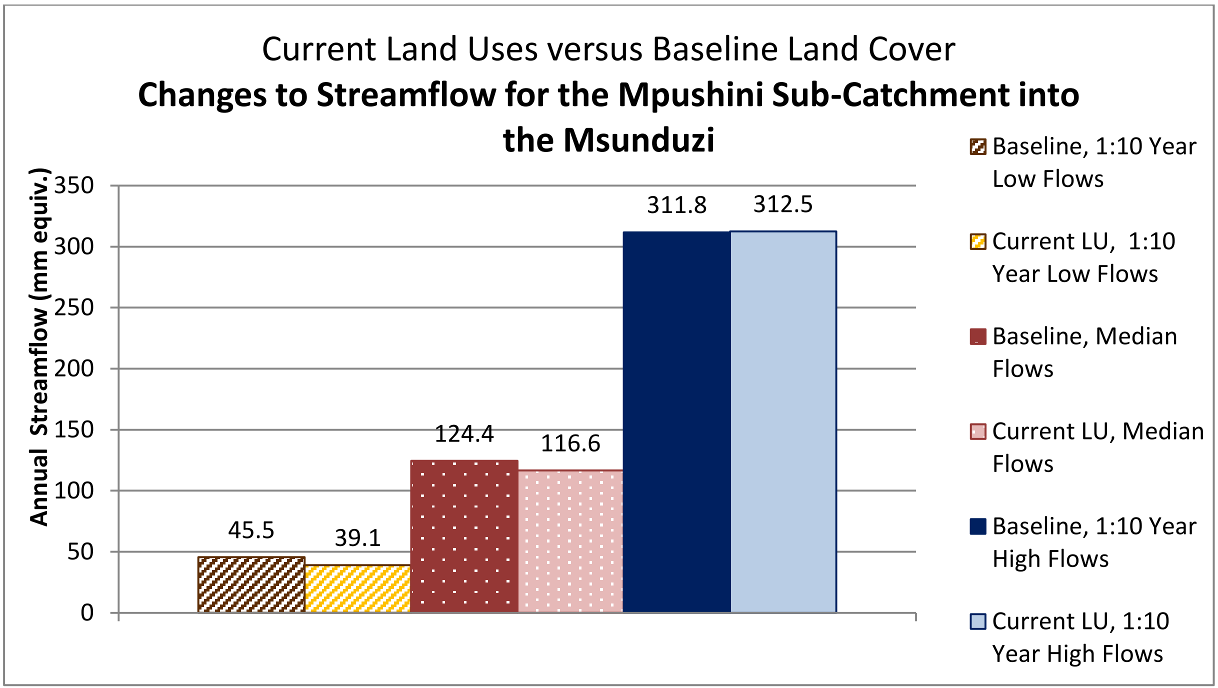

Figure 5.27 Streamflow from the Mpushini Catchment into the Msunduzi, for years of median flows and 1:10 high and low flows, using results from HRU 5 of CU 7 as the example

Interpretation: Figure 5.27 shows very similar overall streamflows for the mosaic of upstream land uses and baseline land cover conditions from the Mpushini catchment into the Msunduzi. The current land uses have reduced the streamflow by 5.4 mm or 14 % in years with 1:10 low flows, and by 7.8 mm or 6 % in years with median flows, but they hardly influence the streamflow in years with 1:10 high flows.

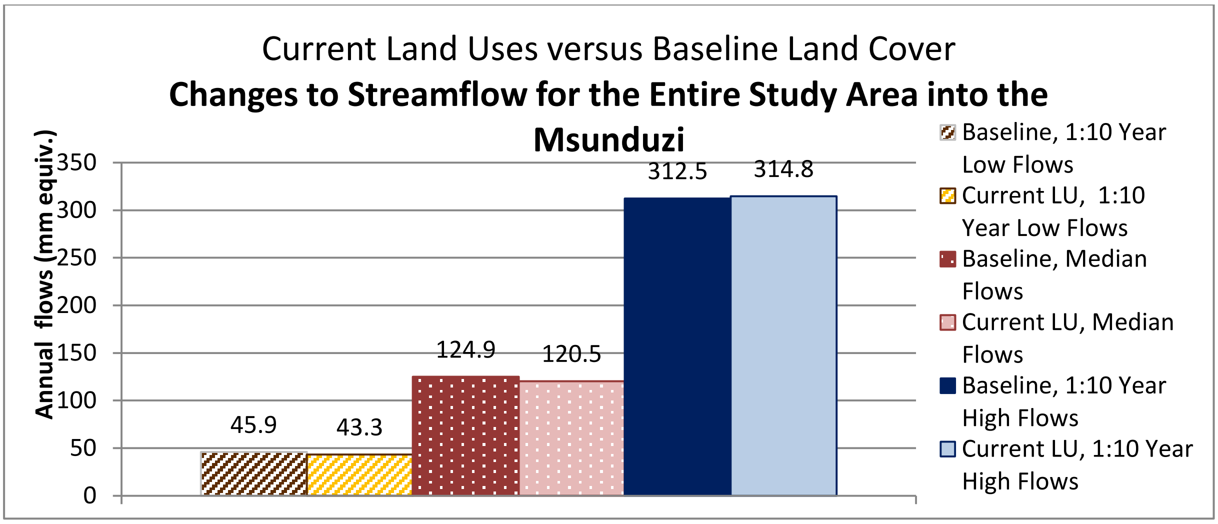

Figure 5.28 Streamflow from the entire Mpushini/Mkhondeni study area into the Msunduzi, for years of median flows and 1:10 high and low flows

Interpretation: As was the case from the Mpushini Catchment (Figure 5.27), Figure 5.28 shows very similar overall streamflows from the mosaic of upstream land uses versus baseline land cover conditions for the entire Mpushini/Mkhondeni study area into the Msunduzi. The current land uses have reduced the streamflow at the outlets by 2.6 mm or 6 % in years with 1:10 low flows, and by 4.4 mm or 4 % in years with median flows. The current land uses hardly influence the streamflow in years with 1:10 high flows, which show a slight increase by 2.3 mm, or less than 1 %, from 312.5 to 314.8 mm.

Having previously shown that the local effects of specific land use changes can have significant impacts on streamflow, and having now shown that overall effects for the larger catchment are relatively small, some of the key differences between local and overall effects on runoff and streamflow contributions are summarised in Table 5.3.

Table 5.3 Comparative influences (%) of selected current land uses on local scale streamflows versus influences of the mosaic of current land uses for the entire study area on streamflow

	Sugarcane, HRU 3 of CU 1	Irrigation, HRU 5 of CU 1	Degradation, HRU 4 of CU 7	Urban Areas, HRU 1 of CU 4	Overall, for the Entire Study Area
Year with 1:10 low flows	-51 %	-63 %	84 %	251 %	-6 %
Year with median flows	-24 %	-33 %	22 %	127 %	-4 %
Year with 1:10 high flows	-10 %	-11 %	5 %	64 %	<1 %

Interpretation of Table 5.3: The individual current land uses can have significant local hydrological effects. Overall, the agricultural land uses with increased biomass (e.g. sugarcane) or local water use (e.g. irrigation) have reduced the streamflow contributions in their specific HRUs, while degraded areas, and especially urban areas, have increased streamflow contributions. At the study areas' outlet the overall effects approximately cancel the respective negative and positive influences, with a decrease of 6 % in years with 1:10 low flows, when a decrease is most significant, a smaller decrease of 4 % in years with median flows, but hardly any change in years with high flows, with an increase of less than 1 %.

Significance: The current land uses have decreased streamflow at the catchment outlet slightly during average years and dry years. In wet years, the influences at the stream outlet are hardly discernible. The increase in runoff from urban areas as a result of increased impervious areas, as well as the added return flow from externally sourced water, has partially compensated for any reductions in downstream streamflows resulting from upstream land uses such as irrigation or high biomass crops such as sugarcane. From an ecosystem services perspective, this implies that water provisioning from the Mpushini/Mkhondeni study area has been reduced in years of median and low flows, but less so for the entire study catchment, than immediately downstream of an irrigation dam. In years with high flows, the current land uses cancel each other out on the scale of the study catchments. Overall, ecosystem services such as stream biodiversity and genetics are thus not likely to be affected too much by current land uses, although this might be very different locally. It is likely, however, that the relative contribution of stormflows to accumulated streamflows has increased as a result of current land uses. An increase of stormflows can be implied to increase sediment yields. Whether or not combined effects of current land uses impact sediment yields is tested in the section which follows.

- Hypotheses: The combined effects of current land uses increase sediment yields for the entire study area, probably as a consequence of higher overall stormflows

Sediment yields for the entire study area were modelled under current land use conditions, and results are compared in Figure 5.2.9 to those modelled under baseline land cover conditions.

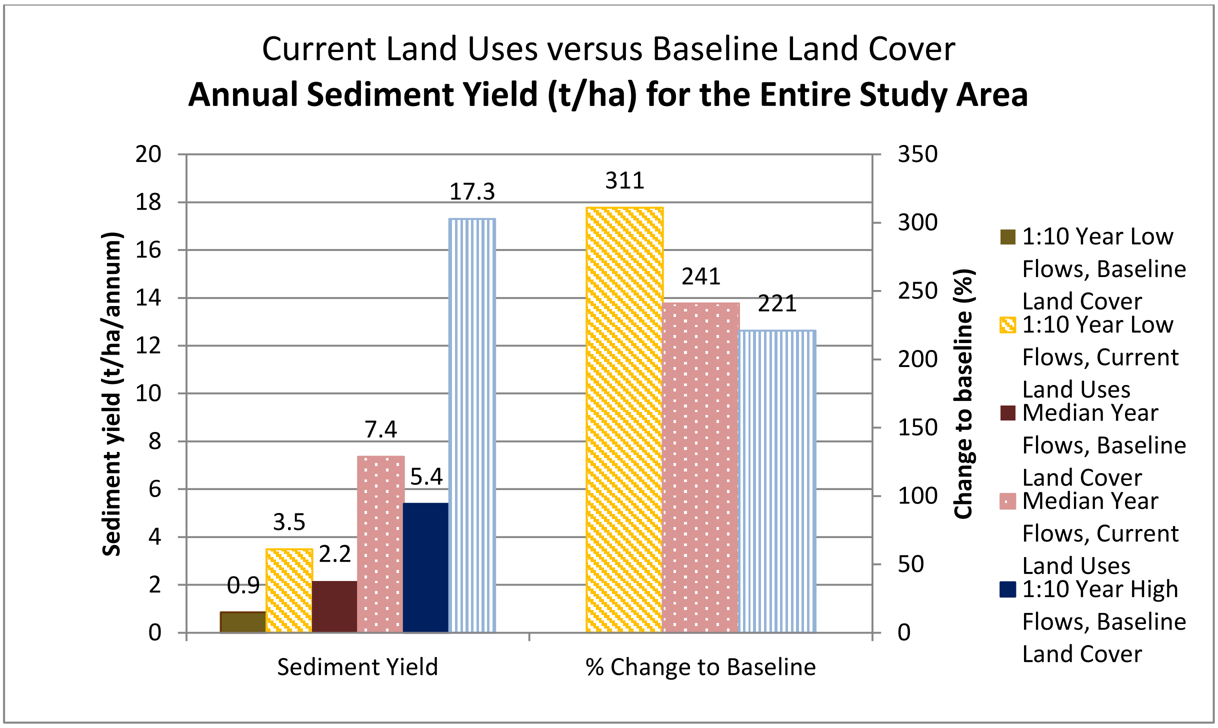

Figure 5.29 Annual sediment yields for the study area under current land uses compared to baseline land cover conditions, for years with median and 1:10 high and low flows

Interpretation: The current land uses have increased the sediment yields. The sediment yields increased by 311 % or 2.6 t/ha, from 0.9 t/ha to 3.5 t/ha, in years with low flows, by 241 % or 5.2 t/ha, from 2.2 to 7.4 t/ha, in years with median flows and by 221 % or 11.9 t/ha from 5.4 to 17.3 in years with high flows.

Significance: The current land uses have very significantly increased the total sediment yield from the study area, this being especially so, in absolute terms, during years with high flows. Relative increases (%) are, however, larger during years with low flows. This is likely to be the result of an overall increase in stormflows. From an ecosystem services perspective an increased sediment yield implies a reduction in physical water quality and reduced storage in water reservoirs, as well as a decrease in the soil fertility from the surrounding landscape component of the catchment.

5.4.6 Summary of results of hydrological responses influenced by the current land uses, compared to those from baseline land cover

This section summarises the results of influences of current land uses on hydrological responses and some of the effects on ecosystem services. A more detailed assessment of the effects of changed hydrological responses on ecosystem services is given in Sections 5.7 and 5.8.

a) Certain land uses, e.g. sugarcane and wattle plantations, reduce runoff compared to that from baseline land cover conditions (cf. Figure 5.12 and 5.13). For sugarcane and wattle (and other high biomass crops) this reduction in runoff is particularly high, in relative terms, during dry years and relatively less so in wet years. The agricultural land uses of grazing under natural vegetation versus improved pastures, while not modelled explicitly, are unlikely to affect runoff significantly, because the pasture's hydrological attributes are similar to those of the baseline land cover they replace.

b) Irrigation from farm dams lead to marked local decrease in streamflow, which is especially significant in years with low flows (cf. Figure 5.14). It also leads to a lag in downstream flow increases at the start of the wet season because a depleted dam first has to be filled before overflows commence. Although dams have a vital role to play in water storage to provide a reliable local water source, the streamflow immediately downstream of the dam is reduced, with the impact being most pronounced immediately below an individual dam used for irrigation. This reduction is comparatively lower further downstream at the outlet of the stream (cf. Figure 5.15). Therefore, ecological stream functioning might be critically reduced immediately downstream of a dam. Ecological flow releases, even from farm dams, are therefore vital for downstream ecological stream functioning, as well as for water provisioning for downstream users.

c) Land degradation is modelled to result in an increase of runoff (cf. Figure 5.16), but a reduction in the runoff component of baseflow (cf. Figure 5.17) and therefore a reduction of water availability during low flow periods. Land degradation is also modelled to increase magnitudes of one day design runoff for selected return periods (cf. Figure 5.18). Furthermore, land degradation was modelled to increase sediment yields (cf. Figure 5.19 and 5.20) and therefore to decrease the physical water quality, as well as to reducing water storage in reservoirs. The effects of degradation could be reversed with rehabilitation, and if all degraded areas within the catchment were to be rehabilitated, this would reduce the sediment yield in years with median flows by 57 Mt/year and in years with 1:10 high flows by 130 Mt/year.

d) Urban areas contain impervious urban surfaces that result in an increase in runoff (cf. Figure 5.21) and affect the runoff components of stormflow and baseflow differently, with most of the increase runoff (in absolute terms) consisting of increased stormflows (cf. Figure 5.22). The magnitudes of one day design runoff were increased (Figure 5.23). The increased runoff generated from the impervious portions of urban areas is likely to be of reduced water quality because of the wash-off effects from roofs and roads. The urban impervious areas resulted in a shift from green and white water flows towards blue water flows (cf. Figure 5.24). While the biomass production on the pervious portions of urban areas was modelled to increase where there is a spill-over from impervious onto pervious areas (when *ACRU* variable DISIMP is > 0), the total catchment biomass production is likely to decrease (as in the case of HRU 1 of CU 4), because the pervious areas on which plants can grow have been reduced in size.

e) Urban areas in the study catchment produced return flows, the water from which was derived from external sources. These urban return flows have a hydrological influence in addition to those of urban impervious areas. Based on assumptions made on modelling urban return flows, they contribute to a consistent increase in downstream flows, irrespective of the month of the year or whether years are wet or dry. These return flows are relatively more significant in dry periods (cf. Figure 5.25 and Figure 5.26). Furthermore, return flows are likely to be of lower water quality than natural flows because they are derived from domestic and/or industrial areas.

f) The combined effects of the current land use mosaic within this particular study area on annual streamflow are relatively small and individual land use impacts cancel each other out partially during years of low and median flows. In wet years, the influences of current land uses on the overall streamflow at the outlets are even smaller (cf. Figure 5.27 and Figure 5.28). When the effects of various land uses and the land use mosaic within the study area are compared, some land uses result in a runoff increase, some in a decrease but overall, the effects on annual streamflow under the current land uses are found to be small (cf. Table 5.3). However, note that alien invasive plants, other than identified wattle plantations, have not been taken into account in this study, and they might have an additional reduction effect on streamflow.

g) The combined effects of the current land uses show a marked increase in aggregated sediment yields with, this being especially significant, in absolute terms, during years with high flows, while the relative increase is bigger during years with low flows (cf. Figure 5.29). This increase in sediment yields is likely because of an overall increased stormflow component to runoff.

The influences of current land uses on hydrological responses were illustrated in this section. The study area is currently relatively rural, is still dominated by natural land cover and is used mainly for extensive grazing and hay baling. However, degraded areas were also found, as were transformed dryland agricultural land uses, mainly sugarcane and unmanaged wattle plantations. Some irrigated agriculture and numerous dams supplying the irrigated areas with water were found to influence streamflows, as did relatively small urban areas. The various proposed future developments (cf. Section 3.4.3) are projected to significantly increase the urban landscape in the form of increased residential and industrial areas. This will lead to increased impervious areas as well as urban return flows, with the latter derived from water from external sources. These proposed land uses can significantly influence the water flows within the hydrological cycle and their effects will be examined in the next section.

5.5 Understanding Impacts of Proposed Land Uses on Catchment Hydrological Responses

In order to understand possible changes in hydrological responses under future proposed land uses, the hydrology of proposed land uses is compared with that of current land uses, the effects of which were examined in the previous section. For this purpose, the model inputs related to increases in impervious areas, either adjunct or disconnected to a stream (as calculated in Section 4.4.9), and those impacts related to projected increases of urban return flows from water sources external to the study area (as was calculated in Section 4.4.10), were adjusted. The climate inputs were assumed to remain unchanged, with no climate change projections taken into account. Modelled changes in runoff, as well as its components of stormflow and baseflow, will be shown, followed by simulated changes in magnitudes in one day design runoff for selected return periods. HRU 1 of CU 3 and HRU 1 of CU9, the two HRUs with the highest degree of proposed urban change, are used as examples to model hydrological responses. HRU 1 of CU 3 is currently rural, with a low aggregated impervious fraction of only 0.16 (ADJIMP = 0.03, DISIMP = 0.13). Its impervious area fraction is calculated to increase to 0.66 (ADJIMP = 0.32, DISIMP = 0.34) as a result of proposed dense industrial developments (cf. Section 4.4.9; Table 4.8). The other example used is HRU 1 of CU 9, which is mainly proposed for increased residential areas. The model inputs would change from a low aggregated impervious fraction of 0.09 (ADJIMP = 0.04, DISIMP = 0.05) to a higher impervious fraction of 0.28 (ADJIMP = 0.09, DISIMP = 0.19; Table 4.8). In addition to the more local effects, the overall effects on the entire study area were modelled for the proposed land use scenario.

- Hypothesis: Runoff is further increased by enhanced urbanisation, with its increased impervious areas and return flows, the latter in this case with water from external sources

The influence of increased impervious areas on runoff, with the effects of urban return flows excluded, is modelled for HRU1 of CU 3 and results are compared in Figure 5.30 to the runoff under current urban land uses.

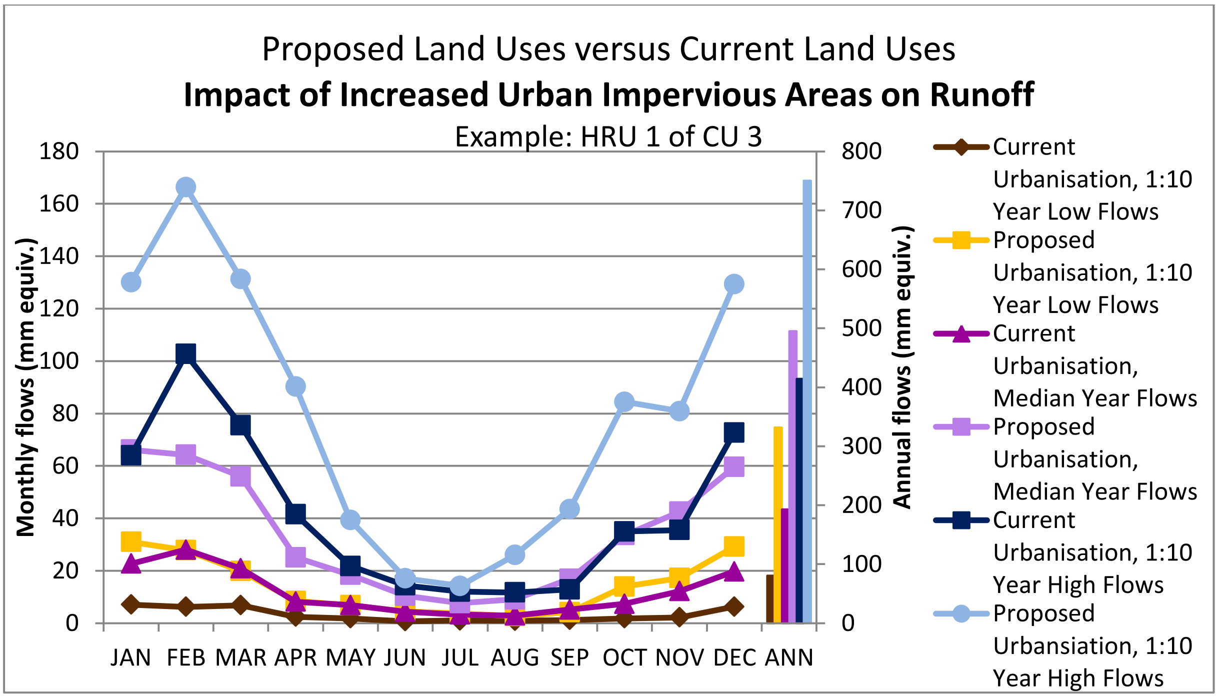

Figure 5.30 Impacts of increased impervious areas on runoff from proposed urbanisation compared to the runoff from current urbanisation, using results from HRU 1 of CU 3 as the example

Interpretation: Proposed changes for HRU 1 of CU 3 were modelled to lead to a significant annual increase of runoff. In years with 1:10 low flows, the annual runoff was modelled to increase by 251 mm or 312 % from 81 to 332 mm, in median flow years by 303 mm or 157 % from 193 to 496 mm and in years with 1:10 high flows by 335 mm or 81 %, from 415 to 750 mm. The increase in runoff is pronounced during the wet summer months, from October to March, when most rainfall events occur.

The significance of these results will be discussed after the next set of figures. The impact of the proposed urbanisation on the runoff components of stormflow and baseflows were modelled and the absolute impacts are shown in Figure 5.31, while the relative contribution of baseflows and stormflows to runoff is shown in Figure 5.32.

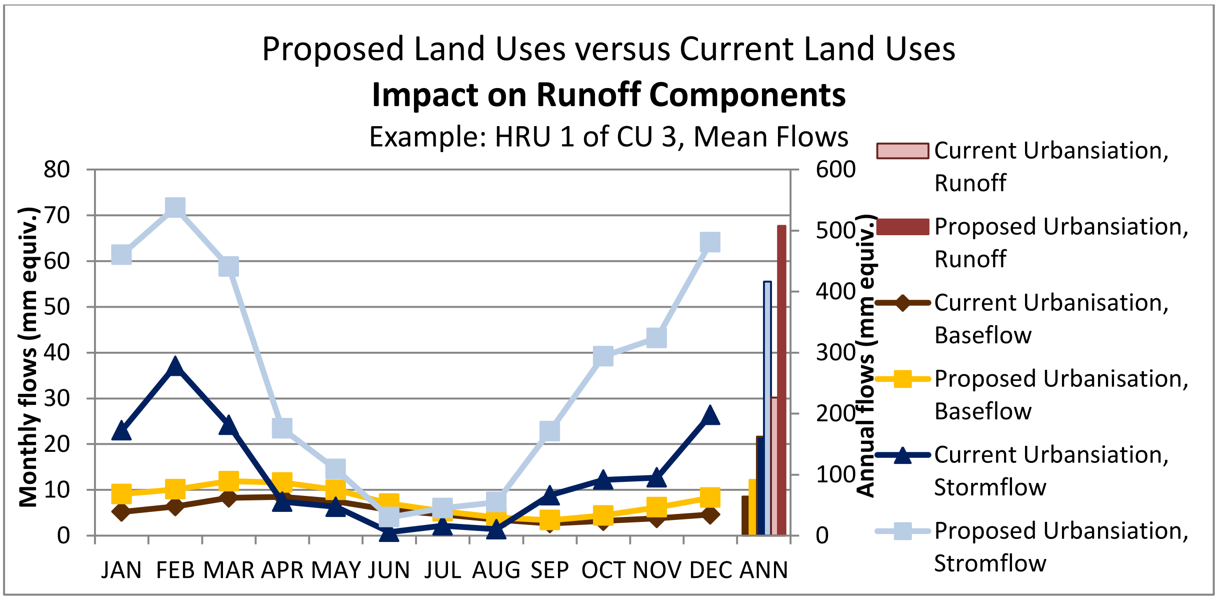

Figure 5.31 Influences of current and proposed urban impervious areas on the stormflow and baseflow components of runoff for a year with mean flows, using results from HRU 1 of CU 3 as an example,

Interpretation: The annual stormflows increased by 156 % from 162.4 to 416.4 mm, while the annual baseflows increased by 43 % from 63.9 to 162.4 mm. The increases in baseflows are higher in absolute terms, during the rainy season (October to May), but lower during the dry season from June to September.

Table 5.4 Influence of urban impervious areas on the baseflow component of runoff, using results from HRU 1 of CU 3 as an example, showing the monthly and annual baseflows (mm), as well as standard deviations and coefficients of variation (%)

Proposed versus current urbanisation														
HRU 1 of CU3	Baseflows	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Current urbanisation	Mean (mm)	5.2	6.4	8.3	8.5	7.5	5.6	4.6	3.5	2.7	3.2	3.8	4.6	63.9
Proposed urbanisation	Mean (mm)	9.1	10.1	11.9	11.6	10	7	5.3	4	3.4	4.4	6.2	8.3	91.4
Current urbanisation	St. dev	7.1	6.6	8.6	8.4	6.6	4.9	4.1	3.2	2.4	3.8	4.8	5.2	53.2
Proposed urbanisation	St. dev	6.4	6.1	6.7	6.7	6.0	3.8	2.5	1.9	1.6	3.7	4.8	5.7	42.4
Current urbanisation	C.V. (%)	135.1	104.2	103.5	99.1	88.3	87.4	89.0	91.5	89.6	121.3	125.0	114.3	83.2
Proposed urbanisation	C.V (%)	70.1	61.0	56.2	57.6	60.4	54.7	47.6	46.0	46.5	84.6	77.9	68.9	46.4

Interpretation: The proposed urbanisation was modelled to lead to increased monthly and annual baseflows but reduced variability in baseflows, both absolute (standard deviation) and relative (coefficient of variation).

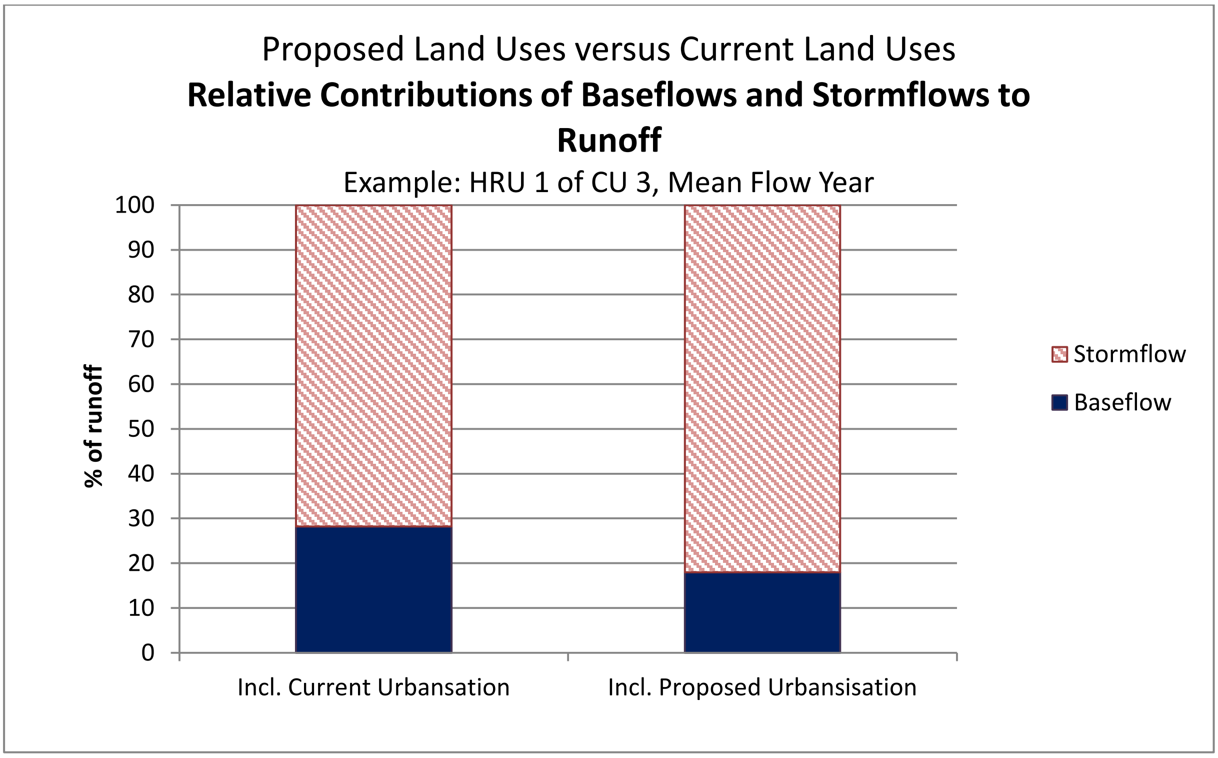

Figure 5.32 Influences of urban impervious areas on the relative contributions of stormflows and baseflows to runoff for a year with mean flows, using results from HRU 1 of CU 3 as an example

Interpretation: With the proposed increases in urbanisation in HRU 1 of CU 3 the relative contribution of stormflows to runoff increases from 72 % to 82 %, while correspondingly the relative baseflow contribution decreases from 28 % to 18 %.

Significance of Figures 5.30 to 5.32 and Table 5.4: The proposed urbanisation would lead to a very much increased runoff. The increase in runoff is made up of increases in stormflows, as well as baseflows, with the stormflow contributing the most in absolute values. The increases in baseflows are more significant, in absolute terms, during the rainy season but the increases are less (in absolute terms) when there is little rain during the dry season. The relative contribution of stormflow is increased with increased urbanisation, while that of baseflows decreased.

Next, the effects of the combined influences of urban return flows and increased urban impervious urban areas are modelled, with results shown for HRU 1 of CU 3 in Figure 5.33 and for HRU 1 of CU 9 in Figure 5.34.

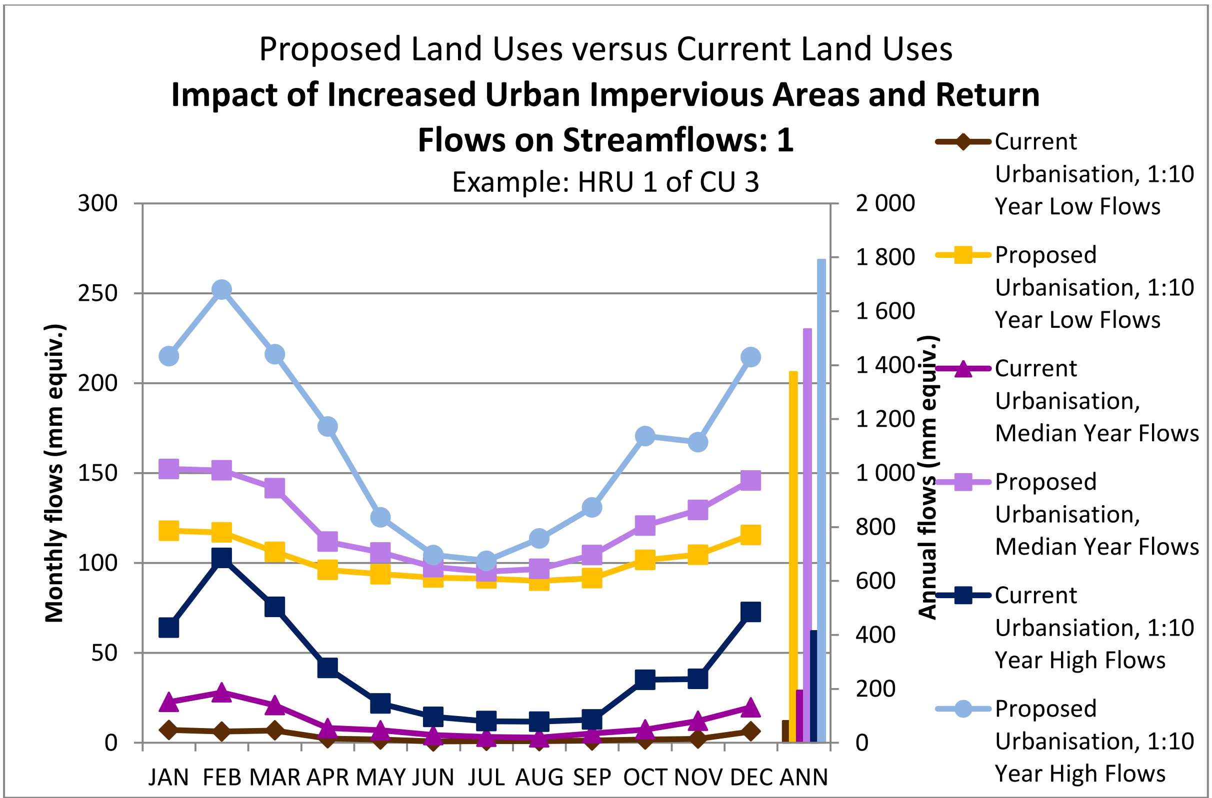

Figure 5.33 Impacts on streamflows of proposed increases in urban areas, including impervious areas and urban return flows from externally sourced water, compared to current levels of urbanisation using results from HRU 1 of CU 3 as an example

Interpretation: For this HRU's very high level of increase in proposed urbanisation the annual runoff in a year with 1:10 low flows has increased by 1 294 mm or 1 607 % from 81 to 1 374 mm, by 1 341 mm or 695 %, from 193 to 1 534 mm in a year with median flows and in a year with 1:10 high flows, by 1 376 mm or 332 %, from 415 to 1 790 mm. These extreme increases reflect the combined effects of return flows derived from water which is sourced from outside the catchment and increased runoff from urban impervious areas.

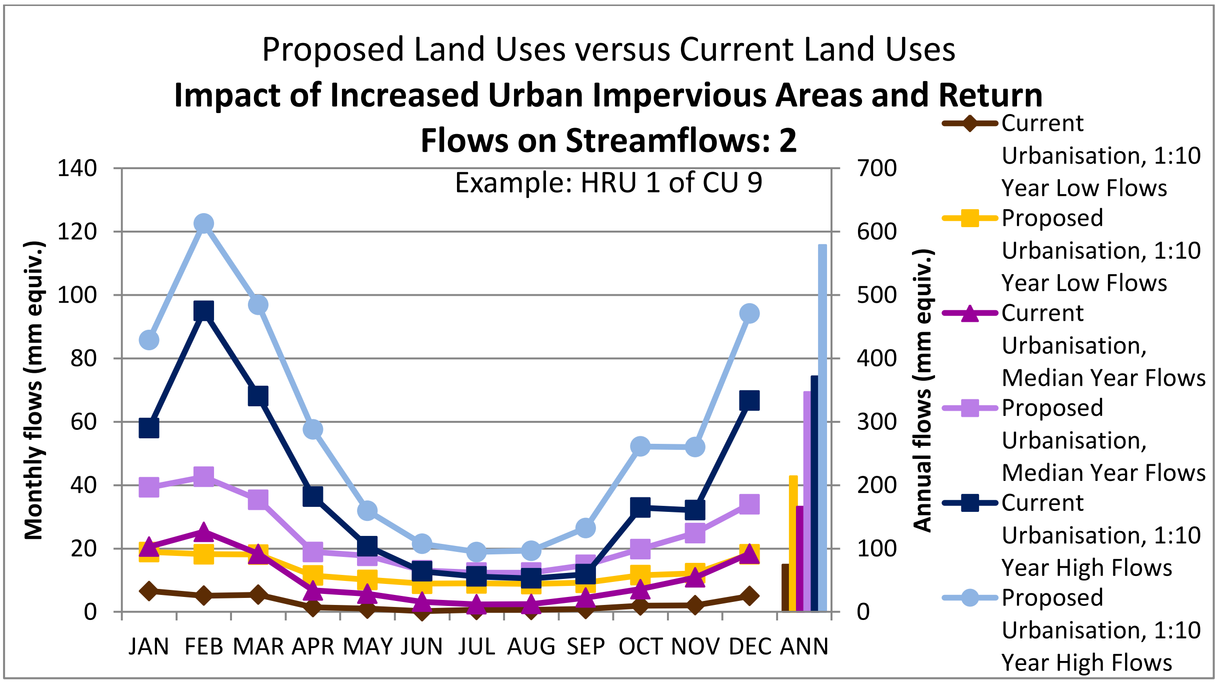

Figure 5.34 Impacts on streamflows of proposed increased impervious urban areas and urban return flows from externally sourced water compared to current levels of urbanisation, using results from HRU 1 of CU 9 as the example

Interpretation: With this HRU's somewhat lower level of increase in urbanised areas than in the previous example, the annual runoff in a year with 1:10 low flows has increased by 140 mm or 188 % from 75 to 214 mm, in a year with median flows by 181 mm or 109 %, from 166 to 347 mm, and in a year with 1:10 high flows by 207 mm or 56 % from 372 to 579 mm. While the increases are still high, they nevertheless are considerably lower than those for the more highly urbanised HRU 1 of CU 3.

In order to be able to compare the impacts of only urban impervious areas with those of only urban return flows the annual runoff from current urban land uses are compared with the annual runoff of proposed urban land uses and the annual streamflow contributions, made up of runoff and urban return flows, are compared by assessing results from simulations on HRU 1 of CU 3. The results are presented in Figure 5.35.

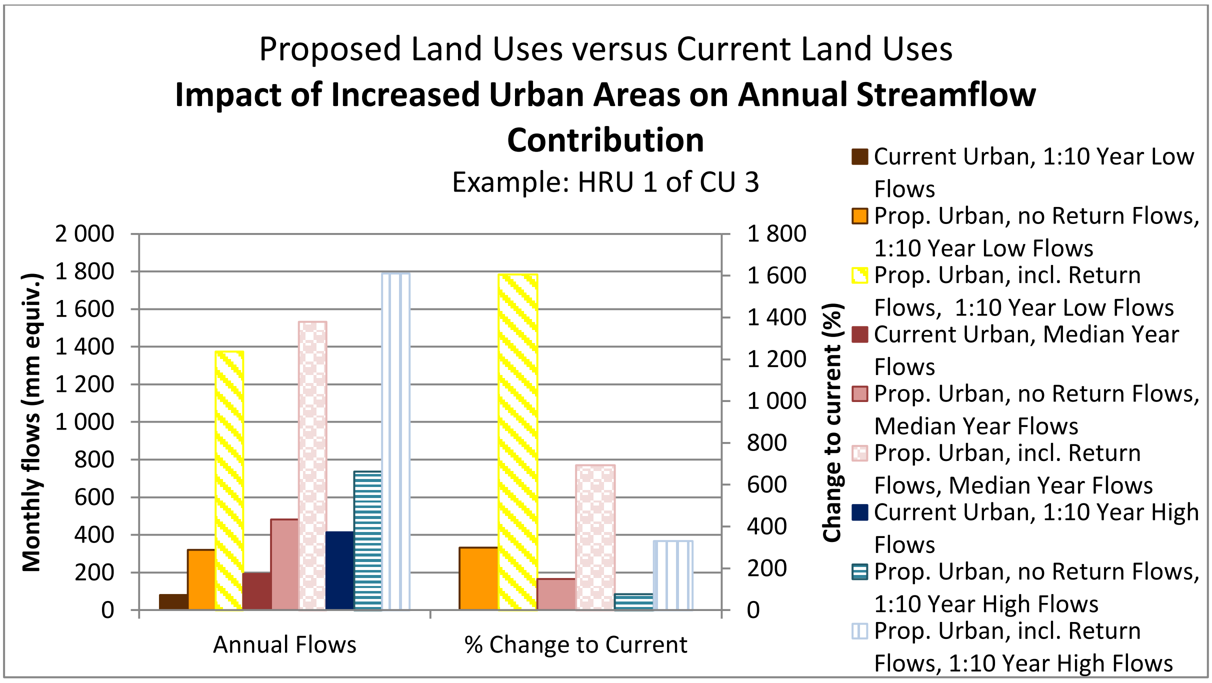

Figure 5.35 Impacts of proposed urban land uses compared to those of current urban land uses, with and without urban return flows, modelled for years of median flows, as well as for years of 1:10 low and high flows, using results from HRU 1 of CU 3 as an example

Interpretation: The proposed land uses were modelled for the highly increased urbanisation (mainly industrial) in HRU 1 of CU 3. Results for years with 1:10 low flows showed increases in the annual streamflow contribution for this HRU of 241 mm or 299 % without return flows and of 1 294 mm or 1 607 % with return flows. For years with median flows, the increase was 289 mm or 150 % without return flows and 1 341 mm or 695 % with return flows. For years with 1:10 high flows, the increases were 322 mm or 78 % without return flows and 1 376 mm or 332 % with return flows. Those increases are already very large for the effect of increased urban impervious areas alone, while when the urban return flows were added, these had an even greater impact, with the return flows being the major contributor. Note again that return flows are derived from externally sourced water.

In the above section, streamflows from individual HRUs which were proposed for major urbanisation were modelled for the current (mostly rural) land uses and the proposed (highly urbanised) land uses and the hydrological responses of runoff and streamflows were compared. To examine the influence of all proposed new urbanisation on streamflow on a catchment scale, the volume increases in streamflow that flow into the Msunduzi River from the study area are examined next.

- Hypothesis: The proposed urbanisation in the Mpushini/Mkhondeni Catchments significantly increases the streamflow volumes that the study area contributes to the Msunduzi River.

The overall effects of proposed developments on the volume of streamflow from the catchment is examined and results shown in Figure 5.36. Because the return flows from urban areas for the entire study area are calculated in mega litre (ML = million litre), the units will be shown in Ml instead of in mm equivalent.

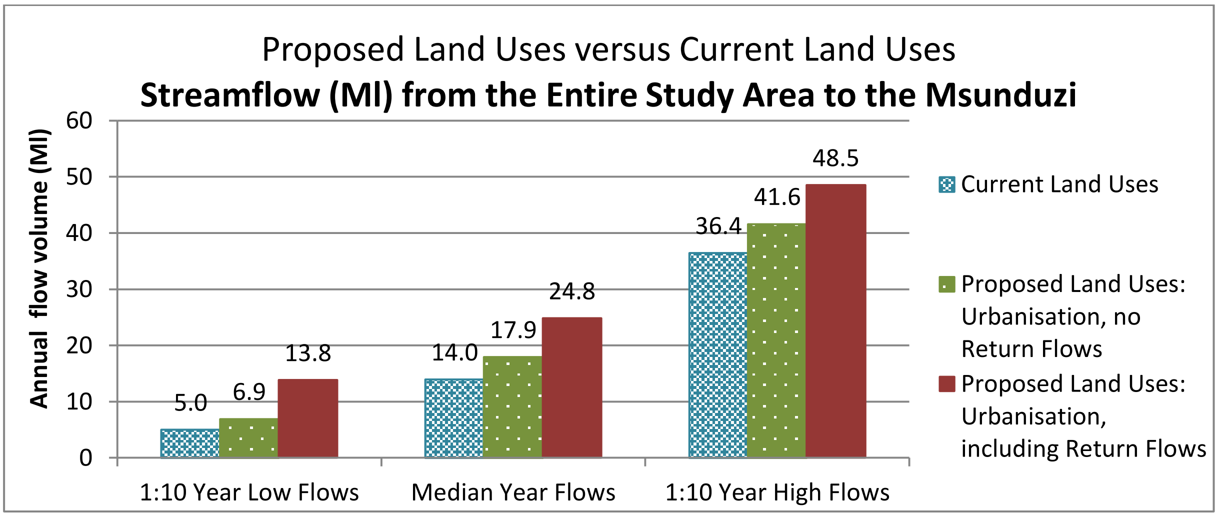

Figure 5.36 Influences of the proposed urbanisation in the Mpushini/Mkhondeni study area, with and without urban return flows, on the streamflow at the catchment outlets, for years of median flows and 1:10 low and high flows

Interpretation: At the study area's outlets the proposed upstream urbanisation was modelled to increase the streamflow by 38 % in years with 1:10 low flows without return flows, and by 176 % to 13.8 Ml with return flows included. For years with median flows the increase was 29 % from 14.0 to 17.9 Ml without return flows and 78 % from 14.0 to 24.8 Ml. In years with 1:10 high flows, the increases were 14 %, from 36.4 to 41.6 Ml without return flows and 33 % from 36.4 to 48.5 Ml when the urban return flows were included. This is a very large overall increase. However, it is less than at the individual development nodes, as was shown in Figures 5.29 and 5.32.

Having shown previously that the local effects of specific land use changes can have significant impacts on local streamflows, some of the key differences between local and overall effects on streamflow for current and proposed land uses are summarised in Table 5.5.

Table 5.5 Comparative influences (%) of selected proposed and current land uses on local scale streamflows versus influences of the mosaic of current land uses for the entire study on streamflows

	Sugarcane, HRU 3 of CU 1	Irrigation, HRU 5 of CU 1	Degradation, HRU 4 of CU 7	Current Urban Areas, HRU 1 of CU 4	Streamflow, for all Current Land Uses for the Entire Study Area	Proposed Urban Areas, HRU 1 of CU 3	Streamflow, including Proposed Land Uses for the Entire Study Area
Year with 1:10 low flows	-51 %	-63 %	84 %	251 %	-6 %	1 607 %	176 %
Year with median flows	-24 %	-33 %	22 %	127 %	-4 %	695 %	78 %
Year with 1:10 high flows	-10 %	-11 %	5 %	64 %	<1 %	332 %	33 %

Interpretation: Columns 2-5 illustrate the local effects of specific land uses, with some reducing and others enhancing flows and the impacts being relatively more sensitive in low flow years. However, the overall effects of the specific land uses examined in this study area are largely self-cancelling. Note, however, that alien invasive plants other than identified wattle plantations have not been taken into account, and their inclusion might have had an additional reduction effect on streamflow. The effects of proposed urbanisation in this study area entirely dominate those of current land uses.

5.6 Summary of Results of the Influences of Land Use Change on Hydrological Responses

Selected hydrological responses under baseline land cover were modelled and assessed first. Thereafter selected hydrological responses from current land use conditions were modelled and compared to those from baseline land cover conditions. Following this, selected hydrological responses under proposed urbanisation were modelled and compared to those under current land uses.

In assessing various influences under baseline land cover, with no current land use influences included yet, the following findings were made for the various hydrological responses within the study area:

a) The annual, as well as monthly, runoff is highly variable between years, with monthly and annual dry season runoff often extremely low.
b) Annually, stormflow contributes more to runoff than baseflow and the contribution of stormflows to total runoff displays major differences between years of high, median and low flows.
c) Differences in baseline land cover can have significant influences on runoff, although these differences are relative small within this particular study area.
d) Blue water flows make up proportionally the lowest fraction of the study area's water budget, when compared to green and white water flows.
e) Differences in green water flows, i.e. transpiration, vary from month to month and from year to year in this study area, depending on available soil water.
f) Sediment yields are increased markedly during years with high flows.
g) Hydrological responses such as sediment yields, stormflows and especially baseflows, amplify any changes in the rainfall regime.

Changes to hydrological responses from the various current land uses, compared to those from baseline land cover, are summarised below:

a) Certain land uses, in this case sugarcane and wattle plantations, reduce runoff, compared to that from baseline land cover conditions.
b) Irrigation from dams lead to a significant local decrease in streamflow, which is especially significant in years with low flows. It also leads to a lag in streamflows when these increase again at the start of the wet season, because a depleted dam first has to be filled before overflows commence. The decrease in streamflow is more pronounced immediately below an individual dam.

c) Land degradation is modelled to result in increases in runoff and sediment yield, but in reductions in baseflows when results are compared to those from baseline land cover conditions. The effects of degradation could be largely reversed through rehabilitation, and if all degraded areas within the catchment were to be rehabilitated, this would reduce the sediment yield in years with median flows by 57 Mt/year and in years with 1:10 high flows by 130 Mt/year.

d) Urban areas in this study area have their return flows generated from externally-sourced water. Based on assumptions made on modelling urban return flows, these contribute to a consistent increase in flows, irrespective of the month of the year or whether years are wet or dry. Return flows of water from external sources increase the overall streamflow, and they are relatively more significant in dry periods.

e) In addition to the above effects from return flows, impervious urban areas were found to increase the runoff and thus blue water flows. The increases are made up of increased stormflows as well as increased baseflows. The magnitudes of one day design runoff for selected return periods also increased when compared to those from baseline land cover conditions.

f) Where there is a spill-over from impervious onto pervious urban areas, the biomass production (as measured by transpiration) from the pervious areas increases. However, the overall biomass production decreases, because the pervious areas have been reduced through urbanisation.

g) The combined effects of the current land use mosaic on annual streamflows for the entire study area at the catchment outlet of this particular catchment, partially cancel out the effects of individual land uses.. For this study area, during average and dry years, the current land uses result in a small reduction in flows. In wet years, the combined influences of current land uses result in essentially the same streamflow at the catchment outlet as under baseline land cover conditions.

h) In contrast to the above, however, the combined effects of the current land uses show a marked increase in sediment yields, which is especially significant, in absolute terms, during years with high flows, while the relative increase is bigger during years with low flows. This is likely as a result of an overall increased stormflow component of runoff, especially for high flow events.

The proposed land uses, consisting mainly of industrial and residential uses, would urbanise and thereby transform the presently mainly rural study area. This proposed urbanisation, with markedly increased impervious urban areas, was found to lead to significantly increased runoff, in absolute terms made up of mainly increases in stormflows, while the often fairly low baseflows would also increase markedly, in relative terms. The increases in baseflows are more significant, in absolute terms, during the rainy season but they increase less (in absolute terms) when there is little rain during the dry season. The relative contribution of stormflows to total runoff increases, while that of baseflows decreases. The increased runoff is modelled to significantly increase streamflows. In addition, urban return flows from water sourced externally to this catchment lead to drastically increased, but less variable, streamflows. Overall, the effect of the proposed urban land uses would be the dominant one on annual streamflow, which at the catchment outlets was modelled to increase by 176 % in years with 1:10 low flows, by 78 % in years with median flows and by 33 % in years with 1:10 high flows, compared with flows from current land uses.

5.7 Linking Hydrological Functions and Responses to Hydrological Ecosystem Services

The theoretical links between the modelled hydrological responses and ecosystem services are explained below. Only selected provisioning, regulating, and supporting hydrological ecosystem services, have been evaluated and it should be noted that this does not include all services. The ecosystem service of water provisioning will be described first (Section 5.7.1), followed by regulating ecosystem services relating to hydrological flow regulations (Section 5.7.2) and thirdly, supporting ecosystem services related to stream biodiversity and genetic diversity, as well as soil fertility affected by sediment yield (Section 5.7.2).

5.7.1 The ecosystem service of water provisioning, separated into "blue" and "green" water flows and their indicators

The ecosystem service of water provisioning includes not only the "blue water" flows, which are visible to the naked eye. In this study area the "green water" flow component makes up a bigger portion of the water budget. Therefore, any available water, whether in the form of blue or green water flows, is classified as an ecosystem service of water provisioning, irrespective of whether the provided water is used directly by humans for consumption, or indirectly, for example for irrigation or industrial purposes.

For the purpose of this study, green water is soil water used by plants to produce biomass which can directly or indirectly be of use to humans. Changes to the ecosystem service of water provisioning through green water flows in this study are indicated by changes in the hydrological response of transpiration, which excludes evaporation from the soil surface or from intercepted water.

Changes to water provisioning through blue water flows can be indicated by changes in the hydrological response's streamflow or on an individual HRU level in the changes to runoff and its components of stormflow and baseflows.

5.7.2 Hydrological regulating services and their indicators

An important ecosystem function is the regulation of catchment flow. When it rains onto an intact landscape, the water in a simple water budget is partitioned into water intercepted, water infiltrated into the soil and stormflows and baseflows making up runoff into streams (Section 2.3.2). The entire catchment ecosystem, including its vegetation and soils, its topography, channel network and water engineered systems, therefore regulates the flow and not only wetlands and floodplains, as is often highlighted in the literature (e.g. Aylward *et al.*, 2005). In contrast, on a concrete parking lot, the same rainfall would result in rapid runoff of almost all the water and therefore cause a spike in the streamflow response. A regulating hydrological ecosystem service, which is of indirect use to humans, would be a *reduction* of the impacts of high flows (e.g. reducing flood damage), or an *increase* in low flows.

Changes in flow regulation resulting from land use changes might be as a result of total increases (or decreases) of the number, and/or the severity, and/or the duration of individual flood events, or alternatively a shift in the seasonality of those occurrences. The model output of daily stormflow is a measure of blue water that could contribute to flooding and is, therefore, an indicator of a regulating service. Changes in stormflows relate directly to changes in flood regimes. The model output of daily baseflows, on the other hand, is a measure of contribution of blue water availability in the non-rainy period and thus regulates dry season flows. Changes in the relation between stormflows and baseflows are an indicator of changes to regulating hydrological ecosystem services, with flow regulation increasing if the relative contribution of baseflows to runoff increases and the relative contribution of stormflows to runoff decreases, and *vice versa*. A good indicator pertaining to changes in extreme floods, which are normally the events that result in damage, are changes to one day design runoff magnitudes for varying return periods.

Another regulating ecosystem service is related to the filtration of water to obtain water of acceptable quality. The only indicator for physical water quality from this particular modelling approach has been sediment yield. To account for chemical and biological water quality, other indicators, the modelling of which falls beyond the scope of this study, need to be used. In addition to the ecosystem service of regulating water quality, sediment yield is also an indicator of soil erosion from the landscape, with associated impacts on, for example, nutrient levels of soils and biomass yield from plants. However, to describe those impacts adequately, additional information is required, which again is beyond the scope of this dissertation.

5.7.3 Supporting ecosystem services

There are various supporting ecosystem services pertaining to water flows and variability, e.g. water to support stream ecology or vital estuaries and other habitats. Many ecological functions rely on a certain minimum flow and stability or seasonal variability and the absence or presence of extreme events of certain magnitudes and frequencies. Indirectly, the indicators of provisioning and regulating services described above are also indicators of such supporting services. However, the indicators of supporting services are not quite as straightforward as those of provisioning and regulating ecosystem services and require research based on biological methods, which are beyond the scope of this dissertation. The Literature Review (Chapter 2) has, however, shown that the ecology in streams has evolved to local conditions and both biodiversity and genetic diversity are negatively affected through streamflow regime changes, physical water quality deterioration and habitat alteration through increased sediment yields (Bunn and Arthington, 2002; Dudgeon *et al*., 2006) . Therefore, a reduction in the ecosystem service of biodiversity and genetic diversity can be indicated through alterations in streamflow, and these could be the increases, decreases or changes in timing of streamflows, low flows, the runoff components of baseflow and stormflow, or increases in magnitudes of one day design runoffs. In addition, increased sediment yield causes a decrease in physical water quality, as well as a modification of the stream habitat, and therefore also indicates a reduction in bio- and genetic diversity. This might, however, also imply that some aquatic species benefit from the altered landscape conditions.

5.7.4 Cultural ecosystem services

There are undoubtedly cultural services related to water quantity and flow, including, but not limited to, the enjoyment of scenery, increased property values, travel to places for eco-tourism or outdoor sports, as well as spiritual or scientific research. The indicators used within this study, however, cannot be used as sole indicators to describe changes to cultural ecosystem services. Therefore, research beyond this dissertation would be required to determine these services with any accuracy.

5.7.5 Summary of the links between selected hydrological responses and selected ecosystem services

A change in flow regimes usually reduces the habitat function which leads to biodiversity as well as the genetic diversity in streams and adjoining edges, as the habitat is altered. A non-exhaustive summary of the changes to modelled hydrological responses, as well as associated provisioning and regulating ecosystem functions, but excluding the just mentioned services related to habitat functions and selected affected ecosystem services, is provided in Table 5.6, which is based on the findings of this study, the Literature Review and the author's understanding of hydrological processes.

5.8 The Link between Land Use Changes and Ecosystem Services, as indicated by Hydrological Responses

From Sections 5.3 to 5.6, links between land use change and modelled hydrological responses were evaluated. In Section 5.7 links between changes in hydrological responses and selected ecosystem services were assessed. The links between the examined land use change and selected ecosystem services will be discussed next, under the broad categories of agricultural land uses and urbanisation.

Table 5.6 A non-exhaustive list of the modelled hydrological responses and their changes, ecosystem functions (excluding habitat functions) and the affected ecosystem services

Hydrological Response	Changes (as a result of land use change)	Affected Ecosystem Function / Process	Affected Ecosystem Service (examples)
Runoff and/or streamflow	Decrease	Provisioning	Less blue water provisioning Possibly more green water provisioning
	Increase	Provisioning	More blue water provisioning (but possibly of poorer quality) Possibly less green water provisioning
		Regulating	Potentially higher flood damage (through increased blue water)
	Change in seasonality/ frequency of events	Provisioning	Changes in seasonal water provisioning
		Regulating	Changes in seasonal flow regulating services
Baseflow component of runoff	Increase	Provisioning, Regulating	Increase in water provisioning during low flow periods
			Increase in low flow regulations
	Steading	Regulating,	Increase in low flow regulations
Stormflow component of runoff	Increase	Regulating	Ecosystem service of flow regulation might not be enough, potentially higher flood damage
Relative relationship of stormflows to baseflows	Increase	Regulating	Decrease in flow regulation
	Decrease		Increase in flow regulation
One day design runoff (for selected return periods)	Increased magnitudes	Regulating	Ecosystem service of flow regulation might not be enough, potentially increased flood damage
Sediment yield	Increase	Provisioning	Decreased blue water provisioning (through a reduction in reservoir capacity and a reduction in physical water quality)
		Regulating	Possibly higher flood damage (through a reduction in reservoir capacity)
		Production	Reduced fertility of surrounding lands and thus a reduction of biomass for food, feed, energy or building materials
Transpiration	Increase	Provisioning, / Production	Increase of biomass for food, feed, energy or building materials (through more green water availability)
	Decrease		Reduction of biomass for food, feed, energy or building materials (through less green water availability)

5.8.1 Agricultural land uses

The production of high biomass crops, as well as irrigated areas, were found to reduce downstream water provisioning. On the other hand, extensive agricultural activities, when well-managed, were found to maintain downstream water provisioning, as well as flow regulation and, if natural vegetation cover is maintained, to contribute towards biodiversity and genetic diversity. The use of farm dams was found to modify streamflow and reduce especially locally important downstream ecosystem services of water provision and stream-related bio- and genetic diversity. However, the dams do provide flow regulating services, with both positive and negative effects. Land degradation, often the result of poor veld management caused by overgrazing or unsuitable burning regimes, was modelled to reduce flow regulation by increasing incidences of stormflows, and to reduce biodiversity and genetic diversity by increasing sediment yields and thereby reducing water quality. While the overall blue water provisioning from degraded areas was modelled to increase over a year, the water availability was shown to decrease during times of low flows, when it is most needed.

5.8.2 Urban land uses

Urban land uses, depending on density, size and type, with their increased impervious areas, compared to natural vegetation and agricultural land uses, and in this study area with water making up the return flows sourced externally to the catchment, were modelled to increase downstream flows. However, these are likely of reduced water quality. With regard to regulating services, urban areas, on the one hand, *decrease* regulation by increasing the "flashiness" of flows resulting from the enhanced stormflows off the impervious areas. Conversely, in this catchment, there is a *greater low flow regulation* by steadying the contribution of return flows, as well as increased water off the unconnected impervious areas spilling over onto adjoining pervious areas and wetting these. Both processes led mainly to an increase in low flows. The overall biomass production of urban areas will be reduced, as impervious areas replace green spaces, while the biomass production on those green spaces is modelled to increase, where there is increased water availability from runoff spill-overs from impervious areas. The increased annual blue water flows from urban areas are also likely to change the ecological functioning of streams. The increase in low flows has consequences of maintaining flows above a minimum threshold, which may be important for particular processes and certain aquatic species and processes. However, stream ecology evolves under local conditions and certain species require drier periods. In addition, a reduced water quality is generated from urban areas. Overall, the impact of urban area on biodiversity and genetic diversity is likely to be negative.

6. DISCUSSION

This chapter fits into the overall research objective and the approach as shown in the overview provided in Figure 6.1.

Objective: To evaluate changes to selected hydrological responses and associated selected ecosystem services provided by the study area, as a result of current and proposed land use modifications					
Approach: The objective is to be achieved by identifying the scenarios of baseline land cover as well as current and proposed land uses; sub-delineating the study area into land use determined hydrological response units; applying an appropriate hydrological simulation model to assess changes in hydrological responses from baseline land cover as well as current and proposed land uses; and relating these changes in hydrological responses to changes in selected ecosystem services					
Sections					
Chapter 1 Introduction	Chapter 2 Literature Review	Chapter 3 Catchment Description	Chapter 4 Methods	Chapter 5 Results	Chapter 6 Discussion
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Figure 6.1 Discussion and recommendations within the context of this dissertation

6.1 An Overview of the Approach Adopted

In this dissertation, after an introduction (Chapter 1), a literature review was undertaken (Chapter 2) covering ecosystem services and, in particular, hydrological ecosystem services, as well as the impact of land use within an ecosystem services context and the links and interactions between hydrological ecosystem services and land use. A special emphasis was placed on the South African context.

It was found that markets worldwide and in South Africa do not protect ecosystem services sufficiently. Individual landowners might often profit more from degrading ecosystems, because environmental and social costs are distributed to society while profits occur to the individual or company. Conversely, often no or little monetary benefit occurs to the landowner or company that sustains land, thus contributing toward ecosystem services which benefit others. Therefore, all tiers of government need to play a role in safeguarding ecosystem services.

A need was found to improve the knowledge base between land use change and the influences on hydrological responses and associated ecosystem services, to which this study has endeavoured to contribute by using a hydrological modelling approach for a real case study area, *viz.* the Mpushini/Mkhondeni Catchment..

Following the literature review, background information on the Mpushini/Mkhondeni study catchment was given (Chapter 3), which included a biophysical outline that placed the study area in a water-limited environment with strong seasonal variances. Different land use scenarios, used for subsequent work within the study were then described. These scenarios were the baseline land cover scenario, which represents the pre-human influenced natural land cover, as well as the current (2008) land use scenario with a mix of land uses, including various agricultural and urban land uses, degraded areas and a large portion of remaining natural land cover. Thirdly, a possible future land use scenario was examined, consisting of submitted proposed land use change applications, which would increase urban areas in the study area considerably.

The methodology used to set up hydrological simulations was then explained in Chapter 4. The methodology was based on a modelling approach, even if this can never be an absolute representation of the natural world. The daily time step and process based *ACRU* hydrological simulation model, which had previously been verified within the uMgeni Catchment was used. In order to set up the model to be able to undertake simulations, the relevant land use-related hydrological inputs were explained first, followed by the catchment delineation into 10 linked smaller catchment units (CUs), based on river networks, topography, location of dams and major current and proposed land uses. The delineation of these CUs remained constant for all three scenarios of baseline land cover, current land uses and proposed land uses, with the various land uses of the three scenarios being identified by using GIS analyses of land cover and land use maps.

Every catchment unit was then further subdivided into a basic configuration of five linked land use determined hydrological response units (HRUs) to facilitate the isolation of local effects of the particular land use in question, with land uses with expected similar hydrological responses being aggregated into relatively homogeneous hydrological units.

This approach allows for each HRU to be modelled individually, thereby isolating the particular local land use influence on hydrological responses.

Various hydrological model inputs were obtained from research previously undertaken in the School of Agriculture, Earth and Environmental Sciences at the University of KwaZulu-Natal. These inputs included the study area's climate data (e.g. daily rainfall, maximum and minimum temperature and potential evaporation), physiographic data (e.g. altitude and slope), as well as soil information (e.g. thickness of soil horizons, soil water retention constants, drainage rates and soil erodibility). These climate and physiographic data and most of the soil information inputs remained constant for all three land use scenarios. The hydrological model inputs related to the respective land use determined HRUs were outlined next. These inputs were taken either from previous research on similar land cover, or were based on expert advice, or were calculated where necessary. This included vegetation-related inputs such as biomass indices, root distribution and colonisation, vegetation cover factor (Sections 4.4.4 to 4.4.6), as well as dam- and irrigation-related inputs (Sections 4.4.7 and 4.4.8), impervious urban areas calculations (Section 4.4.9), urban return flow calculations (Section 4.4.10), as well as inputs related to the catchment configuration (Section 4.4.11).

The *ACRU* model's selected relevant outputs of hydrological responses were then described (Section 4.4.12). These modelled outputs included (a) *stormflow*, i.e. the water which is generated from a specific rainfall event, either at or near the surface, to contribute to flows in the channel of the HRU; (b) *baseflows*, i.e. the delayed water from rainfall that has percolated through the soil horizons into the intermediate and groundwater zones and then contributes as a delayed slow flow to the streams within a HRU; (c) *runoff*, i.e. the water yield from an individual HRU, consisting of stormflow plus baseflow; and (d) *streamflow*, i.e. the runoff from an HRU under consideration plus the runoff contributions from all upstream HRUs. Further relevant outputs were (e) *sediment yield*, which consists of the soil detached from a landscape and which then reaches the stream after a runoff event; and (f) *design one day runoff*, which is the statistically expected daily runoff from an annual maximum series of flows for the 2-, 5-, 10-, 20- and 50-year return periods. Also important is the modelled output of *total transpiration*, which is water that is modelled to have flowed from the soil via a plant into the atmosphere, but excluding direct evaporation from intercepted rainfall or from the soil surfaces. The above output variables of modelled hydrological responses were presented in numerous daily, monthly and annual statistics (Chapter 4 and 5). These statistics included arithmetic *mean* values, *median* values (e.g. of rainfall, flows, sediment yields, etc.), the 1:10 year high value implying that statistically only in 1 year in 10 that value would be exceeded, and the 1:10 low value signifying that the value would be exceeded in 90% of years.

6.2 Summary of the Main Results

In Chapter 5 the results were presented. Selected hydrological responses under baseline land cover were modelled and assessed first. Thereafter, selected hydrological responses from current land use conditions were modelled and compared to those from baseline land cover conditions. Following this, selected hydrological responses under proposed urbanisation were modelled and compared to those under current land uses.

6.2.1 Results assuming baseline land cover

In assessing various influences under *baseline land cover*, with no current land use influences included yet, the following findings were made for the various hydrological responses which were considered within the study area:

a) Monthly runoff is highly variable within a year and between years while annual runoff is, similarly, highly variable from one year to the next, with monthly and annual dry season runoff often extremely low.
b) Differences in baseline land cover can have significant influences on runoff, although these differences are relative small within this particular study area.
c) Annually, stormflow contributes more to runoff than baseflow in this catchment and the contributions of stormflows to total runoff display major differences between years of high, median and low flows.
d) Blue water flows proportionally make up the lowest fraction of the study area’s water budget, when compared to green and white water flows.
e) The differences in green water flows, i.e. transpiration, vary from month to month and from year to year in this study area, depending on soil water content.
f) Sediment yields are increased markedly during years with high flows.

g) Hydrological responses such as sediment yields, stormflows and especially baseflows amplify any changes in the rainfall regime.

6.2.2 Results assuming current land uses

Changes to hydrological responses from the various *current land uses* in the Mpushini/Mkhondeni Catchments were compared to those from baseline land cover and the following findings were made:

a) Certain land uses, in the case of this catchment sugarcane and wattle plantations, were modelled to reduce runoff, compared to that from baseline land cover conditions.
b) Irrigation from farm dams was modelled to lead to significant local decreases in streamflows, with the decreases especially significant in years with low flows. The presence of dams from which water is abstracted for irrigation also leads to a lag in streamflows when these increase again at the start of the wet season, because a depleted dam first has to be filled before overflows commence. The decrease in streamflow is most pronounced immediately below an individual dam.
c) Degraded lands were modelled to result in increases in runoff and sediment yield, but reductions in baseflows when results were compared to those from baseline land cover conditions. The effects of degradation could be partially to largely reversed with rehabilitation, and if all degraded areas within the catchment were to be rehabilitated it would reduce the sediment yield in years with median flows by 57 Mt/year and in years with 1:10 high flows by 130 Mt/year, along with producing reduced stormflows and increased baseflows.
d) Urban areas in this study area have their return flows generated from externally sourced water. Based on assumptions made on modelling urban return flows, these contribute to a consistent increase in flows, irrespective of the month of the year or whether years are wet or dry. Return flows of water from external sources increase the overall streamflow and they are relatively more significant in dry periods.
e) Additional to the above effects from return flows, impervious urban areas were modelled to increase the runoff and, thus, blue water flows. The increases were modelled to be made up of increased stormflows, as well as increased baseflows.
f) The magnitudes of one day design runoff for selected return periods also increased with urbanisation, when results were compared to those from baseline land cover conditions.

g) Where there is a spill-over from impervious urban onto pervious areas, the biomass production (computed from modelled transpiration) from the pervious areas increases. However, the overall biomass production of that HRU decreases because the pervious areas have been reduced.

h) The combined effects of the current land use mosaic on annual streamflows for the entire study area at the catchment outlet in this particular catchment partially cancel each other out. For this study area during average and dry years the current land uses result in a small reduction in flows. In wet years the combined influences of current land uses result in essentially the same streamflow at the catchment outlet as under baseline land cover conditions. In contrast to the above, however, the combined effects of the current land uses show a marked increase in sediment yields over the whole catchment, which is especially significant in *absolute* terms during years with high flows, while the *relative* increase is higher during years with low flows. This modelled result is as a result of an overall increased stormflow component of runoff and high flow events.

6.2.3 Results assuming proposed land uses

The *proposed land uses* in the Mpushini/Mkhondeni Catchments, consisting mainly of envisaged industrial and residential uses, would further urbanise and thereby transform the presently mainly rural study area. This proposed urbanisation, with markedly increased impervious urban areas, was modelled to lead to significantly increased runoff. In absolute terms, this is made up especially of increases in stormflows, while the often fairly low baseflows would also increase markedly in relative terms. The increases in baseflows are more significant in absolute terms during the rainy season and less important (in absolute terms) when there is very little rain during the dry season. The relative contribution of stormflows to total runoff increases, while that of baseflows decreases. The increased runoff is modelled to increase streamflows significantly. In addition, urban return flows from water sourced externally to this catchment lead to markedly increased, but less variable, streamflows. Overall, the effect of the proposed urban land uses would be the dominant one on annual streamflow, which at the catchment outlets was modelled to increase by 176% in years with 1:10 low flows, by 78% in years with median flows and by 33% in years with high flows, compared with flows from current land uses.

6.3 Relating Hydrological Responses to Ecosystem Services

Changes in hydrological responses were proposed as being suitable indicators for changes in selected ecosystem services. The ecosystem service of water provisioning was, for this study, defined as arising from blue or green water flows. Changes to water provisioning through *blue water flows* were indicated by changes in the hydrological responses of accumulated streamflow or by changes in runoff and its components of stormflow and baseflows, the latter from an individual HRU. In this study, changes to the ecosystem service of water provisioning through *green water flows* were indicated by changes in the hydrological response of transpiration. In considering changes to regulating services relating to flow regulation, in regard to *regulation of high flows* these were indicated by changes to stormflow responses, by changes to the relative contribution of stormflows to runoff, as well as by changes to one day design runoff magnitudes for selected return periods. In contrast, changes in *low flow regulation* were be indicated by changes to baseflows. Changes in physical water quality were indicated by changes in sediment yield. Selected supporting ecosystem services were also found to be affected by changes in the hydrological responses described above. The ecology in streams has evolved to local conditions and both biodiversity and genetic diversity are negatively affected by streamflow regime changes, by physical water quality deterioration and habitat alteration through increased sediment yields. Therefore, a reduction in the ecosystem service of biodiversity and genetic diversity can be indicated (together with other biotic and chemical indicators) through alterations in streamflow characteristics, and these could be either increases or decreases or changes in the timing of streamflows, as well as low flows, the runoff components of baseflow and stormflow, or increases in one day design runoff and changes in sediment yield. The changes to flows and sediment yield described above might, however, also imply that some aquatic species benefit from the altered landscape conditions.

6.4 Linking Land Use Change to Changes in Ecosystem Services

As already stated in Section 6.1, it was found in the literature study that markets worldwide and in South Africa do not protect ecosystem services sufficiently. It is reiterated that landowners might profit from land use transformation which might reduce ecosystem services, because environmental costs are distributed to society or future generations, while benefits might occur mainly to the current land owners. Conversely, often no or little monetary benefit occurs to the landowner or company that maintain land, thus the sustenance of ecosystem services that benefit others might not be rewarded. Therefore, to be able to make informed land use change decisions the changes in ecosystem services need to be assessed, including changes to hydrological ecosystem services.

The modelled land use changes in the study area were linked with changes in ecosystem services by using the modelled hydrological responses as indicators, as outlined in Chapter 4 and specifically in Table 4.11. The type of land use was found to have a highly significant influence on hydrological responses and associated ecosystem services.

Land uses that conserve land, as well as those that maintain near natural vegetation, e.g. extensive cattle or game farming, if managed correctly would essentially maintain the ecosystem services that natural vegetation provides. Such activities should therefore be encouraged and even incentivised through rebates or payments for ecosystem services, because they add benefit without really altering ecosystem services.

Modelling revealed that high biomass crops such as sugarcane and wattle plantations reduce streamflows. The benefits of sugarcane plantations, for example to food security, job creation, foreign exchange earnings and other economic benefits, therefore need to be weighed up against the reduced ecosystem services to downstream users. In this catchment the wattle plantations do not consist of managed production plantations, but rather of unmanaged areas of invaded alien wattle (*Acacia mearnsii*). Therefore, the small economic benefit of these alien wattles is likely to be over-ridden by the reduction in water provisioning. It would therefore be beneficial to eradicate this alien vegetation to the benefit of downstream water users.

The greatest relative impact of a reduction in downstream blue water provisioning was modelled as a result of irrigation. Irrigation should, therefore, be applied as efficiently as possible and the benefits of agricultural production be weighed up against the needs of downstream water users.

Degraded lands were found to increase stormflows, decrease low flows and increase sediment yields. This implies that the physical water quality is reduced and the water supply during low flow periods, when most needed, is reduced. On the other hand, degraded areas hold the potential to be rehabilitated, so that increased flow regulation and water provisioning during low flow periods might be re-established. The rehabilitation of degraded land within the study area, therefore, holds potential to increase ecosystem services, and should be incentivised.

Urban land uses were modelled to significantly increase runoff, thereby increasing the quantity of total blue water provisioning, as well as reducing physical water quality and while not simulated in this study, urban land uses are considered to reduce other types of water quality as well (e.g. through wash off of oil or pathogens). The stormflow component of runoff in urbanised areas was found to be increased most markedly, and together with the rapid runoff responses therefore reduce the regulation of high flows. It was modelled that not only stormflows, but also baseflows, increased, the latter through a spill-over of water from impervious onto pervious areas, with the result that variability of baseflows decreased (cf. Table 5.4). This implies that there is an increase in flow regulation for baseflows during periods of rainfall. The increased blue water flows, however, reduce green and white water flows. The conversion of pervious vegetated areas into impervious areas shifts most of the water portion that would have transpired via the vegetation, as well as part of the portion of water that would have evaporated, towards the blue water flows, which is the water that runs off. In addition, the urban return flows generated from water that is imported into the study area, were modelled to increase the blue water flows as well as steadying the flows, thereby increasing low flow regulation. Potential leaking water pipes and outlets from septic tanks were not taken into account in this study, but might increase this effect. While an increase in low flows from urban areas has positive effects in terms of increased water provisioning during low flow periods, it needs to be borne in mind that this water is likely to be of lower water quality and, therefore, an overall negative water provisioning service is likely.

Nevertheless, the increased urban impervious areas and urban return flows create opportunities, which include

a) rainwater harvesting from roofs;
b) water collection from stormwater drains into dams and artificial wetlands;
c) use of treated water from waste water treatment works;

d) use of grey water from households;
e) spill-over from impervious areas onto pervious ones, and thereby slowing flows, resulting in additional infiltration; and hence
f) the production of more biomass on the remaining pervious areas.

If utilised, these positive factors partially mitigate the negative impacts of urban areas, by

a) augmenting the urban water requirements and, therefore, reducing the amount of water brought into the catchment;
b) increasing biomass production in urban areas and thereby creating green areas with possible benefits for recreation, relaxation, biodiversity and food production; and by
c) reducing the downstream ecosystem impacts of upstream urbanisation.

Having evaluated the impacts of individual land uses above, it needs to be emphasised that from a biodiversity and genetic diversity perspective in streams and in adjoining areas, the ecology has evolved according to natural local conditions. The resulting streamflow alterations, and reduced water quality and altered habitat function are, therefore, likely to reduce the biodiversity in streams and in areas adjoining them.

The methodology was found to be suitable for assessing certain changes to hydrological ecosystem services as a result of land use changes. This is assuming that the relevant input variables are available, with regard to climate, soils, geography and land use. For a detailed EIA project, more detailed information is likely to be required than is obtainable from a national database. However, the methodology can be adjusted by using model inputs that were obtained from more detailed local data.

6.5 The Contribution of this Research to Knowledge Creation

An assessment of the contribution of this research to a better understanding of land use change impacts on hydrological responses and associated ecosystem services include the following, in no particular sequence:

a) a case study of an actual impacted area, the results from which are contributing to knowledge that can be used in local decision-making;

b) a better understanding of land use and hydrological responses, by isolating the impacts of individual land uses and the effects of these land uses on hydrological responses, such as the total flows or runoff components of stormflow and baseflow, both locally and on a wider catchment level;
c) the vast potential effects of the proposed urbanisation in the study catchment on hydrological responses;
d) the different effects that various land uses, individually and in combination, have on hydrological responses;
e) the different effects and responses between wet and dry years;
f) a better appreciation of critical land use influences in water-limited areas during low flow periods;
g) an improved understanding of blue and green water flows in water-limited environments;
h) a focus on the diverse land uses of the entire catchment and their contribution to ecosystem services, not only on wetlands and flood plains, as is often the case in the literature;
i) the ecosystem services which are related to water flows, by attempting to link hydrological responses to ecosystem services science and suggesting suitable indicators;
j) an approach to a methodology using hydrological studies and, therefore, to link them to ecosystem services, to be able to form part of an ecosystem services change assessment, where scenarios of alternate futures with changes to multiple key ecosystem services are evaluated; and
k) the suitability of a daily hydrological process based simulation model, such as the *ACRU* model, to model land use impacts on hydrological responses and associated ecosystem services, even in the light of uncertainties being introduced when a modelling approach is used.

6.6 Recommendations for Future Research

During this study, several knowledge gaps became evident to the candidate. These gaps would be beneficial subjects for further research.

a) Only *selected* hydrological ecosystem services were examined in this study. There is still considerable knowledge to be gained in this field by adding more hydrological ecosystem services, particularly those related to water quality, ecological functioning and cultural services. A more complete assessment of hydrological ecosystem services would be of benefit to integrated assessments, as well as a more in-depth assessment of the suitability of hydrological responses as indicators of hydrological ecosystem services.

b) The climate input used in this study was based on historical records. We are, however, living in a world of changing climates which are projected to have major influences on hydrological responses and associated ecosystem services in the future. It would be beneficial to use climate output from downscaled global circulation models, which project climate change, and then to examine how this could change the hydrological responses and associated ecosystem services in this study area.

c) While the interaction of water and landscape was modelled within this study, the on-going monitoring of these interactions is recommended, so that more information becomes available, particularly also the inclusion of already available results on the water use of natural vegetation and of alien invasive vegetation in operational models.

d) Urban areas and their water flows pose certain challenges. One of these challenges is to find better information about potable water requirement projections of existing and new urban areas. While the potable water requirements of an urban area will differ, depending on type and density, those predictions are essential to be able to plan future water service requirements and the effects on downstream ecosystem services.

e) Another challenge concerns the evaporation levels from urban areas. Urban areas, in reality, consist of various different vertical, horizontal and sloped surfaces, which can create wind channels, change evaporation rates and create urban heat island effects. More research in this field would be beneficial, to improve knowledge regarding the hydrological modelling of urban areas.

f) There was very little information available on the effect of land use change in South Africa on microclimate, which can be a major driver of local hydrological responses.

g) It would be beneficial to study the property laws of South Africa regarding the rights or duties of property owners to destroy, alter or maintain certain ecosystem services resulting from that land.

h) Knowledge gained regarding the links between land use and ecosystem services is only beneficial if this information informs agencies of planning and land use enforcement. More studies are required on how to merge scientific findings on links between land use change and hydrological ecosystem services into practice in South Africa and elsewhere.

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