DEVELOPMENT OF TECHNIQUES FOR THE ASSESSMENT OF CLIMATE CHANGE IMPACTS ON ESTUARIES: A HYDROLOGICAL PERSPECTIVE

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DECLARATION

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These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any university. Where use has been made of the work of others it is duly acknowledged in the text.

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ABSTRACT

Global climate change is a naturally occurring phenomenon, influencing weather and climate patterns. However, the greatest cause for concern at present is the rate at which climate change is currently occurring. Natural shifts in climate take place over a period of many thousands of years, not in a matter of decades, which is what is occurring at present. In South Africa, climate change is projected to have different regional effects, which in turn could impact on the components of the terrestrial hydrological system, such as land use. The alteration of the catchment upstream of the estuaries could affect the quantity and quality of streamflows entering estuaries. This could impact negatively upon estuaries, thereby reducing the considerable biodiversity in estuaries and the ecosystems goods and services provided by estuaries which would reduce the significant revenue provided by these systems. The research undertaken in this project investigates the possible effects of climate change, and changes in upstream land use on freshwater inflows into estuarine ecosystems using a daily hydrological model. Owing to the regionality of climate change in South Africa 10 estuaries in different climatic regions were selected for this investigation. Climate output from five GCMs under the SRES A2 climate scenario for the present (1971 – 1990), intermediate (2046 – 2065) and distant future (2081 – 2100) periods was used as input for the selected climate input. Results of these simulations show that the eastern regions of South Africa may experience considerable increases in the occurrence of high intensity rainfall events into the future. This could influence the abiotic factors of the system which may impact upon the biotic components of estuaries, as these systems are physically controlled. In the western regions the difference of the magnitude of flows between present and projected future is minimal. However, projected increases in temperature could influence evaporation, thereby decreasing future flows into estuaries. This, in some instances, may result in systems turning hyper-saline, which could have far reaching implications, both ecologically and economically.

Additionally, an investigation, as to the possible effects of irrigation and climate change combined on flows entering and breaching events of the Klein estuary, was undertaken. Hence, simulations including and excluding irrigation routines have been completed. Results from these simulations illustrate the detrimental effects of irrigation into the future periods,

especially during 1 in 10 low flow years, when flows into the Klein estuary cease completely. Breaching event results illustrate that climate change could have a negative impact on this estuarine system as the number of events decreases into distant future period. The addition of agricultural abstractions decreases the number of breaching events markedly. Therefore, the link between the marine and terrestrial hydrological systems is lost which could, if this estuary is isolated from the ocean for an extended period of time, become extremely detrimental to the ecological integrity of the Klein estuary. This highlights the value and vulnerabilities of estuarine ecosystems in South Africa to future climate and upstream land use changes.

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1 INTRODUCTION

1.1 Background

The interface between the terrestrial and marine hydrological systems is known as the estuarine ecosystem (Kennish, 1986; Allanson and Baird, 1999). For the purposes of this study an estuary is defined as a body of water that is either permanently or periodically open to the ocean, containing fresh and saline water, in addition to other chemicals (McLusky, 1981; Schlacher and Wooldridge, 1996). Inputs from both the marine and terrestrial hydrological systems, in varying quantities, result in a unique and highly variable ecosystem, the characteristics of which are capable of a complete change within a 24 hour period (Allanson and Baird, 1999; Schumann *et al.*, 1999). Marked changes occurring in such short periods of time influence the functioning of estuarine ecosystems significantly. However, it is long term changes, such as modifications in streamflow characteristics, that may determine the survival of estuarine ecosystems (Lamberth *et al.*, 2008). Therefore, the influence that the responses from the terrestrial hydrological system exercises over estuarine ecosystems is considerable (Lamberth *et al.*, 2008). As a consequence, any alterations to hydrological responses resulting from climate change or upstream land use change in South Africa could have considerable impacts on estuarine ecosystems, especially in light of the high variability and regionality of South Africa's hydrology (Schulze, 2005b; Lamberth *et al.*, 2008).

Global climate change is a phenomenon which is causing significant concern, as the rate of change is higher than initially expected and is, according to many experts, accelerating as industry strives to meet the ever increasing demands of the human population (Levin, 1992; IPCC, 2007b; Bates *et al.*, 2008). This phenomenon has been observed from the increasing levels of atmospheric CO_2 concentrations and resultant increased temperatures of between 0.2 and $0.6^{o}C$ since the late 19th century (IPCC, 2007b; Bates *et al.*, 2008). There is apprehension regarding climate change because the potential impacts that surround this phenomenon are, as yet, not fully understood (IPCC, 2007b; Bates *et al.*, 2008). Major concerns surrounding climate change include the magnitude, location and direction of temporal and volumetric shifts in streamflow which may result from projected changes particularly in precipitation (IPCC, 2007b; Bates *et al.*, 2008). Although significant uncertainty still surrounds climate change, sufficient evidence exists to justify further investigations into both the causes and consequences (Schulze, 2005b; IPCC, 2007b; Bates *et al.*, 2008).

The upstream catchment and regional climate characteristics determine the streamflow entering estuarine ecosystems. One of the major characteristics of a catchment which can have a major influence on hydrological responses is land cover. Land cover affects interception, infiltration, overland flow, groundwater recharge and evapotranspiration, all of which could affect streamflows entering estuaries. As a result of anthropogenic interference a change from natural land cover to agricultural land uses, some of which include irrigated areas, has occurred in many parts of South Africa. The change from natural land cover to agricultural land uses could have a major effect on hydrological responses into estuarine ecosystems as a result of changes in canopy, surface and sub-surface characteristics. Therefore, the conversion of natural land cover to agricultural land uses could either amplify or alternatively negate, the possible effects of climate change on hydrological responses into estuarine ecosystems. Aquatic ecosystem responses to variations in the hydrology of a catchment makes them an important subject for research in regard to possible impacts of global climate change (Bates *et al*., 2008).

1.2 Problem Statement

One of the major foci of climate change research in South Africa has been on its primary impacts on hydrological responses (Schulze *et al*., 2005). To a lesser extent, recent studies have been targeted at secondary hydrological impacts, which include ecological responses to shifts in the hydrology (Schulze *et al*., 2010). There is a need to increase the knowledge base in this field of research as many ecological, and particularly estuarine, systems are of intrinsic aesthetic and economic value to South Africa. In addition to the possible effects of climate change on estuaries are those of changes in land cover. The combination of changes in both climate and land cover could have a marked effect on streamflows entering estuarine ecosystems, as stated previously. However, research combining the possible effects of both land use and climate change on estuarine ecosystems in a South African context is still in its infancy.

1.3 Aims and Objectives: Linking Climate Change to Estuarine Responses Through Changes in Freshwater Inflows

In light of the above problem statement, the aim of this project is to conceptualise and demonstrate, through hydrological simulation, potential impacts of climate change on freshwater inflows into 10 selected estuaries around South Africa. The simulations into estuaries are conducted with an appropriate daily time step hydrological model and the breaching of the berm across the mouth of one of the selected estuaries, *viz.* the Klein estuary, is simulated using outputs from the daily hydrological model as inputs to an estuarine water balance model. The Klein was selected for this purpose for the following reasons:

- relatively simple land cover in the catchment upstream of the estuary,
- high ecological integrity of the estuarine ecosystem,
- perennial streamflow into the estuary, and
- the afore-mentioned estuarine water balance model had been developed for this particular system.

In order to achieve these objectives, empirically downscaled climate output from present and future climate scenarios from five General Circulation Models (GCMs) is used as input into the daily time step *ACRU* hydrological modelling system, which is then used to simulate impacts of climate and land cover change on streamflow and sediment yield responses into estuaries. However, climate and land cover changes are two discrete agents of change, which could impact upon streamflow and sediment yield responses, and in this dissertation they are treated as such. Therefore, results from two separate simulations will be reproduced:

- The first illustrates the effects of climate change on hydrological responses into a number of estuaries around South Africa (cf. Sub-section 6.1), and
- The second illustrates the effects of land use change, in combination with climate change, on hydrological responses into single case study system (cf. Sub-section 6.2).

The output from the daily *ACRU* hydrological model is then also used as input for the water balance model in order to determine the frequency of mouth breaching in the Klein estuary. The results of the above-mentioned studies are then used in conjunction with literature to assess the broad impacts of climate and land cover changes on estuarine ecosystems. The research presented in this dissertation builds on previous climate change studies completed and currently being undertaken in the School of Bioresources Engineering and Environmental Hydrology (BEEH) at the University of KwaZulu-Natal, the major foci of which are on refining and developing techniques, increasing the temporal resolution of climate change impact studies and improving the accuracy of output from an appropriate hydrological model through the use of output from recent GCMs.

1.4 Overview of the Chapters which Follow

In this dissertation on the development of techniques for the assessment of potential climate change impacts on estuaries from a hydrological perspective, a brief review of literature on climate change and General Circulation Models in provided in Chapter 2. In Chapter 3 literature pertaining to estuarine ecosystems is reviewed, as are possible effects of variations in environmental flows into estuaries as a consequence of climate change. In Chapter 4 the selection of the estuaries to be used in the practical component of this dissertation is explained. A detailed description of the research and the steps undertaken in order to obtain results for this dissertation is provided in Chapter 5. The results of the afore-mentioned research and processes are provided and discussed in Chapter 6. A detailed discussion, in which the literature reviewed is linked to the results obtained, is then provided in Chapter 7.

2 CLIMATE CHANGE: A BRIEF OVERVIEW

Since the formation of the earth's atmosphere the climate has been in a state of continuous flux (Saunders, 1999). Therefore, it is probable that the climate of the earth will continue to change into the future. However, climate change in the way that it occurs naturally is not the source of concern here; rather, it is the current non-natural rate and magnitude of climate shifts that is of concern (Saunders, 1999). Hence, Sub-sections 2.1 to 2.3 investigate the phenomenon of climate change and the possible explanations for the increasing rapidity of climate changes. In order to mitigate some of the possible effects of rapid climate change, knowledge of possible future climate scenarios is required (Hewitson *et al.*, 2005). This information is gained from the development of advanced atmospheric models; capable of simulating a range of plausible climate scenarios (Hewitson *et al.*, 2005). Sub-section 2.4 investigates the types of models used, as well as the limitations and challenges of these models for use in impacts studies, in this case flows into estuaries.

2.1 What is Climate Change?

Climate change is a naturally occurring and cyclical phenomenon, and during the past 2 000 000 years glacial and interglacial periods having occurred at approximately 100 000 year intervals (Arnell, 1996; Pittock, 2005). However, researchers have recently realised that changes in climate were occurring with unnatural rapidity (Saunders, 1999). Investigations into possible causes of accelerated climate change focused on the enhanced greenhouse effect, which disrupts the natural cycles of climate change, as a major contributor (Arnell, 1996; Saunders, 1999; Pittock, 2005). Climate change may be defined as a statistically significant change in the mean state of the global climate over an extended period of time, i.e. between one century and another (Pittock, 2005). The mean state of the climate is determined using numerous datasets pertaining to many climatic variables such as temperature, precipitation, humidity and wind (Pittock, 2005). Once climate change has commenced it could last for a considerable period, affecting all habitats on earth (Arnell, 1996; Pittock, 2005).

2.2 Natural Climate Change

From past and current investigations it is agreed in the literature that there is no single cause of major natural changes in climate (Arnell, 1996; Saunders, 1999; Pittock, 2005). Research shows slight cyclical variations in the earth's orbit around the sun, termed Milankovitch cycles, resulting in small changes of incoming solar radiation (Arnell, 1996; Saunders, 1999; Pittock, 2005). As a consequence, temperatures may increase as the earth moves closer to the sun, or decrease as the earth moves further away from the sun (Saunders, 1999). In addition to the possible effects of Milankovich cycles on long term climate there are other natural factors such as effects of volcanic eruptions, natural variations in atmospheric carbon dioxide (CO_2) concentrations and changes in oceanic currents (Saunders, 1999). However, since the industrial revolution approximately 150 years ago, humans have significantly influenced the Earth's climate through many fossil fuel burning and agricultural activities (Arnell, 1996; Saunders, 1999; Bates *et al.*, 2008).

2.3 Why is Rapid Climate Change Occurring?

According to research conducted, the rapid changes in climate that have occurred during the previous few decades may be attributed to anthropogenic activities, which have resulted in waste gases that alter the composition of the earth's atmosphere (Arnell, 1996; Saunders, 1999; Berliner, 2003; Pittock, 2005; Bates *et al.*, 2008).

Gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxides (N_2O), water vapour and Chlorofluorocarbons (CFCs) are known as greenhouse gases, as they act like panes of glass in a greenhouse, trapping outgoing longwave radiation in the earth's atmosphere. These gases occur naturally and this phenomenon is known as the greenhouse effect, without which the average surface temperature of the earth would be ~33^{o}C lower than at present (Vorosmarty and Sahagian, 2000). However, anthropogenic activities, such as industry, power generation and agriculture, have increased the concentrations of greenhouse gases in the atmosphere to such an extent that the greenhouse effect has been enhanced, as shown in

Figure 2.3.1 (Arnell, 1996; Saunders, 1999; Vorosmarty and Sahagian, 2000; Berliner, 2003; Pittock, 2005; Bates *et al.*, 2008).

Evidence for the enhanced greenhouse effect has been provided through recorded observations of changes, over time, in temperature, glacial area and biological systems (Saunders, 1999; Berliner, 2003; Pittock, 2005). Reliable temperature records extend back to the 1860s and are obtained through the combination of measurements of land temperatures from reliable climate stations, and sea surface temperatures which are estimated by processing observations made from ships (Saunders, 1999). These observations were then located within grid squares over the earth's surface, and averaged. Individual averages within each grid square were then used to obtain a global average. Results from this investigation indicate an increase of between 0.50 and 0.74°C in global mean surface temperature between the late 19th century and the present, as shown in Figure 2.3.2 (Saunders, 1999; Pittock, 2005; Bates *et al.*, 2008). Supporting these empirical findings is other physical evidence such as continual glacial shrinkage and the increasing poleward migration of floral and faunal species, which can occur only if habitat conditions become more favourable, as is happening through rising global temperatures (Pittock, 2005).

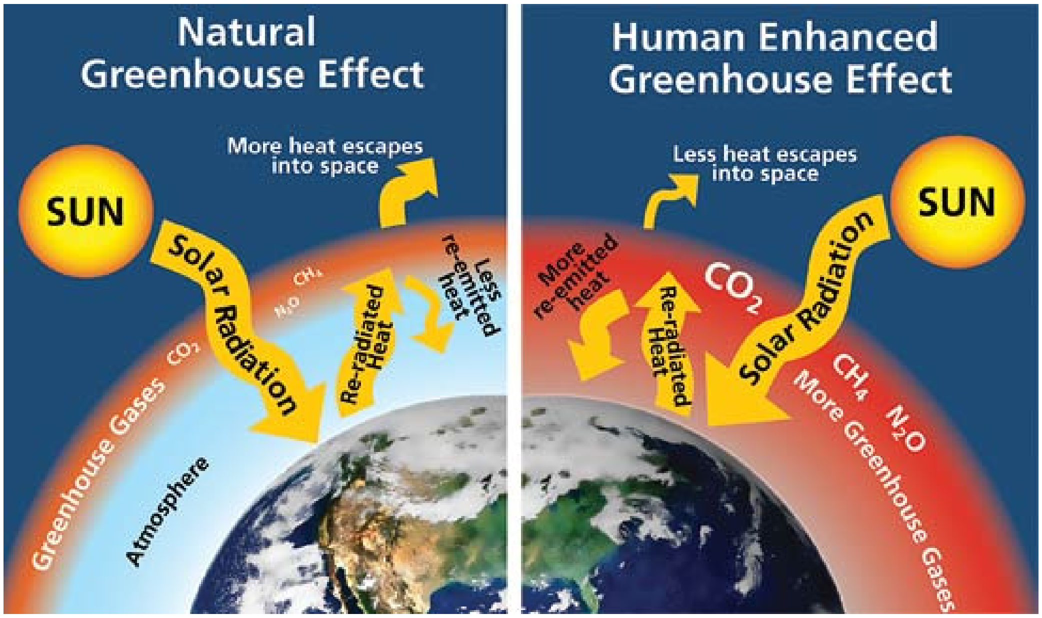


Figure 2.3.1: A schematic of the enhanced greenhouse effect (www.google.com)

In future, climate change is projected to accelerate as a consequence of increasing atmospheric greenhouse gas concentrations. Enhanced greenhouse gas concentrations could cause significant changes in many climatic parameters, which may result in considerable impacts on local environments, but with uncertainties surrounding the impacts still relatively high. In order to reduce uncertainties regarding the earth's future climate, considerable research effort is being expended into the improvement and development of complex atmospheric simulation models.

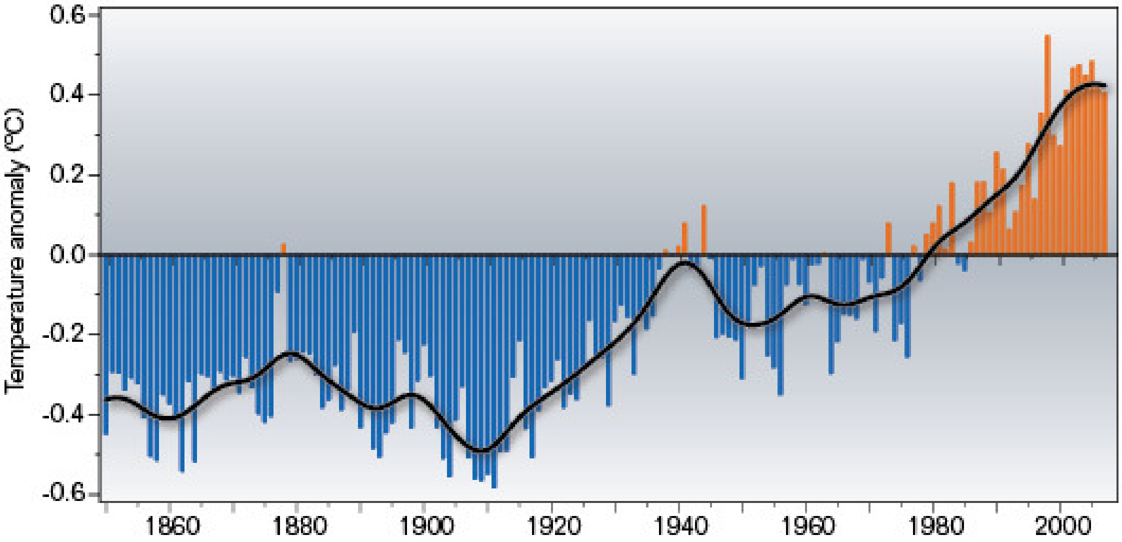


Figure 2.3.2: Global temperature changes from 1850 (Brohan *et al.*, 2006)

2.4 Projecting the Earth's Future Climates

The projection of the earth's future climates rely on numerical models known as General Circulation Models, or GCMs (Hardy, 2003; Burroughs, 2007). GCMs incorporate physical laws of mass, momentum, energy and water, in all its phases, to describe possible future atmospheric changes, i.e. climate change (Burroughs, 2007). Because of the coarse spatial resolution of GCMs, climate change impact studies rely on either empirically downscaled GCM output, or on more regionalised, dynamically downscaled output from Regional Climate Models (RCMs), as discussed in Section 2.4.3 (Hardy, 2003). This section describes the function of GCMs with respect to climate change, as well as the challenges and uncertainties faced by modellers using output from the GCMs (Hardy, 2003; Hewitson *et al.*, 2005).

2.4.1 General Circulation Models

To date, the most credible method of projecting the earth's future atmospheric changes remains the use of output from GCMs (Arnell, 1996; Hardy, 2003; Hewitson *et al.*, 2005). However, the accuracy of future climate projections from early GCMs was not high, as these models relied on either atmospheric or oceanic processes, but did not use a combination of both (Arnell, 1996; Hardy, 2003). Hence, inaccuracies and uncertainties in climate change impact assessments often resulted (Hardy, 2003; Burroughs, 2007). In order to reduce inaccuracies, significant improvements have been made to more recent GCMs which allow the coupling of atmospheric and oceanic processes including feedbacks, through numerical techniques (Hewitson *et al.*, 2005). These coupled GCMs are known as atmosphere ocean general circulation models or AOGCMs (Hardy, 2003; Burroughs, 2007). Furthermore, some of the latest GCMs include biological variables which affect climate change, thus further increasing the accuracy of future simulations (Hardy, 2003; Burroughs, 2007).

Although, current GCMs are capable of satisfying their primary function, which is the simulation of the Earth's past, present and future climates on a global scale over an extended period of time, there still remains uncertainty in their process representations and hence in their outputs (Hardy, 2003; Burroughs, 2007). These are elaborated upon below.

2.4.2 Challenges and Uncertainties Associated with GCMs

GCMs are composed of many complex numerical equations, which are quantitative representations of global climatic variables (Burroughs, 2007). However, despite the internal complexity of GCMs, natural systems are still more complex, and as of yet GCMs are unable to simulate all processes occurring within the global climate (Hardy, 2003; Burroughs, 2007). Therefore, a level of uncertainty and some major challenges remain when using GCMs to project future changes to climatic variables, in particular to secondary outputs of GCMs such as precipitation (Hardy, 2003).

Yet, the major driving force in simulations of projected future hydrological responses to climate change is precipitation, as projected from GCMs (Arnell, 1996; Hardy, 2003; Burroughs, 2007; Lumsden and Schulze, 2007). However, GCMs cannot yet capture individual rainfall events at local scale, only the quantity of precipitation over a set time, which in this instance is a 24 hour period (Arnell, 1996). In South Africa this is a problem as convective rainfall is the dominant form of precipitation over large areas (Hewitson *et al.*, 2005), with a number of discrete rainfall events sometimes occurring on a single day, and each event may differ significantly in magnitude and duration. GCMs are incapable of capturing these important hydrological drivers (Arnell, 1996). This implies that a comprehensive event based flood risk assessment cannot be completed to a high degree of accuracy (Hewitson *et al.*, 2005). In addition to this limitation direct, GCM output cannot be used as input for hydrological models unless it has been downscaled to the spatial resolution appropriate to the catchment (Arnell, 1996; Wilby and Wigley, 1997; Hewitson *et al.*, 2005). This is as a consequence of the coarse spatial resolution of GCM output, which leads to considerable inaccuracies in simulations of hydrological responses to climate change (Arnell, 1996).

In conclusion outputs from, GCMs per se should only be used at large scales, as their accuracy when used as inputs for local scale hydrological studies is inadequate. If climate output is thus required for use with hydrological models then, it must first be downscaled to an appropriate spatial resolution. This is discussed below.

2.4.3 Downscaling GCM Outputs

The climate of a particular region is significantly influenced by local topographic features, which cannot yet be captured by the coarse spatial resolution of GCMs (Arnell, 1996; Wilby and Wigley, 1997; Jackson *et al.*, 2001; Hewitson *et al.*, 2005). Therefore, to bridge the gap between synoptic and local scale climate scenarios, two main approaches to downscaling have been developed, *viz.* dynamical and empirical downscaling (Wilby and Wigley, 1997; Hewitson *et al.*, 2005).

Dynamical downscaling involves high spatial resolution regional climate models (RCMs), which are nested within the programming of GCMs (Hewitson *et al.*, 2005). The boundary conditions of RCMs are defined by GCMs, but much greater detail regarding topographic and land cover features is provided by the RCM, thereby allowing the simulation of smaller scale climatic events, such as orographic rainfall (Hewitson *et al.*, 2005). However, there are two major limitations associated with RCMs the first being that these models amplify errors or uncertainties inherent within the GCM, and the second being that they are computationally intensive (Hewitson *et al.*, 2005). Yet, RCMs continue to grow in popularity, despite several limitations in addition to those already mentioned.

Empirical downscaling is based on the premise that synoptic scale events will evoke a response in local climatic events (Hewitson *et al.*, 2005). Observational data are used in the development of empirical relationships between synoptic and local scale climate, which may then be applied in the downscaling of coarse spatial resolution GCM output (Hewitson *et al.*, 2005). Despite verification of the afore-mentioned premise, local scale forcing such as land use change introduces inaccuracies to downscaled future climate output as it cannot be captured by empirical downscaling methods (Hewitson *et al.*, 2005). Despite inaccuracies, results from empirical downscaling methods have been validated, and have in South Africa been used to generate climate output at a spatial resolution of 0.25^{o} x 0.25^{o} and even down to climate station level (Hewitson *et al.*, 2005). Daily precipitation and temperature output, at the appropriate spatial and temporal resolution as a result of empirical downscaling methods, may be used in hydrological, agricultural and ecological assessment studies (Hewitson *et al.*, 2005; Lumsden and Schulze, 2007).

Downscaling to finer spatial resolution introduces a significant number of opportunities to the possible assessments that may be conducted with respect to hydrological, agricultural and ecological systems. In this dissertation, empirically downscaled climate output is used as input for the daily timestep *ACRU* hydrological modelling system for the simulation of streamflow into estuarine systems during defined present, intermediate and distant future time periods (cf. Chapter 5). From the results of these simulations, impact assessments of climate change on estuaries may be undertaken (cf. Chapter 6). Following the brief discussion on climate change in Chapter 2, a discussion on estuarine ecosystems within in a climate change context follows in Chapter 3.

3 ESTUARINE ECOSYSTEMS IN A CLIMATE CHANGE CONTEXT

Climate change, as described in Chapter 2, may have significant effects on abiotic components contributing to the functioning of estuarine ecosystems. This, in turn, may impact on the biotic components in estuaries (Stone *et al.*, 1978; McLusky, 1981; James *et al.*, 2008). However, the effects of climate change on estuaries are projected not to be uniform across South Africa as a result of differing impacts at different locations (Scharler *et al.*, 1998; James *et al.*, 2008). Additionally, estuaries form the interface between the marine and terrestrial hydrological systems, hence forming unique, highly productive and potentially unstable ecosystems, which may mute, or amplify, the possible effects of climate change (Whitfield, 2001; Adams *et al.*, 2002; James *et al.*, 2008). In order to retain the ecological integrity of estuarine ecosystems under climate change, the interactions occurring between abiotic and biotic components, as well as the marine and terrestrial hydrological systems, must be maintained (Stone *et al.*, 1978; Whitfield, 2001; Adams *et al.*, 2002; Van Niekerk, 2007b; James *et al.*, 2008). In this chapter the focus will be on the ecological functioning of "temporary open closed estuaries" (TOCEs), as these are the more dominant systems found along the South African coastline (Van Niekerk, 2007b; Whitfield *et al.*, 2008).

Approximately 260 functioning estuarine ecosystems can be found along the South African coastline, a fact repeated in Sub-section 3.2.2 (Lamberth and Turpie, 2003). The functioning of these estuarine ecosystems provides a number of ecological services which then translates into economic value (Mander, 2001; Lamberth and Turpie, 2003). For example estuaries provide some commercial fish species with nursery areas. Hence, the ecological nursery function of an estuary can be translated into an economic value as these juvenile fishes will, in future, be caught by fishermen, thus providing them with a livelihood (Mander, 2001; Lamberth and Turpie, 2003).The roles and benefits provided by estuaries, the manner in which flow regimes influence the functioning of estuarine ecosystems, and the potential impacts of climate change on estuaries will be described later in this chapter.

3.1 A Brief Introduction to the Functioning of Estuarine Ecosystems

The estuarine environment is characterised by constantly changing salinity concentrations, which present an adaptive challenge to the physiology of many faunal and floral species within estuaries (McLusky, 1981; Mander, 2001; Elliot *et al.*, 2002). Despite the above statement, it has been claimed that estuaries are amongst the most productive natural habitats in the world (McLusky, 1981; Mander, 2001; Whitfield *et al.*, 2008). Therefore, in order to explain the considerable productivity of these systems, the physical features that mould and regulate the estuarine environment will be investigated in regard to estuarine systems. These are:

- circulation,
- sedimentation,
- chemistry, and
- biota.

The literature the in the immediately following sections describes the afore-mentioned features, thereby providing a knowledge base of the relationship between estuaries and the streamflows entering these systems. From this knowledge base and the results obtained (cf. Chapter 6), a discussion of the possible effects of changes in streamflow on estuaries will be presented in Chapter 7.

3.1.1 Estuarine Circulation

The circulation occurring in estuaries is based on freshwater and tidal inputs which, in combination with other abiotic factors, form a major determinant of the distribution of biodiversity in estuarine ecosystems (Kennish, 1986; Whitfield, 1992; O'Donnell, 1993; Whitfield, 2001; Montagna *et al.*, 2002; Van Niekerk, 2007b; Whitfield *et al.*, 2008). The circulation occurring in estuaries may be classified into the following four categories, *viz.*

- highly stratified,
- moderately stratified,
- vertically homogenous, and
- sectionally homogenous,

each of which will be described in more detail below.

In general, *highly stratified* estuaries are narrow and shallow, with high freshwater inflows and negligible tidal influence. Therefore, freshwater is dominant in these estuaries, but as a consequence of tidal forcing, a wedge of salt water enters the system. Owing to the greater density of salt water, freshwater will continue to flow over the top of this layer, hence setting up a velocity difference between the fresh and salt water layers. This generates internal waves at the halocline. These break up and mix seawater upward into the freshwater. Hence, the salinity of the system increases steadily downstream, forming a longitudinal gradient along the length of the estuary. However, during low freshwater inflows the salt wedge may migrate towards the head of the estuary, thereby increasing salinity concentrations throughout the system. In contrast, high freshwater inflows will force the salt water wedge downstream, and in some instances even out of the estuary mouth (Schumann and Pearce, 1997). However, this is rare and does not occur in estuaries which are not classified as highly stratified systems (McLusky, 1981; Kennish, 1986; Schlacher and Wooldridge, 1996).

Moderately stratified estuaries are typically wide and shallow, and are characterised by slow moving water. These systems are less dominated by freshwater inflows as a consequence of increased tidal forcing, which may vary considerably in different regions. Turbulent eddies forming in these systems result in mass transfers of water in both directions across the halocline. Hence, the halocline is replaced by a column of water with a gradual increase of salinity from top to bottom. Nevertheless, a two layered flow still exists, but is not as defined as in a highly stratified system. Additionally, a longitudinal salinity gradient exists in these systems, with concentrations increasing in a seaward direction (Schroeder, 1978; McLusky, 1981; Kennish, 1986; Whitfield, 1992; Schlacher and Wooldridge, 1996).

In *vertically homogenous* estuaries tidal inflows exceed freshwater inflows by a considerable margin. Additionally, friction created by the estuarine substrate, in combination with the limited depth of these systems, may result in the removal of the halocline and the vertical salinity gradient. However, the longitudinal and lateral salinity gradients still remain, with salinity concentrations increasing in a down-estuary direction. Typically vertically homogenous estuaries are very similar to moderately mixed systems, as they are wide, shallow and the circulation occurring is normally dominated by tidal influences (Schroeder, 1978; Whitfield, 2001; Van Niekerk, 2007b; Whitfield and Bate, 2007).

In *sectionally homogenous* estuaries with strong vertical mixing, and a ratio of width to depth that is sufficiently small, lateral mixing forces may be intense, hence resulting in lateral and vertical homogeneity. Therefore, only the longitudinal salinity gradient will be maintained in these systems. In sectionally homogenous systems topographical irregularities in the substrate may result in considerable friction, which plays a major role in the horizontal transfer of saline water, through various mixing processes, to the upper reaches of the estuary. Hence, if the friction between substrate and water is low, then the up-estuary transfer of saline water is very slow, and vice versa (Schroeder, 1978; Whitfield, 2001; Van Niekerk, 2007b; Whitfield and Bate, 2007).

Therefore, circulation in estuaries is principally determined by tidal and freshwater inflows, as well as by benthic topography. In South Africa, estuaries may change the circulation category into which they fit on an annual basis, depending on the seasonality of freshwater inflows, and the constituents of substrate within the system (cf. Chapter 7).

3.1.2 Estuarine Sediments

In South Africa outflows from estuaries are volumetrically smaller and more variable than those in many other regions (Kennish, 1986; Van Niekerk, 2007b). Additionally, the tidal energy along the South African coastline is, in many instances, extreme. This results in considerable entrainment and deposition of marine sediments (Theron, 2007; Van Niekerk, 2007a; Van Niekerk, 2007b). This, in conjunction with freshwater inflows, significantly influences the mouth state of a number of South African estuaries (Van Niekerk, 2007a). Consequently, estuaries may be divided into:

- permanently open estuaries (POEs), and
- temporary open closed estuaries (TOCEs; (Van Niekerk, 2007b).

Owing to highly variable streamflows in South Africa, estuarine mouth closure, as a consequence of berm formation, is not uncommon for TOCEs (Kennish, 1986; Van Niekerk, 2007a). For example, storms can increase wave energy which, in extreme circumstances, may result in the onshore migration of sand bars (McLusky, 1981; Kennish, 1986; Van Niekerk, 2007a). If in the correct position, the onshore migration of a sand bar could result in the closure of the estuarine mouth, thereby isolating it from the ocean (Van Niekerk, 2007a). Conversely, freshwater inflows, and tidal interactions into estuarine systems, will maintain an open mouth state as a consequence of the scouring effect of outflows, which remove sediment deposits from the mouth (Van Niekerk, 2007a). This halts, and in some instances reverses, the build-up of sediments in the estuary mouth, so preventing the formation of a berm (Van Niekerk, 2007a). In contrast, reduced outflows from estuarine systems may cause mouth closure as a consequence of decreased scouring action, which may then be exceeded by high energy wave action, hence resulting in considerable sediment deposition in the estuary mouth (Van Niekerk, 2007a).

The fluvial sediment load which is transported into estuaries is determined by various physical factors of upstream catchments, such as land cover, slope, soil texture and the intensity of rainfall, changes of which are illustrated in Sub-section 6.2 (Van Niekerk, 2007a). However, as a consequence of high energy wave action at the mouth of many estuaries, a greater percentage of the substrate in these systems will consist of marine sediments (Van Niekerk, 2007a). If the estuary is of significant size, such as the St Lucia or Kosi Bay systems, then fluvial sediments may be deposited at the head and middle reaches (Theron, 2007). Additionally these fluvial sediment deposits play a significant role in maintaining biodiversity in estuaries (Kennish, 1986; Bonner *et al.*, 1990; Autenrieth *et al.*, 1991).

Organic nutrients in the form of detritus derived from fauna and flora upstream of (Thrush *et al.*, 2004) estuaries may be a major constituent of fluvial sediments which, in turn, add to the nutrient supply for micro-organisms (McLusky, 1981; Kennish, 1986; Bonner *et al.*, 1990; Autenrieth *et al.*, 1991). Hence, it is imperative that freshwater inflows into estuaries are maintained, as marine sediments contain negligible quantities of nutrients (Theron, 2007). Therefore, in systems such as the Thukela estuary it is imperative that sediment inflows are maintained (Oliff, 1960; McCormick and Cooper, 1992). If the influx of sediments into the Thukela system decreases then it is possible that the ecological integrity of this estuary could be threatened (Oliff, 1960; McCormick and Cooper, 1992). However, a significant influx of sediments into estuaries may result in an increase in turbidity. This, in turn, would reduce the light penetration, and hence primary production in these systems, despite the influx of nutrients (Thrush *et al.*, 2004).

Therefore, freshwater sediment inputs into estuaries form a major physical component on which estuary productivity relies (McLusky, 1981; Bonner *et al.*, 1990; Autenrieth *et al.*, 1991). In addition to the organic nutrients within the sediments, there are various trace metals and other chemicals which are filtered out and utilised in estuarine processes, as described in Sub-section 3.1.3 and discussed in Chapter 7 (McLusky, 1981; Kennish, 1986; Bonner *et al.*, 1990; Autenrieth *et al.*, 1991).

3.1.3 Estuarine Chemistry: A Brief Summary

The water in estuaries is not simply diluted sea water, yet some constituents within the system may behave as if this were so (McLusky, 1981; Kennish, 1986). The water in estuaries contains various ions and trace metals introduced into the system by both freshwater and marine inflows. These ions and trace metals are made use of in biological and non-biological processes (McLusky, 1981; Kennish, 1986; Whitfield, 2001; Cyrus *et al.*, 2009; MacKay *et al.*, 2009).

Salinity within estuaries is a function of freshwater inflows, with concentrations ranging from 0 – 35 practical salinity units, or PSUs (Kennish, 1986; Van Niekerk, 2007a). Therefore, in a so-called positive, or normal, estuary the freshwater inflows maintain adequate mixing, with a longitudinal gradient of increasing salinity downstream (McLusky, 1981; Kennish, 1986). Hence, higher ratios of carbonate and sulfate to chloride, and of calcium to sodium, are found when compared with sea-water, as river water is mainly a solution of calcium bicarbonate (Kennish, 1986). In a so-called negative estuary a longitudinal gradient of increasing salinity in an upstream direction could occur, hence indicating a reversal in the concentration of these ions (Kennish, 1986). In addition to the presence of these ions there are other major constituents which aid in facilitating the proper functioning of estuarine ecosystems. Table 3.1.3.1. shows the sources of inorganic nutrients, and the purposes they serve in estuaries.

Table 3.1.3.1: Inorganic nutrients, their source and function in estuarine ecosystems (Kennish, 1986)

Ion	**System in which Constituent is Most Abundant**	**Further Information**
Calcium	River	Actively extracted, and used in the construction of shells
Magnesium	Sea	Co-precipitation of magnesium with calcium carbonate by shell secreting organisms extracts magnesium
Silicon	River	Subject to organic removal by diatoms
Sulfate	River	Used by bacteria in anoxic conditions which then produce hydrogen sulfides
Chlorine	Sea	Abundant in evaporites
Flourine	Sea	N/A
Bromine	Sea	N/A
Bicarbonate	River	Forms carbonic acid when dissolved in rainwater, which dissolves limestone to be extracted and used by shell building organisms

The combination of chemicals, as shown in Table 3.1.3.1, results in a unique ecosystem in which both terrestrial and marine organisms may thrive (Correll, 1978; McLusky, 1981; Kennish, 1986; Scharler *et al.*, 1998; Wepener, 2007). In addition to these major constituents, there are several minor trace metals which facilitate some biological processes, while inhibiting others. This adds to the uniqueness of estuaries (Correll, 1978; McLusky, 1981; Kennish, 1986; Scharler *et al.*, 1998; Wepener, 2007).

Antimony, arsenic, cadmium, chromium, cobalt, copper, iron, lead, mercury, nickel, silver, vanadium and zinc are all trace metals which are transported into estuaries by either freshwater or marine inflows (McLusky, 1981; Kennish, 1986). These trace metals may enter the estuary in one of the following phases:

- in solution,
- as coating on detrital particles, or
- in pure particulate phase.

In many instances they are absorbed into the system (Kennish, 1986; Wepener, 2007). The absorption of trace metals into the estuary occurs through:

- the adsorption and co-precipitation of trace metals in solution,
- the flocculation of trace metal particles, and
- the flocculation of detrital particles to which trace metals have adhered (Kennish, 1986).

Hence, estuarine sediments act as sinks for the majority of trace metals entering the system. This is an ideal situation as these trace metals are readily available for use in the biological processes shown in Table 3.1.3.2.

Table 3.1.3.2: Trace metals and their function in estuarine ecosystems (Kennish, 1986).

Trace Metal	**Biological Processes**
Iron, manganese and vanadium	Essential to photosynthesis
Cobalt and iron	Used in metabolic processes
Copper, manganese and zinc	Important for growth and nutrition
Arsenic, lead and mercury	Inhibitor because of toxicity

Of the trace metals utilised in biological processes, a small portion may be released back into the system after utilisation, usually in the form of detritus (McLusky, 1981; Kennish, 1986; Wepener, 2007).

Therefore, the chemical processes occurring in estuarine ecosystems are often reliant on the substrate within estuaries, which act as a sink for both organic and inorganic nutrients, thereby supporting the high biodiversity in estuaries. Thus, estuaries act as reasonably efficient filtration systems, incorporating elements which, in excessive quantities, could become a problem in coastal waters, thereby negatively influencing the productivity of many organisms (cf. Sub-sections 3.2.1, 3.2.2 and Chapter 7).

3.1.4 Estuarine Energy Transfers Between Biota

Estuarine food webs are dependent on a number abiotic factors, such as nutrient availability and solar energy inputs (Correll, 1978; Kennish, 1986; Scharler *et al.*, 1998; Whitfield, 2001; Cloern and Jassby, 2008). The conversion of these inputs into useable energy, and the transfers between the different trophic levels that may occur thereafter, as shown in Figure 3.1.4.1, will be broadly described in this sub-section.

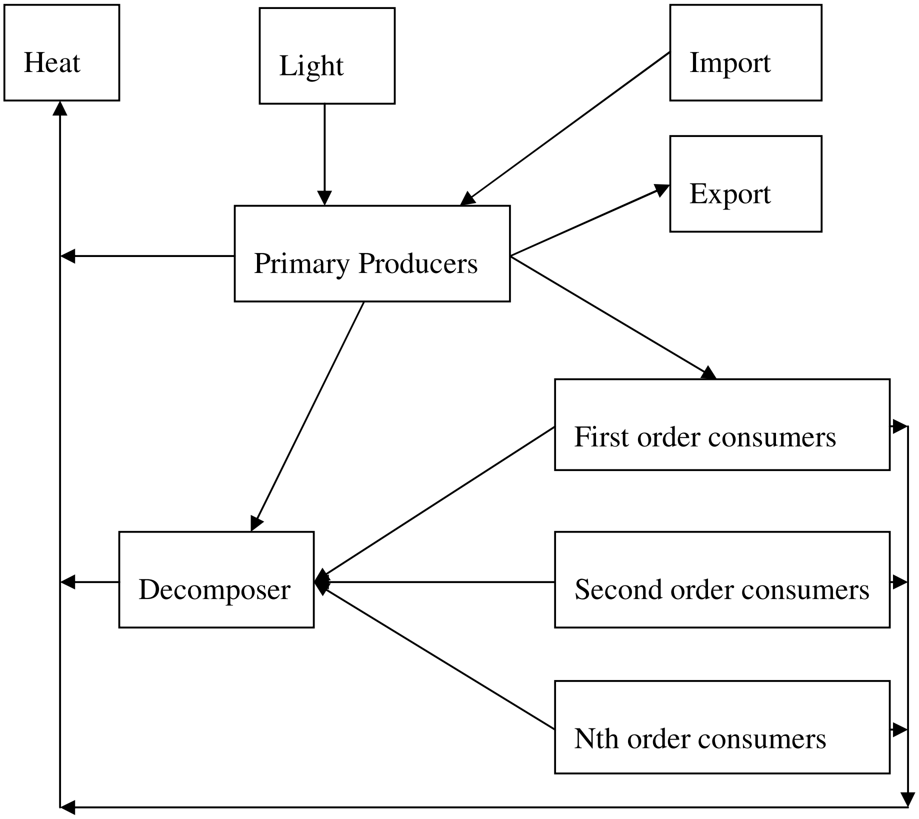


Figure 3.1.4.1: Simple of energy transfers between trophic levels in an ecosystem (Lindemann, 1942)

Primary producers form the first trophic level, as these organisms use solar energy inputs in the process of photosynthesis, which is used to produce energy in order to meet their metabolic requirements (Correll, 1978; Scharler *et al.*, 1998; Whitfield, 2001; Elliot *et al.*, 2002; Cloern and Jassby, 2008). The primary producers in estuaries consist of various species of:

- phytoplankton,
- micro- and macro-algae,
- seagrasses,
- sedges, and
- mangroves.

In combination, these make significant contributions to energy budgets within estuarine ecosystems (Correll, 1978; Kennish, 1986; Whitfield, 2001). However, contributions to energy budgets may vary considerably in accordance with changes to abiotic components, such as nutrient inputs. These changes are driven either through anthropogenic interference, or by natural causes (Correll, 1978; Kennish, 1986; Whitfield, 2001).

Owing to the inability of certain primary producers, such as phytoplankton and different types of algae, to control their internal equilibrium by osmotic regulation, they are vulnerable to changes in abiotic factors affecting estuaries, such as salinity. These changes can lead to a decrease in the number of primary producers (Copeland, 1966; Correll, 1978; Jerling and Wooldridge, 1994; Schumann and Pearce, 1997; Scharler *et al.*, 1998; Whitfield, 2001). A decrease in the density of primary producers may occur during periods of hyper-salinity, which can occur as a result of mouth closure and increased evaporation. In extreme drought conditions evaporation may exceed freshwater inflows and seepage contributions thus turning a system hyper-saline (Copeland, 1966; Correll, 1978; Jerling and Wooldridge, 1994; Schumann and Pearce, 1997; Scharler *et al.*, 1998; Whitfield, 2001). Additionally, nutrient contributions made by freshwater inflows will change accordingly. This may destabilise the system, thereby detrimentally affecting primary producers (Copeland, 1966; Correll, 1978; Scharler et al., 1998; Whitfield, 2001). Hence, as a result of the direct relationship between primary producers and consumers, the possible impacts of changes in freshwater inflows may be felt throughout the food web (Copeland, 1966; Correll, 1978; Jerling and Wooldridge, 1994; Scharler *et al.*, 1998; Whitfield, 2001; Cloern and Jassby, 2008). This is further discussed in addition to the possible effects of climate change on streamflow into estuaries in Chapter 7.

Primary consumers within estuaries, such as zooplankton and other micro-invertebrates, are physiologically vulnerable to salinity variations, as many of these organisms are incapable of the necessary osmoregulation required for survival in hyper- and hypo-saline environments (Correll, 1978; Jerling and Wooldridge, 1994; Scharler *et al.*, 1998; Whitfield, 2001; Cyrus *et al.*, 2009; MacKay *et al.*, 2009). Therefore, in South Africa, it has been established that the highest concentrations of primary consumers are to be found in temporary open closed estuaries (TOCEs), which experience occasional overtopping and breaching, thereby aiding in maintaining salinity concentrations within a tolerable range. This facilitates the survival of these organisms, as discussed in Chapter 7 (Correll, 1978; Jerling and Wooldridge, 1994; Scharler *et al.*, 1998; Eggleston *et al.*, 1999; Whitfield, 2001; Cyrus *et al.*, 2009; MacKay *et al.*, 2009).

Owing to the inability of primary consumers to photosynthesize, the density of these organisms in estuaries relies on the availability of primary producers (Kennish, 1986; Scharler *et al.*, 1998). In order to survive, primary consumers must prey on primary producers, thereby facilitating a transfer of energy from the primary producer to the primary consumer, as shown in Figure 3.1.4.1 (Kennish, 1986; Scharler *et al.*, 1998). However, the transfer of energy between primary producer and primary consumer is not as efficient as those occurring at higher trophic levels (Correll, 1978; Scharler *et al.*, 1998; Whitfield, 2001). Hence, a considerable portion of energy is not absorbed by the primary consumer, and this may be transferred back to the energy base of the estuary in the form of detritus (McLusky, 1981; Kennish, 1986; Scharler *et al.*, 1998; Whitfield and Bate, 2007). However, a considerable quantity of energy may be lost to the system through various respiratory processes (McLusky, 1981; Kennish, 1986).

Secondary consumers consist of carnivorous organisms preying on primary consumers, as shown in Figure 3.1.4.1 (Correll, 1978; Scharler *et al.*, 1998; Whitfield, 2001; Cyrus *et al.*, 2009; MacKay *et al.*, 2009). Secondary consumers consist of various species of fish and waterfowl and, unlike primary consumers, have a much greater tolerance of changes to salinity concentrations (Correll, 1978; Scharler *et al.*, 1998; Eggleston *et al.*, 1999; Whitfield, 2001; Pihl *et al.*, 2002; Cyrus *et al.*, 2009; MacKay *et al.*, 2009). Hence, secondary consumers have a wider distribution within estuarine systems, as a result of their greater adaptability, and this translates into greater habitat availability (Correll, 1978; Scharler *et al.*, 1998; Whitfield, 2001; Pihl *et al.*, 2002; Cyrus *et al.*, 2009; MacKay *et al.*, 2009). However, the distributions of secondary consumers will often mirror those of their prey, as the highest density of organisms is, in most instances, found in close proximity to their primary food source (Correll, 1978; Scharler *et al.*, 1998; Whitfield, 2001; Pihl *et al.*, 2002; Cyrus *et al.*, 2009; MacKay *et al.*, 2009).

Therefore, estuaries are complex ecosystems, in which abiotic components, such as freshwater inflows, exercise considerable influence (Kennish, 1986; Whitfield, 2001; Whitfield and Bate, 2007). Without either marine or freshwater inputs, a significant decrease in the biodiversity of these systems would occur (Kennish, 1986; Whitfield, 2001; Whitfield and Bate, 2007). The result would be an impoverished ecosystem, hence decreasing the functionality, ecological integrity, and the economic contributions of that system. Such impoverished ecosystems could occur under conditions of climate change.

3.2 The Importance of Estuaries

Owing to the location of estuaries at the marine freshwater interface, a unique environment is established on which a considerable quantity of marine and terrestrial biodiversity relies for survival (McLusky, 1981; Kennish, 1986; Whitfield, 2001). Hence, the ecological importance of estuaries is high. This, in turn, may then translate into economic value, as described in this section (McLusky, 1981; Kennish, 1986; Whitfield, 2001).

3.2.1 Ecological Importance of Estuaries

Owing to the wide range of feeding opportunities occurring in estuaries, the biodiversity in these systems is considerable as a result of a highly productive combination of various abiotic components (McLusky, 1981; Beckley, 1984; Whitfield, 2001).

Because of the high concentration of nutrients found in estuarine ecosystems, numerous plant species are able to survive, thereby supporting a significant number of micro-invertebrates such as zooplankton, as well as macro-invertebrates, such as molluscs (Kennish, 1986; Scharler *et al.*, 1998; Eggleston *et al.*, 1999). As a consequence, of this readily available food supply, many fish species may spawn in estuaries, hence ensuring the survival of a higher percentage of juveniles than would have survived in coastal waters in which the density of predators is significant. Hence, estuaries serve an important nursery function to many fish species (Correll, 1978; Day, 1981; Beckley, 1984; Kennish, 1986).

Numerous commercial fish species, depending on their origins and physiology, are obligate species, i.e. a portion of their life cycle must be spent in the estuarine environment (Beckley, 1984; Kennish, 1986; Ngoile and Horrill, 1993; Scharler *et al.*, 1998; Eggleston *et al.*, 1999; Whitfield, 2001; Able, 2005). Marine fish species are dominated by a group whose juveniles are dependent, to varying degrees, on estuaries as nursery areas (Beckley, 1984; Kennish, 1986; Whitfield, 2001; Able, 2005; Lamberth *et al.*, 2008). Additionally, many species of fish may spend their entire lives in estuaries, only occasionally venturing out into open coastal waters (Beckley, 1984; Eggleston *et al.*, 1999; Whitfield, 2001; Able, 2005; Lamberth *et al.*, 2008). Therefore, if the number of estuaries were to be reduced, for example, by the effects of climate change on inflows into the estuaries, the number of individuals in several commercial fish species would decrease considerably (Whitfield, 2001). Owing to the significant diversity of both flora and fauna in estuaries, a large number of avian species are therefore attracted to these ecosystems (Whitfield, 2001).

As a consequence of the considerable feeding opportunities present in estuarine ecosystems, numerous bird species make use of these systems as nesting sites, feeding areas and, in the case of migratory species, as stop-over points (Kennish, 1986; Whitfield, 2001). Additionally, predators of many avian species are largely absent in estuaries, which provides are strong case for nesting in these systems (Kennish, 1986; Whitfield, 2001). The absence of predators in these systems, and the abundant feeding opportunities may, in addition to attracting local species, attract significant numbers of migratory species (Whitfield, 2001).

Therefore, estuaries serve a number of ecological functions, such as water filtration, nursery areas, nesting sites and stop-over points, without which South Africa's coastlines would be impoverished of a significant portion of the biodiversity currently present in these areas. Aesthetically, this translates into economic value as tourists are often attracted to these areas for recreational purposes. This being one of the many economic assets that can be attributed to estuaries.

3.2.2 The Economic Importance of Estuaries

Estuaries are highly productive systems, providing a number of services ranging from recreational to commercial (Mander, 2001; Lamberth and Turpie, 2003). In South Africa, approximately 260 functional estuaries contribute to the goods and services provided, and in doing so these systems contribute significantly to the GDP of the country (Lamberth and Turpie, 2003).

The greatest contributor to the economic value of estuaries is that of fishing (Mander, 2001; Lamberth and Turpie, 2003). As already mentioned, estuaries provide nursery areas for many obligate commercial fish species, with the abundance of these species in coastal waters being reliant on the ecological integrity of estuarine systems (Ngoile and Horrill, 1993; Mander, 2001; Lamberth and Turpie, 2003). Therefore, if the number of functional estuaries in South Africa were to decrease significantly through, for example, the possible impacts of climate change, then it is probable that the abundance of commercial fish species in our coastal waters would decrease accordingly, as stated in Sub-section 3.2.1 (Mander, 2001; Lamberth and Turpie, 2003). This, in turn, could result in job losses and economic hardship for many people relying on fishing for survival (Ngoile and Horrill, 1993; Mander, 2001; Lamberth and Turpie, 2003). In addition to the contributions of the commercial fishing sector, the recreational fishing sector is a significant contributor, as many people vacation in coastal regions in which estuaries form a major attraction (Mander, 2001; Lamberth and Turpie, 2003). Hence, the overall annual contribution of estuaries to the GDP of South Africa is an estimated R1.2 billion, of which R900 million may be attributed to fishing (Mander, 2001; Lamberth and Turpie, 2003).

Other services provided by estuaries include:

- erosion control,
- water filtration,
- nutrient cycling,
- waste treatment,
- aesthetic appreciation, and the
- production of raw materials.

However, insufficient data exist regarding the economic value of the above-listed services. Suffice to say that without these services the South African coastal areas would be economically worse off (Mander, 2001; Lamberth and Turpie, 2003).

Hence, estuarine ecosystems are of considerable economic value. However, the future values of these systems could be under threat as a consequence of possible changes in climate that are projected to occur. In many instances, depending on the magnitude and direction of these changes, estuaries may be detrimentally affected, which could result in economic losses.

3.3 Indicators of Hydrological Alteration with Special Reference to Estuarine Ecosystems

In light of the importance of freshwater inputs into estuarine systems, and the possible impacts that climate change may have on these inputs, it is imperative that the hydrological regime into estuaries be modelled (Richter *et al.*, 1996; Richter *et al.*, 1997). This modelling may be undertaken through the use of Indicators of Hydrological Alteration (IHA), which are often used to assess changes in hydrological regimes, and which form part of the eco-hydrological toolkit (Richter *et al.*, 1996; Richter *et al.*, 1997). IHA can be used to summarise large datasets of daily hydrological observations or simulated values into more manageable and relevant statistics (Richter *et al.*, 1996; Richter *et al.*, 1997). The IHA consists of 67 parameters used in the description of the hydrological regime (Richter *et al.*, 1996; Richter *et al.*, 1997). The IHA indicators represent the five components of the streamflow regime, *viz.*

- magnitude,
- frequency,
- duration,
- timing, and
- rate of change.

In the following section the description of each of the five components and its significance is summarised with reference to estuarine ecosystems.

- The *magnitude* of monthly means represents the average of daily flow conditions during a specific month. This defines freshwater and sediment inputs for that particular month, thereby defining estuarine conditions during that same month (Richter *et al.*, 1996; Richter *et al.*, 1997; Theron, 2007; Van Niekerk, 2007b).
- The *frequency* of extreme events, such as floods or droughts, may determine how often an estuary becomes hypo- or hyper-saline. Additionally, these events play a significant role in mouth breaching and closure, thereby determining the frequency of freshwater-marine interactions (Copeland, 1966; Correll, 1978; Richter *et al.*, 1996; Richter *et al.*, 1997; Theron, 2007; Van Niekerk, 2007b).
- The *duration* of events may determine the future status of estuarine ecosystems. Short duration event may have a negligible impact, while an extended flood or drought may have a much greater impact on the overall integrity of the system (Richter *et al.*, 1996; Richter *et al.*, 1997; Van Ballegooyen *et al.*, 2006; Van Niekerk, 2007b).
- Many estuarine species rely on seasonal cues to complete different lifecycle stages. Hence, a significant change in the *timing* of seasonal cues may cause species to enter different life cycle stages at the incorrect time, hence resulting in a high mortality amongst many species, thereby reducing the biodiversity in the estuary (Gunter, 1961; Kennish, 1986; Richter *et al.*, 1996; Richter *et al.*, 1997; Lamberth *et al.*, 2008).
- Many species in estuaries are adapted to change, yet it is often not necessarily the change *per se* that results in high mortality, but rather the *rate at which change* occurs. Many

species are not adapted to cope with rapid changes of considerable magnitude, which may occur as a result of climate change (Gunter, 1961; Kennish, 1986; Richter *et al.*, 1996; Richter *et al.*, 1997; Whitfield and Bate, 2007; Lamberth *et al.*, 2008).

In this dissertation a subset of the 67 IHA will be utilised to determine how hydrological regimes may change as a consequence of changes in precipitation, temperature, evaporation and land cover, as a result of climate change, and how this might affect estuarine functioning (cf. Sub-sections 3.4 and Chapter 7).

3.4 Factors Affecting Flow Regimes into Estuaries

Hydrological responses in South Africa are reliant on:

- precipitation,
- temperature,
- evaporation, and
- land cover, and
- soils (Schulze, 2010c).

The first four of these are discussed below as they constitute the major elements that are perturbed under conditions of climate change (Schulze, 2010c) and which may then, in turn, negatively affect the functioning of estuarine ecosystems (McLusky, 1981).

3.4.1 Projected Future Trends in Temperature

Downscaled outputs from many GCMs are nowadays available, in order to estimate some of the possible impacts of climate change, at a regional scale (Easterling *et al*., 2000; Hewitson *et al*., 2005). One of the main climatic variables impacted upon by climate change is that of temperature.

In South Africa, significant research into future climate scenarios has been undertaken (Hewitson *et al.*, 2005; Schulze and Kunz, 2010a). The results obtained from this research show projected changes in future temperatures over South Africa. According to output from multiple research the following changes are projected to occur:

- By mid-century, daily maximum temperatures in midsummer are expected to increase by approximately 1.5 ^{o}C to 2.5 ^{o}C along the coast as a result of the moderating influence of the ocean, and 3^{o}C to 3.5^{o}C in the interior (Schulze *et al.*, 2005; Schulze, 2010c; Schulze and Kunz, 2010a).
- Increases of between 3 ^{o}C and 4.5 ^{o}C along the coast and 4 ^{o}C and 6 ^{o}C in the interior may be experienced in South Africa towards the end of the century (Schulze *et al.*, 2005; Schulze, 2010c; Schulze and Kunz, 2010a).
- Under future climate conditions, in the more continental interior, a reduction of approximately 70% of present cold spells, which may be defined as 3 or more consecutive days with minimum temperatures <2.5 ^{o}C, is projected to occur (Schulze, 2010c; Schulze and Kunz, 2010a).
- Although temperature increases in South Africa are not spatially uniform, significant portions of the country are projected to experience increases of 30 % to 60 % in the occurrences of extreme heat waves by the middle of the century. Extreme heat waves may be defined as 3 or more consecutive days with temperatures >35 ^{o}C (Schulze, 2010c; Schulze and Kunz, 2010a).

Owing to the influence of temperature on many components of the terrestrial hydrological system, such as relative humidity, rainfall generating mechanisms, evaporation and transpiration, streamflows and water temperatures are projected to be significantly impacted upon by climate change (Barichievy and Schulze, 2010; Schulze, 2010c; Schulze and Kunz, 2010a).

3.4.2 Projected Future Trends in Reference Potential Evaporation

The changes in evaporation that are projected to occur across South Africa will not be uniform, as evaporation rates are determined by:

- solar radiation,
- temperature,
- relative humidity, and

- wind turbulence,

all of which may influence the atmospheric demand (Schulze, 2010c; Schulze *et al.*, 2010d). If the atmospheric demand is fully met, then potential evaporation in that area occurs, either from open water bodies, or from crops not under soil water stress (Schulze, 2010c; Schulze *et al.*, 2010d). Owing to the manner in which evaporation occurs, temperature is the major driver in determining the quantity of water that is lost (Barichievy and Schulze, 2010; Schulze, 2010c; Schulze and Kunz, 2010a; Schulze *et al.*, 2010d). Hence, the estimation of changes in evaporation, occurring in areas projected to experience considerable temperature increases, is important for adaptive water management practices (Barichievy and Schulze, 2010; Schulze, 2010c; Schulze *et al.*, 2010d).

The physically based Penman-Monteith Method (Penman, 1948; Monteith, 1981) has been used as the reference for the estimation of potential evaporation in South Africa (Schulze *et al.*, 2010d). The results obtained show the following:

- An increase in evaporation of 5 % to 10 % across South Africa by mid-century; with
- patches of increases > 10 % along the west coast; and
- increases of 15 % to 20 % along the periphery, and 20 % to 25 % for the interior of South Africa by the end of this century.
- A sensitivity analysis for South African conditions showed that in January a 2°C increase could increase the reference potential evaporation by approximately 3.5%, while in July the percentage increase is even higher (Schulze *et al.*, 2010d).

Therefore, water in the western regions and adjacent interior of South Africa is likely to become an even scarcer resource that it currently is, as a result of the following:

- Faster drying of soils between rainfall events,
- higher rates of transpiration, and
- increased evaporation from open water surfaces (Schulze *et al.*, 2005).

Hence, freshwater inflows into estuaries in the western regions of South Africa may be significantly reduced based on the increases of evaporation alone. This, in turn, may detrimentally affect estuarine ecosystems to a greater extent along the west coast than on the east coast, irrespective of changes in rainfall.

Enhanced rates of evaporation as a result of changes in temperature may thus have far reaching implications regarding the integrity of estuarine ecosystems, which may be exacerbated in any areas of reduced future precipitation.

3.4.3 Projected Future Trends in Precipitation

Owing to the importance of precipitation in the hydrological cycle it is imperative that accurate projections of future rainfall characteristics be made, hence facilitating the estimation of future water availability for allocation to various users, including the environment (Schulze *et al.*, 2005; Schulze and Kunz, 2010d). These projections should ideally include changes in the quantity, intensity, seasonality and duration of precipitation events (Bullard, 1966; Hewitson *et al.*, 2005; Schulze, 2005b; Schulze and Kunz, 2010d).

Projections of future precipitation patterns over South Africa still display high levels of uncertainty (Hewitson *et al.*, 2005; Schulze, 2005b), but recent results from multiple GCMs (Schulze and Kunz, 2010d) show the following:

- An increase in precipitation over much of South Africa is projected to occur into the intermediate future (2046 – 2065), with greater increases occurring over the eastern regions than the western regions (Lumsden and Schulze, 2007; Schulze and Kunz, 2010d).
- Projections made for the more distant future (2081 – 2100) indicate increases in the frequency of high intensity events in the eastern regions (Lumsden and Schulze, 2007).
- Along the western seaboard and adjacent interior, a decrease in the number of rain days, and the total quantity of precipitation is projected to occur (Lumsden and Schulze, 2007; Schulze and Kunz, 2010d).
- The inter-annual variability of precipitation is projected to increase throughout South Africa (Lumsden and Schulze, 2007; Schulze and Kunz, 2010d).

The most severely impacted regions are likely to be those projected to experience decreases in precipitation and increases in temperature, as systems are already stressed by low precipitation, and could lose still more water to evaporation (Schulze *et al.*, 2005; Lumsden and Schulze, 2007; Schulze and Kunz, 2010d). Hence, many aquatic ecosystems such as estuaries may, in such regions, cease to function properly as a consequence of decreased streamflow (Gunter, 1961; McLusky, 1981; Kennish, 1986; Scharler *et al.*, 1998; Lamberth *et al.*, 2008; Cyrus *et al.*, 2009; MacKay *et al.*, 2009). In contrast, the water deficit in regions such as KwaZulu-Natal, which are projected to experience an increase in both temperature and precipitation, are likely not to be as high (Schulze *et al.*, 2005; Lumsden and Schulze, 2007; Schulze and Kunz, 2010d). Hence, the aquatic systems in these regions are likely not to be as stressed as in other regions, thus more likely maintaining their ecological integrity (Gunter, 1961; McLusky, 1981; Kennish, 1986; Scharler *et al.*, 1998; Lamberth *et al.*, 2008; Cyrus *et al.*, 2009; MacKay *et al.*, 2009).

3.4.4 Land Use as a Factor Affecting Flow Regimes into Estuaries

Most anthropogenic activities occur on the land surface, thereby altering the bio-physical characteristics of river catchments (Falkenmark *et al.*, 1999; Falkenmark and Rockström, 2004). As a consequence of the many demands on water resources, competition and conflict may arise among the many activities consuming water (Falkenmark *et al.*, 1999; Falkenmark and Rockström, 2004).

Owing to the diversity of anthropogenic activities occurring in catchments, it is highly probable that hydrological responses into estuaries may change considerably. Evidence for this is provided by the following contrasting examples:

- Commercial forestry plantations could intercept and transpire considerable quantities of the precipitation received, and in addition to their deeper roots systems and litter layer, may increase infiltration and reduced both surface runoff and baseflow.
- A highly built up area would have much less interception, no litter layer and, as a result of a high percentage of impervious areas could result in low infiltration, high surface runoff and reduced baseflow.

When compared to one another, the hydrographs of streamflow from catchments in which commercial forestry plantations are the dominant land use, generally have a considerable lag period and low peaks, while the hydrographs of streamflows from urban areas could have a short lag times and high peaks. Additionally, the rising limb of streamflow hydrographs from commercial forestry plantations are normally smoother and may last for extended periods of time before peaking and then gradually descending to “normal” flow levels. In contrast, the rising limb of streamflow hydrographs from urban areas could be steep, and last for only a brief period before peaking and descending to "normal" flow levels. The afore-going examples illustrate the possible effects of a land cover and land use on hydrological responses into estuaries. However, before further discussion two terms "land cover" and "land use" must first be defined.

Land cover is defined as the bio-physical state of the earth's surface and sub-surface in terms of broad categories, such as cropland, grassland or man-made forests. Land use is defined as the conversion of land cover, through anthropogenic alteration, usually for agricultural and human settlement purposes.

The magnitude of alteration to natural ecosystems through anthropogenic activities may be categorized by their effects on water resources present in the area (Schulze, 2003a). Therefore, the scale of modification to an ecosystem will fit into one of the following categories:

- Conserved ecosystems, implying negligible modification, e.g. game parks (Schulze, 2003a);
- Utilised ecosystems, which is the exploitation of a natural system without impacting on the hydrological system e.g. recreation (Schulze, 2003a);
- Replaced ecosystems, which is the replacement of an indigenous ecosystem with a simpler system designed for a single purpose, such as forestry which would impact on the partitioning of rain water flows in the catchment, thereby affecting hydrological responses (Schulze, 2003a); and
- A completely removed ecosystem implying the destruction and replacement of the natural ecosystem by a man made system, e.g. urban and industrial areas (Schulze, 2003a).

Therefore, the magnitude of impacts on downstream systems, from a hydrological perspective, is directly related to the scale of modification to an ecosystem, i.e. the greater the modification of upstream ecosystems, the greater the impacts on downstream ecosystems (Schulze, 2003a). Hence, if the land cover upstream of an estuary is altered through anthropogenic interference then the impacts on the estuary could be significant, as illustrated by the case study of the Klein estuary. In this case study daily streamflow output from simulations using natural or baseline land cover were compared to daily streamflow output from simulations using actual land use (cf. Sub-section 6.2). The results of this study illustrate the marked effect on this estuary of altered upstream land cover. The selection of the Klein estuary as the case study for this dissertation was as a consequence of ecological and land cover related factors which are discussed in greater detail in Chapter 5. However, as a consequence of the high variability of land cover and climate zones throughout South Africa, hydrological responses due to the same anthropogenic activity, will differ considerably (Schulze, 2003a). Therefore, the response of estuarine ecosystems throughout South Africa, to changes in both land use and climate change, are likely to differ considerably.

In this chapter on estuarine ecosystems in a climate change and land use change context, an introduction into the functioning of estuarine ecosystems was followed by discussion on the importance of estuaries and indicators of hydrological alteration with reference to estuarine ecosystems (cf. Chapters 6 and 7). Factors affecting flow regimes into estuaries were then described, with the climatic factors focusing on possible impacts of climate range and land use impacts in more general terms.

The reviews in chapters 2 and 3 set the scene for describing the sites for this study (cf. Chapter 4), methodologies applied (cf. Chapter 5) and the results obtained (cf. Chapter 6).

4 SELECTION AND DESCRIPTION OF STUDY SITES

Estuarine ecosystems are moulded by abiotic factors such as freshwater and marine inputs, which influence the circulation, substrate and chemistry of these systems. These factors, in turn, determine the diversity of the biotic component within estuaries. Therefore, as climate change will have a highly variable influence on the abiotic components of estuaries, it is prudent to expect considerable, but varied responses on the biotic components. In order to adequately represent the many climate regions in South Africa, the Köppen-Geiger climate classification system, which facilitated the selection of estuaries for closer study in this project, and the estuaries selected will be introduced in this chapter.

The Köppen-Geiger climate classification system is based on the highly relevant hydrological variables of rainfall and temperature (Köppen, 1931). This system operates in a hierarchical manner, with up to three levels of detail, which are based on:

- Rainfall magnitude,
- rainfall seasonality,
- rainfall concentration, and
- durations of above or below threshold temperatures on a monthly basis.

From the inputs of monthly rainfall and temperature data, an accurate map of the Köppen climate regions found in South Africa can be generated, as shown in Figure 4.1. Therefore, this classification system facilitated part of the estuarine selection process.

Ten estuarine systems were selected for this study and these were chosen based on the following criteria:

- The climate region in which the catchment is located,
- the area of the catchment, and
- the freshwater inflow regime into the estuarine ecosystem.

In order to meet the above criteria, the following maps covering South Africa were examined, in addition to that of the Köppen climate regions:

- mean annual precipitation (MAP),
- mean annual temperature (MAT),
- seasonality of rainfall,
- concentration of rainfall,
- mean annual runoff (MAR).

Based on the aforegoing information, the selection of representative estuaries, and their catchments, in each of the major climate regions in South Africa, could be completed satisfactorily, considering also subsequent assessments of the possible changes in regional climate and the potential effects of these changes on freshwater inflows. Additionally, the catchments were selected to span a range of categories of areas from small to large according to size categories, shown in Table 4.2, thereby accounting for the possible effects that differing catchment areas, although in similar climate zones could exert on freshwater inflows. However, since part of the aim of this dissertation is to research the possible ecological impacts of climate change on estuarine systems, the current ecological characteristics of estuaries must be included in the selection criteria (cf. Figure 4.1 and Table 4.1).

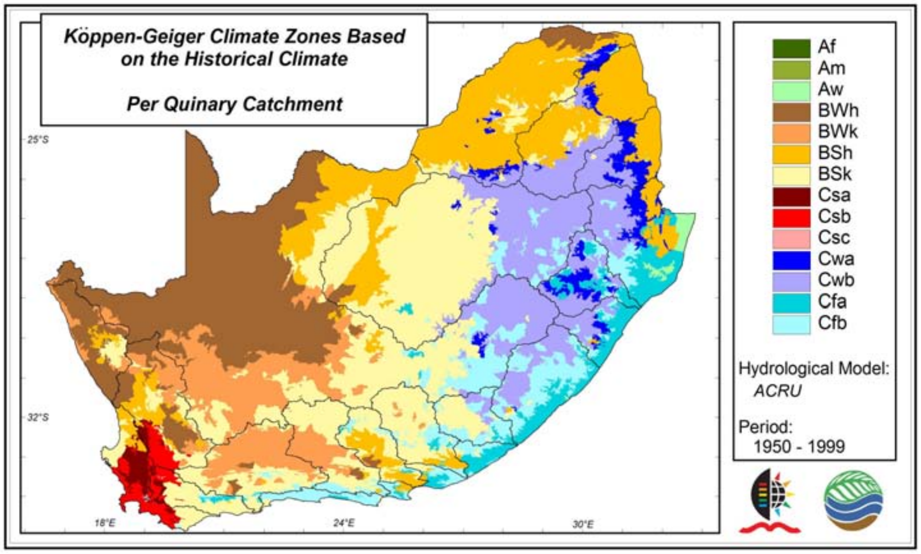


Figure 4.1: Köppen-Geiger climate zones in South Africa (Schulze *et al.*, 2007), illustrating the various climate regimes in which the 10 selected catchments are located

Table 4.1: Percentages of Köppen-Geiger climate classes in South Africa (Schulze *et al.*, 2007)

Köppen-Geiger Class	**Climate Characteristics**	**% in South Africa**
Aw	Tropical wet, dry winter season	1.53
BSh	Semi-arid, hot and dry	15.55
BSk	Semi-arid, cool and dry	17.95
BWh	Arid, hot and dry	16.34
BWk	Arid, cool and dry	9.97
Cfa	Wet all seasons, summers long and hot	4.69
Cfb	Wet all seasons, summers long and cool	8.10
Csa	Summers long, dry and hot	0.24
Csb	Summers long, dry and cool	0.89
Cwa	Winters long, dry and hot	10.10
Cwb	Winters long, dry and cool	14.61
Cwc	Winters dry, summers short and cool	0.02

Table 4.2: Size criteria for the selection of systems based on catchment area

Catchment Category	**Catchment Area (km^2)**
Small	0 - 1000
Medium	1000 - 5000
Large	5000 - ∞

With the assistance of estuary specialists at the CSIR in Stellenbosch, and taking cognisance of the following three criteria, *viz*:

- the ecological importance of specific estuaries (as described in Section 3.2.1),

- the ecological requirements of estuaries, from a hydrological perspective (as described in Section 3.1.1), and
- the economic importance of estuaries (as described in Section 3.2.2)

Ten estuarine systems and their corresponding catchments were selected along the South African coastline. as shown in Figure 4.2. Information on the characteristics of the estuaries and their corresponding catchments is present in Figures 4.3 to 4.12 and Tables 4.3 to 4.12.

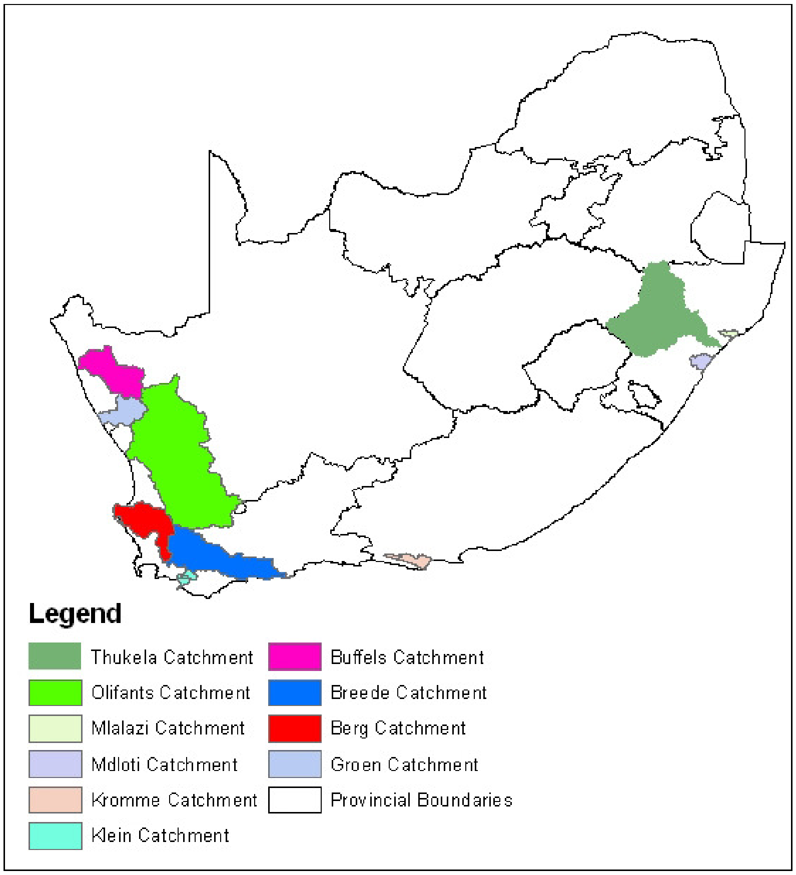


Figure 4.2: Location of the 10 selected estuaries and their catchments, which were selected for this study

Figure 4.3: Berg estuary and immediate environs (Googleearth.com, 2010)

Table 4.3: Characteristics of the Berg catchment

Variable	Description
Area (km^2)	8990.29
Altitude (m)	0 – 1200 (Schulze and Horan, 2007)
Topography	Flat in the lower reaches, increasing in altitude towards the more mountainous upper reaches (Schulze and Kruger, 2007)
MAP (mm) Range and Seasonality	200 – 1000, winter rainfall (Schulze and Kunz, 2010c; Schulze and Kunz, 2010b)
Climate Regions	***Cfa (Schulze et al., 2007)***
Baseline Land Cover (Acocks, 1988)	Strandveld, macchia, coastal rhenosterveld, coastal macchia, mountain rhenosterveld
Actual Land Cover (NLC, 2000)	Cultivated areas, shrubland and low fynbos
Flow Characteristics	Highly seasonal, peak flows during winter (Van Niekerk, 2010a)
Estuary Characteristic	Permanently open and is used as a harbour(Van Niekerk, 2010a)
Reason for Selection	Large catchment; winter rainfall region; economically important catchment for farming

Figure 4.4: Breede estuary and immediate environs (googleearth.com, 2010)

Table 4.4: Characteristics of the Breede catchment

Variable	Description
Area (km^2)	12623.01
Altitude (m)	0 – 1825 (Schulze and Horan, 2007)
Topography	Mountainous in the middle to upper reaches, flattening out towards the lower reaches (Schulze and Kruger, 2007)
MAP (mm) Range and Seasonality	250 – 800, all year and winter rainfall (Schulze and Kunz, 2010c; Schulze and Kunz, 2010b)
Climate Regions	***Cfb (Schulze et al., 2007)***
Baseline Land Cover (Acocks, 1988)	Coastal macchia, coastal rhenosterveld, false macchia, karroid broken veld, mountain rhenosterbosveld
Actual Land Cover (NLC, 2000)	Shrubland, low fynbos, cultivated temporary commercial dryland agriculture, thicket, bushland, bush clumps, high fynbos. Bare rock and soil.
Flow Characteristics	Highly seasonal, peak occurring during winter (Van Niekerk, 2010a)
Estuary Characteristic	Permanently open (Van Niekerk, 2010a)
Reason for Selection	Large catchment; winter rainfall region; economically important catchment

Figure 4.5: Buffels estuary and immediate environs (googleearth.com, 2010)

Table 4.5: Characteristics of the Buffels catchment

Variable	Description
Area (km^2)	9848.98
Altitude (m)	0 – 1100 (Schulze and Horan, 2007)
Topography	Catchment is largely flat with altitude and topographical variability increasing in the upper reaches (Schulze and Kruger, 2007).
MAP (mm) Range and Seasonality	100 – 400, winter rainfall (Schulze and Kunz, 2010c; Schulze and Kunz, 2010b)
Climate Regions	***Csa, Cwb (Schulze et al., 2007)***
Baseline Land Cover (Acocks, 1988)	Namaqualand broken veld, strandveld, mountain rhenosterbosveld succulent karoo
Actual Land Cover (NLC, 2000)	Shrubland and low fynbos, unimproved (natural) grassland
Flow Characteristics	Peaks during winter, yet the magnitude of variation is not significant and flows may cease during the dry season (Van Niekerk, 2010a)
Estuary Characteristic	Temporarily open/closed (Van Niekerk, 2010a)
Reason for Selection	Large catchment; winter rainfall region; arid region

Figure 4.6: Groen estuary and immediate environs (googleearth.com, 2010)

Table 4.6: Characteristics of the Groen catchment

Variable	Description
Area (km^2)	4916.16
Altitude (m)	0 – 450 (Schulze and Horan, 2007)
Topography	Flat towards the lower reaches with more mountainous regions in the upper reaches (Schulze and Kruger, 2007)
MAP (mm) Range and Seasonality	100 – 400, winter rainfall (Schulze and Kunz, 2010c; Schulze and Kunz, 2010b)
Climate Regions	***Csa, Cwb (Schulze et al., 2007)***
Baseline Land Cover (Acocks, 1988)	Namaqualand broken veld, succulent karoo, strandveld, mountain rhenosterveld
Actual Land Cover (NLC, 2000)	Shrubland, low fynbos
Flow Characteristics	Slight peak during late winter, with magnitude of seasonal flow variations negligible, and flows ceasing on a regular basis (Van Niekerk, 2010a)
Estuary Characteristics	Opens rarely (Van Niekerk, 2010a)
Reason For Selection	Medium size catchment; arid region; winter rainfall region

Figure 4.7: Klein estuary and immediate environs (googleearth.com, 2010)

Table 4.7: Characteristics of the Klein catchment

Variable	Description
Area (km^2)	988.94
Altitude (m)	0 – 900 (Schulze and Horan, 2007)
Topography	Altitude is variable throughout the catchment, two dominant high altitude areas in the catchment, forming watershed boundaries (Schulze and Kruger, 2007)
MAP (mm) Range and Seasonality	400 – 600, winter rainfall (Schulze and Kunz, 2010c; Schulze and Kunz, 2010b)
Climate Regions	***Cfb (Schulze et al., 2007)***
Baseline Land Cover (Acocks, 1988)	Coastal macchia, macchia, coastal rhenosterbosveld
Actual Land Cover (NLC, 2000)	Shrubland and low fynbos, with cultivated, temporary, commercial as well as, dryland farming and thicket, bushland, bush clumps, high fynbos
Flow Characteristics	Continuously flowing, with peaks occurring during winter except during years of severe drought (Van Niekerk, 2010a)
Estuary Characteristic	Temporarily open/closed (Van Niekerk, 2010a)
Reason for Selection	Small catchment; semi-arid, winter rainfall; high ecological importance

Figure 4.8: Krom estuary and immediate environs (Googleearth.com, 2010)

Table 4.8: Characteristics of the Krom catchment

Variable	Description
Area (km^2)	1017.99
Altitude (m)	0 – 500 (Schulze and Horan, 2007)
Topography	Numerous watersheds divide the catchment into several sub-catchments (Schulze and Kruger, 2007)
MAP (mm) Range and Seasonality	400 – 800, all year rainfall (Schulze and Kunz, 2010c; Schulze and Kunz, 2010b)
Climate Regions	***BSk; Cfb (Schulze et al., 2007)***
Baseline Land Cover (Acocks, 1988)	False macchia, valley bushveld, succulent mountain scrub and Karoo broken veld
Actual Land Cover (NLC, 2000)	Improved grassland, Bare rock and soil, thicket bushveld and high fynbos
Flow Characteristics	Continuous flow throughout the year, with distinct peak seasons, ceasing only during periods of severe drought (Van Niekerk, 2010a)
Estuary Characteristics	Permanently open (Van Niekerk, 2010a)
Reason for Selection	Small catchment; all year rainfall region.

Figure 4.9: Mdloti estuary and immediate environs (Googleearth.com, 2010)

Table 4.9: Characteristics of the Mdloti catchment

Variable	Description
Area (km^2)	601.89
Altitude (m)	0 – 700 (Schulze and Horan, 2007)
Topography	Highly variable altitude with a number of watersheds creating sub-catchments (Schulze and Kruger, 2007)
MAP (mm) Range and Seasonality	800 – 1000, late summer (Schulze and Kunz, 2010c; Schulze and Kunz, 2010b)
Climate Regions	***Cfa (Schulze et al., 2007)***
Baseline Land Cover (Acocks, 1988)	Coastal forest, thornveld, valley bushveld and ngongoni bushveld
Actual Land Cover (NLC, 2000)	Permanent cultivated commercial lands with some natural grasslands situated in the vicinity of urban built up and informal areas.
Flow Characteristics	Strongly seasonal with peaks occurring during summer, and flows occasionally ceasing during severe drought (Van Niekerk, 2010a).
Estuary Characteristic	Temporary open/closed mouth (Van Niekerk, 2010a)
Reason for Selection	Small catchment; summer rainfall region; estuary is still ecologically intact

Figure 4.10: Mlalazi estuary and immediate environs (Googleearth.com, 2010)

Table 4.10: Characteristics of the Mlalazi catchment

Variable	Description
Area (km^2)	503.46
Altitude (m)	0 – 500 (Schulze and Horan, 2007)
Topography	Highly variable altitude with a number of watershed boundaries created by high lying areas (Schulze and Kruger, 2007)
MAP (mm) Range and Seasonality	800 – 1200, late summer (Schulze and Kunz, 2010c; Schulze and Kunz, 2010b)
Climate Regions	***Cfa (Schulze et al., 2007)***
Baseline Land Cover (Acocks, 1988)	Coastal forest, thornveld, valley bushveld and ngongoni bushveld
Actual Land Cover (NLC, 2000)	Permanently cultivated lands used for commercial farming, interspersed with some natural grasslands, Included some urban areas
Flow Characteristics	Strongly seasonal, with summer peaks, and flows occasionally ceasing during droughts (Van Niekerk, 2010a)
Estuary Characteristic	Temporary open/closed mouth (Van Niekerk, 2010a)
Reason for Selection	Small catchment; summer rainfall region

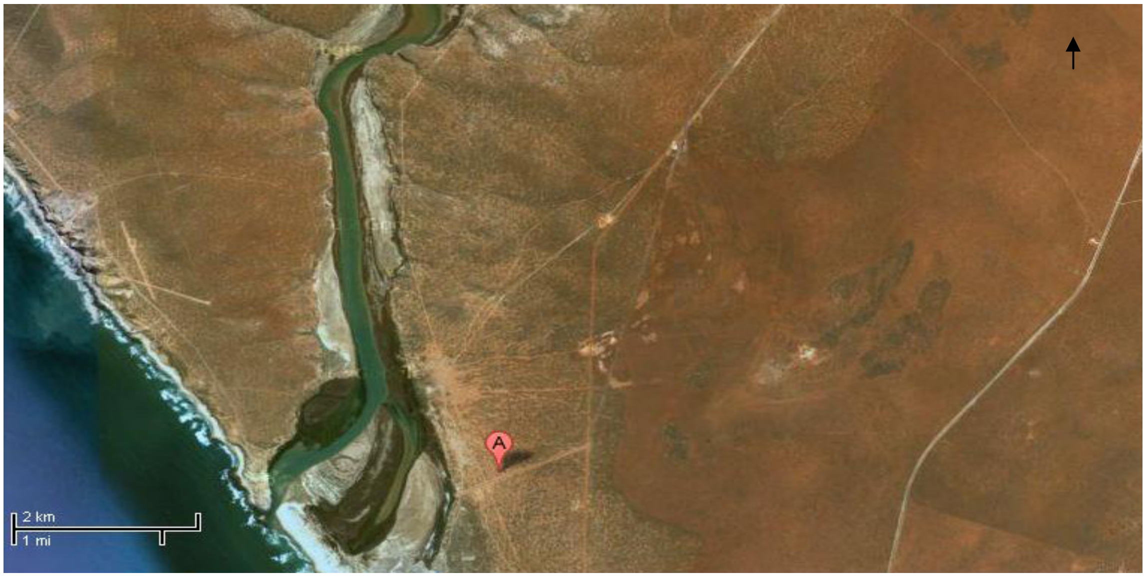


Figure 4.11: Olifants estuary and immediate environs (Googleearth.com, 2010)

Table 4.11: Characteristics of the Olifants catchment

Variable	**Description**
Area (km^2)	49414.49
Altitude (m)	0 – 1200 (Schulze and Horan, 2007)
Topography	Includes the Cederberg mountain range in upper regions, and decreases in altitude to flatlands of the lower reaches (Schulze and Kruger, 2007).
MAP (mm) Range and Seasonality	200- 800, winter rainfall (Schulze and Kunz, 2010c; Schulze and Kunz, 2010b)
Climate Regions	***BWh; BSh; BSk (Schulze et al., 2007)***
Baseline Land Cover (Acocks, 1988)	False succulent karoo, succulent karoo, western mountain karoo. Macchia, strandveld
Actual Land Cover (NLC, 2000)	Shrubland and low fynbos with some cultivated, temporary, and commercial, dryland agriculture
Flow Characteristics	Highly seasonal, with peaks occurring during winter and flows occasionally ceasing during mild droughts (Van Niekerk, 2010a)
Estuary Characteristic	Permanently open (Van Niekerk, 2010a)
Reason for Selection	Large catchment; winter rainfall region; recognised internationally as an important wetland system

Figure 4.12: Thukela estuary and immediate environs (Googleearth.com, 2010)

Table 4.12: Characteristics of the Thukela catchment

Variable	**Description**
Area (km^2)	29220.94
Altitude (m)	0 – 2500 (Schulze and Horan, 2007)
Topography	Highly variable including the Drakensberg mountain range (Schulze and Kruger, 2007)
MAP (mm) Range and Seasonality	600 – 2000, early, mid and late summer rainfall (Schulze and Kunz, 2010c; Schulze and Kunz, 2010b)
Climate Regions	***Cwa; Cwb; Cfa; Cfb*** **(Schulze et al., 2007)**
Baseline Land Cover (Acocks, 1988)	Southern tall grassveld, valley bushveld, natal sour sandveld, highland and dohne sourveld, coastal forest and thornveld
Actual Land Cover (NLC, 2000)	Thicket, bushland, bush clumps, high fynbos. Forest. Unimproved (natural) grassland, also degraded. Urban/built up (residential, informal township). Cultivated, temporary, subsistence, dryland
Flow Characteristics	Flows continuously, with summer peaks, with very low flows during very severe droughts (Van Niekerk, 2010a)
Estuary Characteristic	Permanently open (Van Niekerk, 2010a)
Reason for Selection	Large catchment; summer rainfall region

The 10 catchments selected for this study had to satisfy the three criteria stated at the start of this chapter. Following is a brief review of the critera this study takes into account:

- the climatic region in which the catchment is located,
- the area of the catchment, and the
- freshwater flow regime into the estuarine ecosystem.

The apparent bias towards the selection of estuaries in the Western Cape is due to the estuary catchments exhibiting both wet and dry winter rainfall conditions along the west coast and all year rainfall conditions along the southern coast. From the tables and figures presented in the previous pages the 10 catchments selected for this study include:

- nine Köppen climate zones,
- five large catchments, one medium sized catchment and four small catchments, and
- six catchments are located in the winter rainfall region, three catchments are located in the summer rainfall region and one catchment is located in the all year rainfall region.

Hence, it is considered that sufficient representation of the diverse climatic regions, catchment size, the highly variable topography and natural land cover found throughout South Africa has been achieved for the purposes of this study.

5 METHODOLOGY

From the literature reviewed in Chapter 3 it may be stated that strong links exists between estuarine ecosystem integrity and freshwater inflows. Because of these links, it is highly probable that the potential impacts of climate change could markedly affect the functioning of estuarine ecosystems. Therefore, it is imperative that comparative assessments, based on simulations of present and projected future freshwater inflows, be undertaken, in order to determine the possible direct and indirect impacts of climate change on estuarine ecosystems from a hydrological perspective. In this chapter methods used to achieve the above will be described.

5.1 Brief Review of the Problem

Key problems to be addressed in this study have been outlined in Chapter 1, and consist of several components, which are summarised as follows:

- The ecological functioning of estuarine ecosystems may become unstable as a consequence of altered daily freshwater inflows, which could negatively or positively affect the biota in these systems.
- Present knowledge of the potential impacts of climate change on streamflows into estuarine ecosystems in South Africa is incomplete and, to date, has been at a coarse temporal scale (monthly time step).

In order to address these two problems, the 10 estuaries, with catchments of different areas (Figures 4.3 to 4.12) and from different climate regimes (Figure 4.1; Tables 4.3 to 4.12), along the South African coastline were selected. For each of these catchments simulations were undertaken with a daily hydrological model for a range of historical as well as present to future GCM derived climate scenarios in order to assess projected changes in streamflow and sediment yield responses into their respective estuarine systems. Simulations of hydrological responses from each of the 10 selected catchments were undertaken under baseline land cover conditions which were represented by Acocks (1988) Veld Types. It should be re-iterated that the focus of this study is the development and application of techniques for the assessment of possible impacts of climate change on estuarine ecosystems from a *hydrological* perspective, i.e. from a more abiotic as opposed to a more biotic perspective. However, in one catchment, *viz*. the Klein catchment, simulations of streamflow were undertaken using *actual* land use in addition to the simulations using baseline land cover, in order to demonstrate the possible effects of upstream land use changes (including dams and irrigation) on responses into estuaries, both without and with climate change. The reasoning behind using only a single catchment for the land use impacts study on estuaries is due to the significant time and effort required to configure complex catchments with dams, off-takes and return flows accurately for the *ACRU* modelling system. Furthermore, in the case study of the Klein catchment, the inflows into that estuary, together with precipitation onto and evaporation from the estuary, together with information on breaching of the estuary mouth at threshold volumes, were used in a daily estuary water balance model to assess frequencies of breaching under different climate scenarios (cf. Sub-section 5.8).

The techniques developed and demonstrated from simulations of streamflow and sediment yields in the 10 selected estuaries, but especially for the Klein estuary may, in the absence of comprehensive ecological data, be used to provide a basic assessment of the ecological integrity of estuarine ecosystems.

In order to facilitate the climate change component of this study, output must be obtained from GCMs, as alluded to in Sub-section 5.2. However, before a description is made of the GCMs used in this study, and the manner in which daily climate output from the GCMs was used as input to a daily hydrological model, a review is provided on how climate data was obtained for simulations of hydrological responses under current (i.e. historical) climate conditions..

5.2 Review of Methods to Obtain Climate Data for the Simulation of Hydrological Responses from Quinary Catchments

In order to obtain a reference against which to evaluate GCM derived present day flows (i.e. 1971 - 1990) into the 10 selected estuaries, a historical dataset of rainfall and temperatures for the same period was used as input to hydrological simulations. The manner in which this historical dataset was obtained is reviewed in Sub-section 5.2.1 and 5.2.2. Thereafter the GCM output used in analyses is reviewed in Sub-section 5.2.3.

5.2.1 A Review of the Estimation of Daily Rainfall Values for Simulations During the Historical Period (1971 – 1990)

In order to validate simulations that used GCM outputs, a time period common to both GCM output and observed rainfall data had to be selected. This common time period was selected by Lumsden *et al* (2010) to be 1971 – 1990. The daily rainfall values for this historical period were derived from a 50 year daily dataset of 1950 – 1999 (Lynch, 2004), the development of which is reviewed below. The historical rainfall values throughout South Africa for 1950 – 1999 were computed using complex relationships of rainfall with physiographic factors in a geographically weighted regression to calculate rainfall values at stations with quality controlled data (Lynch, 2004). The rainfall values generated at the stations were then aggregated into a Quaternary catchments database developed in the School of Bioresources Engineering and Environmental Hydrology (Schulze *et al.*, 2005), which could then be used for a number of purposes, such as the analysis of trends in rainfall (Schulze, 2010b). In this dissertation these historical rainfall values were extracted by the candidate for the period 1971 – 1990 for the validation of GCM output, which is shown in Sub-section 5.4.

However, in this research the *Quinary* (and not the Quaternary) catchments database, also developed in the School of BEEH, was used (Schulze *et al.*, 2010a). In order to obtain accurate hydrological responses from each Quinary catchment, i.e. a further level of spatial disaggregation from the Quaternary of catchments in South Africa (Schulze and Horan, 2010), the climate input into the selected hydrological model must be unique to each Quinary catchment. Therefore, rainfall records appropriate to each of the 5 838 Quinary catchments covering South Africa, Lesotho and Swaziland were generated from the data of the rainfall stations selected to represent the parent Quaternary catchment (Schulze *et al.*, 2010a).

The so-called "driver" rainfall stations of each Quaternary catchment were selected by first determining the centroid of these catchments (Schulze and Horan, 2010). Then, using a daily rainfall extraction utility program, the 10 stations closest to the centroid were chosen and ranked using 10 reliability criteria (Kunz, 2004). In order to ensure the validity of the afore-going assumption, the highest ranked station was then subjected to further manual evaluation (Schulze *et al.*, 2005). The end result of this study was that 1 248 stations were selected to "drive" the hydrological simulations of the 1 946 Quaternary catchments (Schulze *et al.*, 2005). Hence, in many instances a single rainfall station had to drive a number of Quaternary catchments (Schulze *et al.*, 2005; Schulze *et al.*, 2010a). However, in response to further research, the driver stations of 11 Quaternary catchments were changed in order to obtain better representation of rainfall within these catchments. This resulted in a decrease in the number of selected rainfall stations from 1 248 to 1 240 (Schulze *et al.*, 2010a). These 1 240 station were then used in the generation of rainfall for each of the 1 946 Quaternary catchment and then, in turn, for the 5 838 Quinary catchments (Schulze *et al.*, 2010a).

Adjustment factors were then developed by (Schulze *et al.*, 2010a) for each Quinary catchment by calculating the 12 spatial averages of all 1 arc minute (1.7 km x 1.7 km) gridded median monthly rainfall values which had been generated for South Africa by (Lynch, 2004). The ratio of each catchment's median monthly rainfall values to the respective driver station's median monthly rainfall values was calculated, thus resulting in 12 monthly adjustment factors. The adjustment factors were then applied to the daily rainfall values occurring in each Quinary in order to obtain a unique 50 year daily rainfall record for each Quinary catchment.

These rainfall values were then used by the author for those Quinary catchments making up the 10 selected study catchments, and they could then be used in validation studies of simulations of hydrological responses during 1971 -1990, as described in Sub-section 5.4.

5.2.2 A Review of the Estimation of Daily Temperature Values for Simulations During the Historical Period (1971 – 1990)

Temperature is a major driver of the hydrological cycle as it can be related to other components such as reference evaporation through complex equations, such as the Penman-Monteith equation (Schulze *et al.*, 2010e). Hence, daily temperature values are important for hydrological simulations when applying the *ACRU* hydrological model, which is described in Sub-section 5.3. In the present sub-section a brief review is given in the methods used to calculate daily temperature values for any location in South Africa for the period 1950 - 1999, from which values for the validation period 1971 – 1990 were extracted.

The estimation of daily temperature was undertaken after stringent quality control checks were completed, in order to ensure the integrity of data used (Schulze and Maharaj, 2004). The estimation of daily maximum and minimum temperature is made by using control stations at which 50 years of daily temperature had been generated (Schulze and Maharaj, 2004). In total 973 temperature stations in South Africa qualified as control stations (Schulze and Maharaj, 2004). These temperature records were then adjusted in accordance with specified lapse rates, which account for the differences in altitude between the control station and the point of interest (Schulze and Maharaj, 2004; Schulze and Kunz, 2010e). However, lapse rates are unique to particular regions and seasons, and this resulted in the division of South Africa into 12, and later 11, different lapse rate regions (Schulze *et al.*, 1997).

The determination of lapse rates for each of the lapse rate regions was completed by using information from all qualifying temperature stations within each region, and those falling into a 15 arc minute zone surrounding each of the specific regions (Schulze and Maharaj, 2004). The stations in each region were then used in the computation of unique temperature lapse rates for that specific region on a month by month basis and maximum and minimum temperatures. Differences in maximum and minimum temperature lapse rates were found to vary considerably both spatially and temporally over South Africa (Schulze and Maharaj, 2004).

To generate a 50 year daily temperature dataset at each of the 973 control stations, nine "patching" stations were selected to infill missing values, or extend the record, to the common 50 year period. The patching stations were selected based on the following criteria:

- distance from the control station, and
- altitude in relation to the control station (Schulze and Maharaj, 2004).

In order to infill missing daily temperature values, and extend records, two methods were developed by Schulze and Maharaj (2004), *viz.*

- The Mean Temperature Difference Method (MTDM), and the
- Difference in Standard Deviation Method (DSDM).

Both techniques were tested across a range of climate conditions and against observed data. However, the DSDM was selected for use in further calculations as it better accounted for similarities in temperature variance between patching and control stations (Schulze and Maharaj, 2004).

For the 50 year period 1950 – 1999 the infilled and extended records from each of the 973 selected control stations were used to compute daily minimum and maximum temperature records at a spatial resolution of 1 arc minute or (1.7 km x 1.7 km) over South Africa, Lesotho and Swaziland. These records are considered to be detailed enough for most analyses that have been, and are currently being, carried out (Schulze and Maharaj, 2004).

From the above, historical temperature records for the centroid of each of the 5 838 Quinary catchments in South Africa were supplied to the Quinary catchments database (Schulze *et al.*, 2010a). Hence, for this study the *ACRU* model could use the temperature values for 1971 - 1990, in addition to rainfall values for the same period to generate freshwater inflows into the 10 selected estuaries.

5.2.3 A Review of GCM Output Used in the Analyses Undertaken

Several types of general circulation models (GCMs) have been used in simulations of future climates under the various emission scenarios. In this study the GCMs used are all coupled atmospheric-oceanic general circulation models, i.e. AOGCMs (Lumsden *et al.*, 2010). This implies that a higher confidence level in the results is generally obtained from these models, than those obtained from separate atmospheric or oceanic general circulation models (AGCMs or OGCMs). AOGCMs using the A2 emission scenarios were used in this study for three time periods, *viz*:

- the present, from 1971 – 1990,
- the intermediate future, from 2046 – 2065, and
- the distant future from, 2081 – 2100 (Lumsden *et al.*, 2010).

The A2 emissions scenario is defined by the Intergovernmental Panel on Climate Change (IPCC), as the business as usual scenario (IPCC, 2007b; IPCC, 2007a). In this scenario, carbon emissions continue to increase at the current rate (IPCC, 2007b; IPCC, 2007a). However, despite simulations being conducted under the A2 emission scenario conditions, indications from recent GCM simulations are that the possible consequences of climate change are still being under-simulated by a significant margin (Hewitson *et al.*, 2005; IPCC, 2007b; IPCC, 2007a). One of the major weak points of GCMs is that of the coarse spatial scale of climate output, which necessitates downscaling in order to facilitate the use of this climate output in local scale research.

In order to account for local topographic effects on local climate responses, the spatially coarse climate output obtained from each of the GCMs was empirically downscaled by the Climate Systems Analysis Group (CSAG) of the University of Cape Town, to point station level. At these stations present and future daily rainfall and temperature records are provided for use as input to the *ACRU* hydrological model, in order to simulate future daily streamflows from each of the 5 838 Quinary catchments over South Africa, Lesotho and Swaziland (Lumsden *et al.*, 2010).

In order to conduct accurate simulations of future climate scenarios, an ensemble of GCMs is required (Hewitson *et al.*, 2005). This is due to the inability of the user to detect any errors occurring in the climate output from a single GCM, as no comparisons can be made, and any errors occurring, would be further amplified in simulations using this output (Hewitson *et al.*, 2005). Therefore, it is more scientifically sound to use outputs from an ensemble of GCMs for the simulation of possible impacts of climate change. For this study, output from five

GCMs was provided to BEEH by CSAG (CSAG, 2008; Lumsden *et al.*, 2010). Table 5.2.3.1 provides information as regards the five GCMs chosen for use in this project:

Table 5.2.3.1 Information on the five GCMs used in this study (Schulze *et al.*, 2010c)

Institute	**GCM**
Canadian Center for Climate Modeling and Analysis (CCCma), Canada	Name: CCCM3.1(T47) First Published: 2005
Metro France Centre National de Recherches Meteorologiques (CNRM), France	Name: CNRM-CM3 First published: 2004
Max Planck Institute for Meteorology (MPI-OM), Germany	Name: ECHAM5/MPI-OM First Published: 2005
NASA/Goddard Institute for Space Studies (GISS), USA	Name: GISS-ER First Published: 2004
Institute Pierre Simon Laplace (IPSL), France	Name: IPSL-CM4 First Published: 2005

However, it was recently highlighted that the GISS-ER GCM over-simulated rainfall over parts of South Africa. As the results obtained from this GCM had already been processed before the error was notified to the candidate, results from the GISS-ER GCM have been retained in this study for the baseline land cover runs, but not for the simulations with actual land use on the Klein estuary which were performed in 2011 (Schulze, 2010a).

Hydrological responses for present (1971 – 1990), intermediate (2046 – 2065) and distant future (2081 – 2100) climate scenarios were simulated using climate output from each of the selected GCMs. The major climate outputs such as temperature and precipitation obtained from GCMs were used as inputs to the *ACRU* model for simulations of future hydrological responses.

5.2.4 A Review of the Estimation of Daily Rainfall Values for Simulations with Future Climate Scenarios

Owing to the importance of future projections of hydrological responses, it is imperative that future climate output is available for these simulations. However, this climate output cannot be collected from stations as it is future data. Therefore it must be simulated using GCMs which operate based on assumptions regarding the future state of the earth (Hewitson *et al.*, 2005).

As a consequence of the coarse spatial scale of the output from the five selected GCMs (cf. Table 5.2.3.1) empirical downscaling to point station level was necessary for the present (1971 1990), intermediate (2046 – 2065) and distant future (2081 – 2100) time slices (Lumsden *et al.*, 2010). Then, using a similar approach as was used for the baseline historical climate study, 1 061 stations were identified from the 2 642 stations in South Africa, as suitable driver stations for use in this study. Of the 1 061 driver stations used in this study 1 023 stations were represented in the baseline climate study (Hewitson *et al.*, 2005).

The monthly adjustment factors calculated during the baseline climate study were then applied to the rainfall records generated for each of the respective future climate scenarios. This was based on the assumption that the monthly adjustment factors calculated for the baseline climate study would be equally applicable to future climate. This assumption was made in the absence of median monthly rainfall adjustments which are required for the calculation of monthly adjustment factors, across South Africa for each of the GCM derived time periods (Lumsden *et al.*, 2010).

Based on the above, simulations of future hydrological responses from each Quinary catchment in South Africa could be undertaken, thereby providing information regarding future flows. However, in addition to rainfall, input hydrological models require other climate inputs, such as solar radiation and vapour pressure deficit, both of which can be calculated using temperature. The estimation of daily temperatures for simulations with future climate scenarios is reviewed below.

5.2.5 A Review of the Estimation of Daily Temperature Values for Simulations with Future Climate Scenarios

Future climate scenarios require future climate output from GCMs; hence, minimum and maximum temperature records for the present, intermediate and distant future periods were obtained from the five selected GCMs after downscaling to temperature station level. This section will briefly describe the processing of this output.

Empirically downscaled minimum and maximum daily temperature values from stations common to the five selected GCMs were supplied by CSAG for each of the three time periods. Two stations were then selected to represent daily maximum and minimum temperatures in each Quinary catchment, based on distance and altitude differences between the Quinary catchment centroid and station (Lumsden *et al.*, 2010). The same month-by-month lapse rates for the 11 lapse rate regions in South Africa which were applied to historical minimum and maximum daily temperature values were then applied to the daily values obtained from each of these two selected temperature stations. A weighted average of the adjusted temperature values from each of the two selected stations was calculated to represent temperature in each Quinary catchment (Lumsden *et al.*, 2010). This resulted in a 20 year time series of daily minimum and maximum temperature values for each of the five selected GCM for each time period and for each of the 5 838 Quinary catchments.

Therefore, using both simulated temperature and rainfall values simulations of hydrological responses from each Quinary catchment during both simulated present and future periods could be completed (Schulze and Kunz, 2011).

5.3 Simulation of the Daily Streamflows and Sediment Yields using the *ACRU* Model

The *ACRU* hydrological modelling system was selected for use in this study, as it is a conceptual-physical multi-purpose and multi-level model based on a two horizon soil water budget capable of simulating streamflows and other hydrologically related output at a daily time step (Schulze, 1995; Schulze and Smithers, 2004).

Empirically downscaled climate output from each of the five selected GCMs was utilised as the climate input to the *ACRU* hydrological model as stated previously (Schulze and Kunz, 2011). This facilitated the simulation of streamflows and other relevant output from the hydrologically relatively homogeneous Quinary catchments in South Africa. Therefore, analyses using daily streamflows which are output from the *ACRU* model can be completed for various ecological and management studies in a particular area. The daily output from the *ACRU* simulations contains the following information relevant to this study, for each of the 5 838 Quinary catchments in South Africa:

- soil water content in the top- and sub-soil horizons,
- potential and actual transpiration from the top- and subsoil horizons,
- potential and actual evaporation from the soil surface,
- stormflows,
- groundwater recharge into the intermediate and groundwater zone,
- baseflow,
- total runoff,
- sediment yield, and
- accumulated streamflows from the Quinary catchments in question, including streamflows from all upstream Quinaries.

From the output variables listed above, future changes in streamflows into estuaries, as a consequence of climate change, may be determined. These changes could affect the functioning of estuarine ecosystems either negatively or positively. To the author’s knowledge no simulations of daily streamflows into multiple estuaries have been undertaken in South Africa. Hence, this study will provide information on a much higher temporal resolution than previous South African estuarine studies, as shown in Chapter 3, thereby enabling an improved evaluation of processes affecting estuarine functioning. The main processes relevant to this study are summarised below. The exception to this is the description of irrigation processes, which is outlined in Section 5.6.

5.3.1 A Review of the Estimation of Streamflow with the *ACRU* Model

Streamflow in the *ACRU* model is comprised of stormflow and baseflow, the computations of which will be described in this sub-section.

Stormflow, or Q_s is defined as the water either at or near the soil surface in a catchment, generated as a result of specific rainfall event (Schulze *et al.*, 2010b). The *ACRU* model utilises the following equation to calculate stormflow in mm equivalents.

$$Q_s = (P_n - I_a)^2 / (P + I_a + S) \qquad \text{for } P_n > I_a$$

where

P_n = net rainfall (mm), i.e. the measured rainfall minus any for interception losses,

I_a = initial abstractions (mm) before stormflow commences, consisting mainly of infiltration occurring before stormflow commences, and depression storage, and

S = the soil's potential maximum retention (mm), which is equated to the soil water deficit and may be used to express the wetness or dryness of the soil (Schulze, 1995).

In *ACRU* the daily multi-layer soil water budget is used to calculate the soil water deficit S. Additionally S, used in stormflow calculations, is determined from a critical soil depth, D_{sc}, which is used in soil water deficit calculations (Schulze, 1995).

Soil water content is a major determinant of initial abstractions. Hence, I_a is expressed as a coefficient, c, of S in order to eliminate estimations of both I_a and S in the stormflow equation. The coefficient c is defined as a coefficient of infiltrability into the soil and varies with rainfall intensity, tillage practices and surface cover (Schulze, 1995). These variables, in addition to others, control the time taken for the stormflow generated, from a rainfall event, to exit a catchment (Schulze, 1995).

Not all the stormflow generated from a rainfall event exits a catchment on the same day hence; a stormflow response coefficient, F_{sr}, has to be input. This controls the "lag" of stormflows and is, *inter alia*, an index of interflow (Schulze, 1995). From experimentation the value of F_{sr} has been found to be typically 0.3 for use in South Africa at a spatial scale of Quinary catchments (Kienzle *et al.*, 1997).

Baseflow is computed explicitly from recharged soil water stored in the intermediate/groundwater store. The water stored in this zone is derived from previous rainfall events occurring over the catchment. Water infiltrating the soil profile fills each soil horizon to its drained upper limit before percolating into the soil horizon below. Hence, in the version of *ACRU* used in this study, water will drain into the intermediate/groundwater store only when the drained upper limit of the deepest soil horizon is exceeded. The rate of drainage of this "excess" water into the intermediate/groundwater store is dependent on the texture class in that particular soil horizon (Schulze, 1995).

Conversely, the rate of release is of water from the groundwater store into the stream is determined by a release coefficient F_{bff}, which is dependent on the physiographic features of the catchment, such as slope, area and geology. This coefficient operates as a decay function which is input for a catchment as a single value. However, based on previous experiences with *ACRU*, F_{bff} is either enhanced, retained at the input values, or decreased internally in *ACRU*, depending on the previous day's groundwater store (Kienzle *et al.*, 1997). For all simulations in this dissertation an experimentally determined value of F_{bff} of 0.009 has been applied to all Quinary catchments in South Africa (Kienzle *et al.*, 1997).

5.3.2 A Review of the Estimation of Peak Discharge with the *ACRU* Model

Peak discharge is a variable in the estimation of sediment yield. Higher peak flows result in greater sediment yields (Williams and Berndt, 1977; Lorentz and Schulze, 1995) which, could impact negatively on the functioning of estuarine ecosystems.

For the purposes of this dissertation the simulation of peak discharge was completed using the SCS peak discharge equation, modified by Schmidt and Schulze (1995), as shown below:

$$q_p = 0.2083Q_sA/1.83L$$

where

q_p = peak discharge (m^3/s)

Q_s = stormflow depth (mm)

A = catchment area (km^2)

L = catchment lag (response) time (h)

= $(A^{0.35}MAP^{1.1})/(41.67S_{\%}^{0.3}f_{30}^{0.87})$ according to Schmidt and Schulze (1984)

MAP = mean annual precipitation (mm)

$S_{\%}$ = average catchment slope (%), and

f_{30} = 30 minute rainfall intensity (mm/h) for the 2 year return period.

Hence, the information for each Quinary catchment is:

- the 30 minute rainfall intensity for the two year return period,
- the mean annual precipitation, and
- the average catchment slope.

The information in the above list is then used as input for the peak discharge equation. The results of this equation are then, in turn, used as input to for the Modified Universal Soil Loss Equation, MUSLE (Williams, 1975).

5.3.3 A Review of the Estimation of Sediment Yield with the *ACRU* Model

In the *ACRU* model sediment yield Y_{sd} is estimated on a daily event-by-event basis when stormflow has occurred. In the MUSLE approach, the estimation of sediment yield is a function of stormflow, peak discharge, soil properties, catchment slope and cover characteristics, as well as management practices. MUSLE is utilised in the *ACRU* model in order to quantify the effects of the afore-mentioned variables on sediment yield estimations. MUSLE (Williams, 1975) is expressed as:

$$Y_{sd} = \alpha_{sy}(Q_v \text{ x } q_p)^{\beta sy}K \text{ x } LS \text{ x } C \text{ x } P$$

where

Y_{sd} = sediment yield (t) from an individual stormflow event
Q_v = stormflow volume for the event (m^3),
q_p = peak discharge for the event (m^3/s),
K = a soil erodibility factor (t h/N/ha) (dimensionless),
LS = a slope length and gradient factor (dimensionless),
C = a cover and management factor (dimensionless), and
P = a support practice factor (dimensionless).

The coefficients α_{sy} and β_{sy} are location specific and climate zone specific (Simons and Senturk, 1992). However, for the simulations undertaken in this dissertation, the default values of 8.934 for α_{sy} and 0.56 for $\beta_{sy,}$ as determined by (Williams, 1975), were assumed for sediment yield estimations. From the above equation the information required for each Quinary catchment for the estimation of sediment yield is as follows:

- The soil erodibilty factor, K: This was determined from an erosion hazard rating for all soil series found in South Africa (Schulze, 1995).
- The slope length factor LS: This is calculated using an empirical equation relating slope gradient to slope length (Schulze, 1979), the former variable having been determined using a 200 m resolution Digital Elevation Model (DEM).
- The cover factor C: In this dissertation C was determined by making use of the information in Table 5.17.8 (Smithers and Schulze, 2004).
- The support practice factor P: This is not applicable to simulations under baseline (i.e. natural vegetation) conditions; neither were any soil conservation practices apparent in the Klein catchment. Hence, the support factor is set to 1 throughout.
- The factor proportioning the quantity of sediment generated during a stormflow event and which reaches the outlet of the respective Quinary on the same day of the event, in order to account for temporary storage in the river system, is set at its default value of 0.45 (Schulze, 1995).

From the afore-going equations sediment yield can be estimated on a daily basis during each of the three given climate scenarios, which provides information important to the conservation of estuarine ecosystems in South Africa.

5.3.4 A Review of Climate Inputs for *ACRU* Streamflow Simulations

The climate input files entered into the *ACRU* hydrological modelling system consisted of downscaled daily output from each of the five selected GCMs. The climate files in this format contain the following which are relevant to this study:

- A Quinary catchment identity,
- year,
- month,
- day,
- daily rainfall in mm,
- daily maximum temperature in °C,
- daily minimum temperature in °C,
- daily Penman-Monteith reference potential evaporation equivalent in mm,

Each of the climate files entered into the *ACRU* model is unique to each Quinary catchment in each of the 10 selected study catchments. Using the output files obtained from *ACRU* model simulations, statistical analyses could be undertaken, and the possible effects of climate change on inflows into estuaries, could be determined. Since, the results of the simulations of each climate scenario from each of the GCMs are unique, as a consequence of differing climate output produced by each GCM, a number of variables must be altered in the *ACRU* menus before each simulation can be started. Table 5.3.4.1 shows the climatic variables which were altered for each simulation in order to accommodate each unique climate scenario from each GCM.

Table 5.3.4.1: Variables altered for each GCM to accommodate unique climate scenarios of these five GCMs for each of the three given time periods

Variable	***ACRU* Variable Name**	**Reason for Alteration**
Mean annual precipitation	MAP	Changes with GCM and period
Daily rainfall input	IRAINF	Changes with GCM and period
Start year and end year	IYSTRT; IYREND	Changes with period

2 year return period for the 30 minute rainfall intensity (used in sediment yield computations)	XI30	Changes with GCM and period

5.3.5 A Review of the *ACRU* Streamflow Simulations Under Baseline Land Cover Conditions

Land cover affects a number of hydrologically significant processes, such as interception loss, infiltration, evaporation from the soil surface, transpiration, runoff and sediment yield, all of which influence the quantity and quality of water in river systems (Schulze, 2005a). Therefore, it is imperative that simulations of hydrological responses, which are to reflect only the effects of climate change on streamflows into estuaries, and no other influences, be undertaken with a constant, i.e. baseline, land cover.

The *ACRU* hydrological modelling system was used in the simulation of streamflows with Acocks (1988) Veld Types representing the baseline land cover. Included in the Quinary Catchments Database are the following hydrological attributes of the 70 Acocks (1988) Veld Types (Schulze and Smithers, 2004):

- Water use coefficient, which expresses the transpiration and soil water evaporation losses to the atmosphere under conditions of sufficient soil moisture and is expressed as a fraction of atmospheric demand;
- Interception losses per rain day, which depends on the maximum canopy and above ground biomass;
- Root distribution, which is expressed as the fraction of active roots in the critical topsoil horizon compared with those in the total active soil profile;
- Coefficient of infiltrability, which expresses the abstractions of rainfall by surface detention and by initial infiltration into the soil profile before stormflow commences; and a

- Soil cover factor, which accounts for above ground and ground level biomass and which influences the evaporation of soil water from the topsoil as well as the sediment loss from that Veld Type.

The spatially dominant Acocks (1988) Veld Type was selected for each of the 5 838 Quinary catchments in South Africa (Schulze *et al.*, 2010a). Using the above information, streamflow and sediment yield responses could be simulated for each Quinary catchment, for each of the three given times periods, and for each of the five selected GCMs used in this research project.

The outputs from these simulations highlight the possible effects that changes in climate between the present, intermediate and distant future periods could have on hydrological responses into estuaries. Although the streamflow values obtained from these simulations highlight the possible effects of climate change, they do not incorporate actual upstream land use patterns, which can have a considerable impact on the hydrological responses of a catchment. In order to expose the possible effects of actual land use on hydrological responses into estuaries, an additional set of simulations was completed in a case study of the Klein catchment, as described in the next sub-section.

5.3.6 *ACRU* Streamflow Simulations Under Actual Land Use Conditions

Vegetation can have a considerable influence on the flow regime from a catchment. In the previous sub-section the vegetation in each of the simulations was held a constant for a specific Quinary catchment, while the climate inputs for each simulation were altered. In this section the methods used to simulate the possible effects of actual land use changes on hydrological responses from the Klein catchment are described. In this case study both climate and land use will change and, as the possible effects of climate change on hydrological responses have already been simulated, any further alterations to hydrological responses from the Klein catchment may then be attributed to land use changes.

The catchment and estuary of the Klein was selected for this case study for the following reasons:

- the high ecological integrity of the Klein estuary,

- relatively simple land use changes upstream of the estuary,
- perennial streamflow, and the fact that
- the estuary is a temporarily open system,
- a water balance model has been developed for this system.

In Chapter 4 information regarding the land use, climate and topography of the Klein catchment is provided in Table 4.7. However, this table provides insufficient information concerning the nine Quinaries contained within the Klein catchment.

In order to begin the simulation of streamflows into the Klein estuary, the land uses contained within each Quinary catchment had to be defined. As field based information of the land uses within the Klein catchment was unavailable, the National Land Cover, (2000) database for the catchment of the Klein, as shown in Figure 5.3.6.1, was used by the candidate in conjunction with Google Earth maps to categorize the following land uses:

- dryland cultivated area,
- natural shrubland,
- irrigated areas,
- natural thicket,
- bare rock,
- urban areas,
- wetlands, and
- dams.

It was decided that three land use categories per Quinary catchment would be adequate for the accurate simulation of land use related hydrological responses into the Klein estuary. The decision to delineate three land use categories was based, first, on the relative hydrological homogeneity of the land uses within the Klein catchment, and secondly, on the manner in which the *ACRU* model can accommodate urban areas, bare rock, and irrigation from farm dams without the necessity of additional sub-delineation. The listed land uses in the Klein catchment were then combined into three land use categories per Quinary catchment, using the combinations shown in Table 5.3.6.1. However, the conventional configuration of the *ACRU* hydrological modelling system does not allow for more than one land use per Quinary catchment. Therefore, in order to accommodate multiple land uses, each Quinary was divided into discrete Hydrological Response Units (HRUs) based on the land use combinations developed in Table 5.3.6.1.

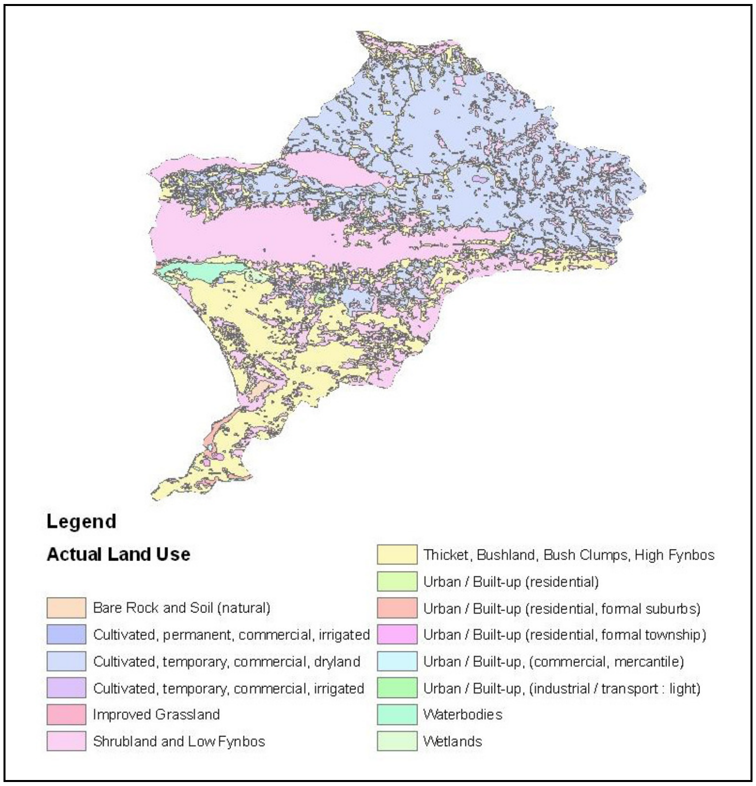


Figure 5.3.6.1: Land uses within the Klein catchment, derived from the National Land Cover (2000) database

Table 5.3.6.1: Rules for the division of each Quinary catchment in the Klein catchment

HRU Number	Land Use Categories
1	All natural vegetation, including wetlands and riparian zones
2	Dryland agriculture, plus urban areas, bare rock
3	Irrigated crops and farm dams

The areas of the nine Quinaries making up the Klein catchment, and the areas of the HRUs making up each Quinary, are given in Table 5.3.6.2. Where an HRU was not present in a

Quinary, it was assigned a nominal area of 0.01 km^2 to avoid divisions by zero in simulations.

In order to determine the single land use type to be represented by each HRU, the spatial dominances of the land uses contained within each HRU were established by the candidate. These procedures facilitated having more than one land use per Quinary catchment, thereby increasing the overall accuracy of these simulations.

Following this, the Klein catchment is now represented by 27 HRUs, each of which is treated as a discrete sub-catchment by the *ACRU* model. The flow routing of HRUs within and between Quinaries of the Klein catchment are shown in Figure 5.3.6.2, and follow the configuration rules for Quinaries developed by Schulze and Horan, (2007). The alterations made by the candidate to the baseline land cover *ACRU* menus are shown in Table 5.3.6.3, illustrating again how actual land uses can be accommodated for impacts studies.

This methodology demonstrates the possible effects that land uses, in combination with climate change, could have on hydrological responses into estuarine ecosystems. What follows now is the methodology of the manner in which the accuracy of rainfall and streamflows were validated

Table 5.3.6.2: Quinary and HRU sub-catchment areas used in *ACRU* simulations

Quinary Catchment Code	**Area of Quinary (km^2)**	**HRU Area (km^2)**		
		1	**2**	**3**
2758	14.36	14.34	0.01	0.01
2759	56.52	56.19	0.22	0.11
2760	98.78	49.86	41.71	7.21
2761	12.74	12.72	0.01	0.01
2762	175.31	70.74	103.96	0.61
2763	243.69	47.64	193.44	2.61
2764	30.95	30.93	0.01	0.01
2765	99.68	99.19	0.33	0.16
2766	256.90	217.89	37.10	1.91
Total Area (km^2)	988.93	599.50	376.79	12.64

Table 5.3.6.3: Alterations to the baseline menu in order to accommodate hydrological simulations with actual land use in the Klein catchment

Variables	***ACRU* Variable Abbreviation, where (I) designates 12 monthly values**	**Reason for Alteration from Baseline Land Cover**	**Source of Information**
Average monthly water use (crop) coefficients	CAY (I)	Changes with land use	*ACRU* Manual
Interception loss by vegetation on a monthly basis	VEGINT (I)	Changes with land use	*ACRU* Manual
Fraction of effective root system in the topsoil	ROOTA (I)	Changes with land use	*ACRU* Manual
Fraction of catchment occupied by impervious areas connected directly to streams (eg. Formal urban areas)	ADJIMP	Urban zones contain impervious areas that are directly contributing to streamflows	Calculated from the National Land Cover, (2000) database
Fraction of catchment occupied by impervious areas not	DISIMP	Urban zones contain impervious areas that are not directly	Calculated from the National Land Cover, (2000) database

Variables	*ACRU* Variable Abbreviation, where (I) designates 12 monthly values	Reason for Alteration from Baseline Land Cover	Source of Information
connected directly to streams (eg. certain areas within urban zones)		contributing to streamflows	
Storage capacity of impervious surfaces to be filled before surface runoff commences	STOIMP	Occurs on impervious surfaces	*ACRU* Manual
Coefficient of initial abstraction i.e. an index of infiltrability	COIAM (I)	All terrestrial surfaces will have a coefficient of initial abstraction	*ACRU* Manual

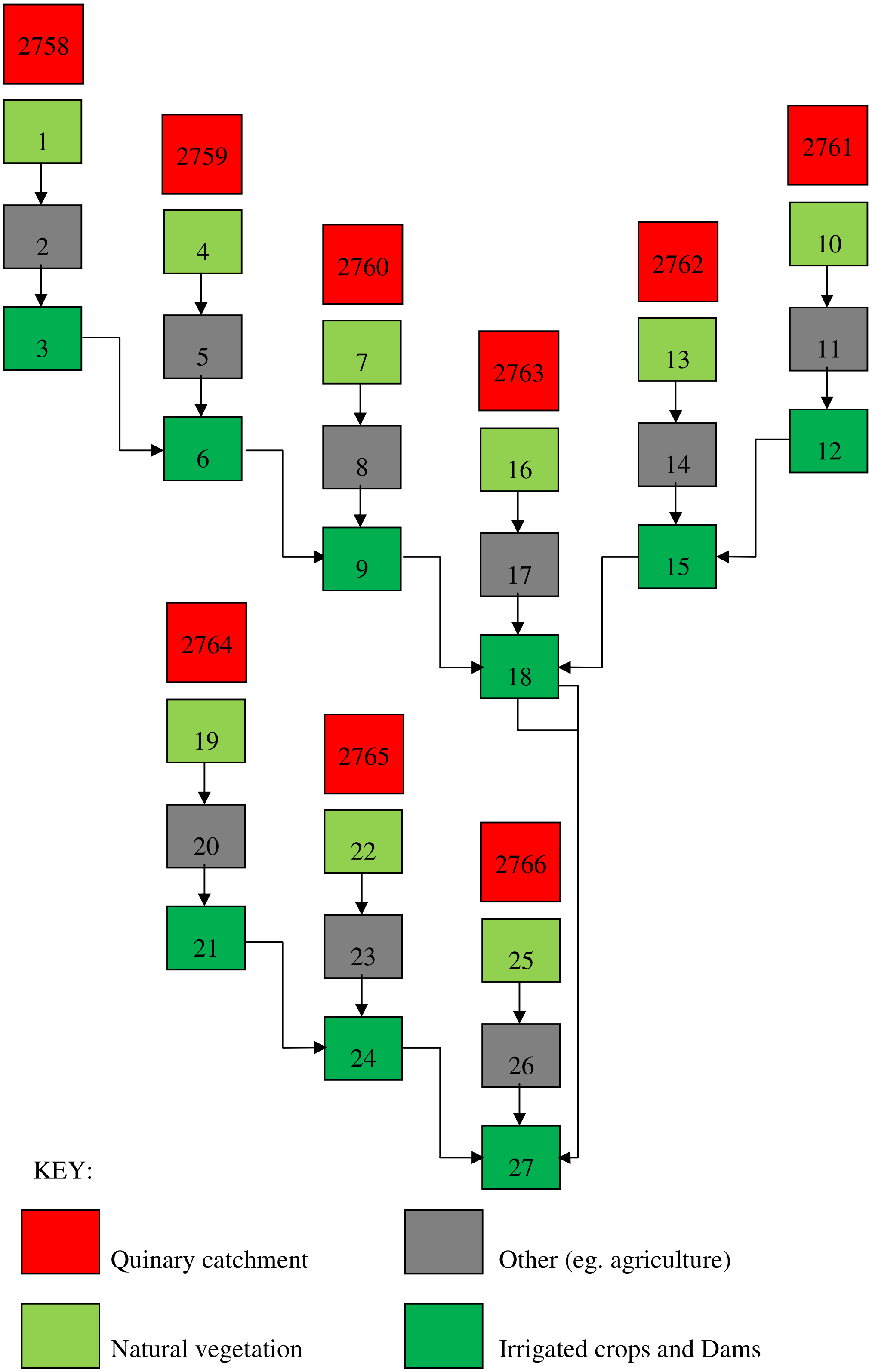


Figure 5.3.6.2: Configuration of the Klein catchment's HRUs to accommodate influences of multiple land uses per Quinary catchment, as per Table 5.3.6.1

5.4 Validation of Climate and Streamflow Simulations

Simulations using the five selected atmospheric-oceanic general circulation models (AOGCMs) have resulted in some of the most comprehensive projections of future climate scenarios to date. As stated previously, a high level of confidence in GCM output is desired, as the climate output obtained from GCMs is used as climate input for the simulation of streamflows. If errors exist in this climate input, significant amplification of these errors could occur during hydrological simulations, thereby reducing the confidence when hydrological impact studies are undertaken. This may have far reaching implications, especially with respect to management strategies, which are frequently, at least in part, based on the output of computer simulations. Therefore, a validation study using the results of the five selected GCMs was undertaken, firstly by a relative error analysis, as and secondly by regression analysis. The results graphs for the following sub-sections indicate 100 % as showing no change. The reason for this is due to the change in streamflow and sediment yield values originally being calculated in ratio values. These ratio values were then converted to percentage values; hence a ratio value of one will give a value of 100 %, thus indicating no change. Therefore, a ratio value of 1.2 will give a percentage value of 120, indicating an increase of 20 % from the historical values. This is illustrated by the graphs pertaining to the following sub-sections.

5.4.1 Data Preparation for a Relative Error Analysis: Example Using Rainfall

This validation study is a comparison between a set of climate outputs from the GCM derived present (1971 – 1990) and outputs from the same time period of historical data. This comparison was made for the most downstream Quinary of each of the 10 selected catchments. From this validation study the accuracy of outputs from GCM simulations, and those models making use of these GCM outputs, may be ascertained.

Owing to the significant quantity of daily output, and the extended period of time that would have been required to sort through it manually, a macro was written by the candidate which processed the daily rainfall output in the following sequence:

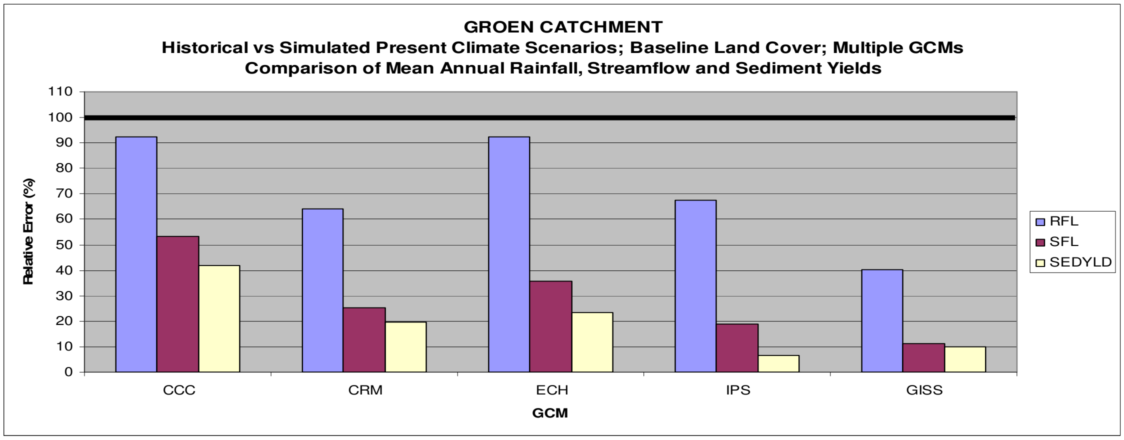
1. The period 1971 to 1990 was cropped from the historical period 1950 to 1999.
2. The daily rainfall values were seperated into monthly aggregates, also taking into account leap years.
3. The daily rainfall values occurring during each month were then summed to obtain a monthly rainfall value.
4. Rainfall values for each individual month were then summed for the 20 year period.
5. The sorted rainfall outputs from each of the five GCMs for the present period were then tabulated with rainfall output cropped from the historical period.
6. This facilitated a graph of the historical vs simulated accumulated rainfall.

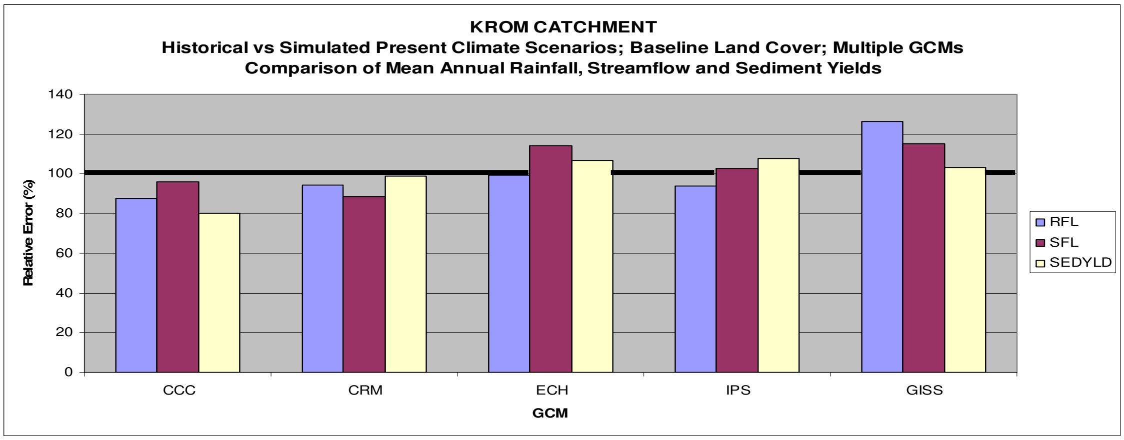
A similar procedure for the relative error analysis was repeated in order to compute the accumulated streamflow and sediment yield values at the exits of the 10 selected catchments for the same period, the results of which are shown in the following sub-section.

5.4.2 Validation of Rainfall, Streamflow and Sediment Yield, by Relative Error Analysis

A comparison between historical and simulated present rainfall, streamflow and sediment yield values was undertaken for each of the 10 selected catchments. In this sub-section, Figure 5.4.2.2 highlights the accuracy of rainfall, streamflow sediment yield outputs from three of the 10 selected catchments. These three catchments cover three major climatic regions, with the Groen representing the winter rainfall region, the Krom the all year and the Thukela the summer rainfall region. Results from the other seven catchments are given in Appendix A. Figure 5.4.2.2 illustrates the tendency of four of the five GCMs to under-estimate rainfall, the exception being the GISS GCM which is known to over-estimate rainfall in the eastern regions of South Africa (Schulze, 2010a). These errors, expressed as ratios and then converted to percentage values, illustrated in rainfall estimations are amplified in higher order hydrological responses, such as streamflow (cf. also the results in Appendix A). These errors are still further amplified by the estimation of sediment yield, the reason being that both peak discharge and stormflows are utilised in the MUSLE calculation of event-by-event sediment yield (cf. Sub-section 5.3.3). In addition, it is illustrated that certain GCMs offer more accurate simulations in different regions.

Based on this validation for each of the 10 selected catchments it was assumed that simulations of future periods, i.e. for the intermediate (2046 – 2065) and distant (2081 – 2100) future, would have similar levels of accuracy. From this validation study it is illustrated that the output from most GCMs is reasonably accurate. In order to confirm that this is the case for higher order hydrological variables, an additional validation of streamflow by regression analysis has been undertaken and is described in the following section.





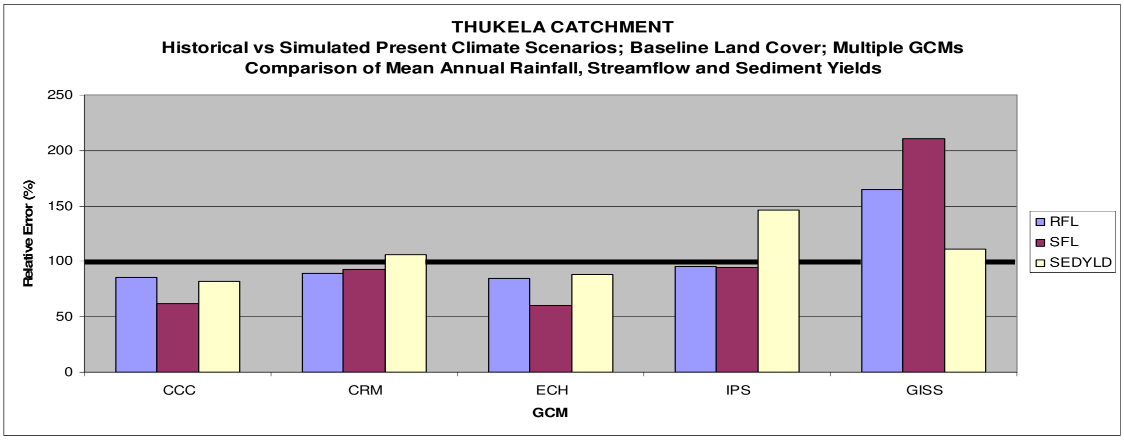


Figure 5.4.2.2: Relative errors (%), in GCM derived rainfall, streamflow and sediment yield for selected estuaries in the winter rainfall region (Groen; semi-arid), the all year rainfall region (Krom; sub-humid) and the summer rainfall region (Thukela, sub-humid), with the values derived from the historical climate data for the same period used as the reference

5.4.3 Validation of Streamflows by Regression Analysis

The validation of streamflow output at the exit Quinary of each of the 10 selected catchments is imperative in estuary studies as it demonstrates firstly, the integrity and accuracy of the simulations undertaken with output from GCMs and secondly, the value of the results for management decisions.

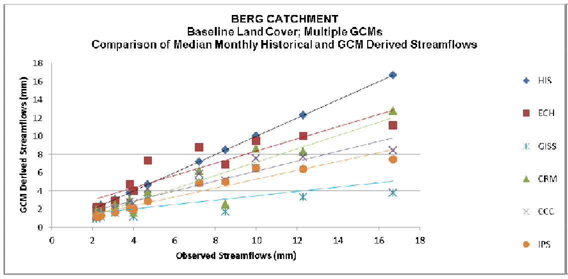
The median monthly streamflow values for the exit Quinary of each of the 10 selected catchments were obtained for both the GCM derived present period and the same historical period. Median values mute the effects of extreme outlier values. Using these monthly streamflow values, scatter plots were created and regressions and the equations for each of the five GCMs for each of the 10 selected catchments were derived, as shown in Figure 5.4.3.1.

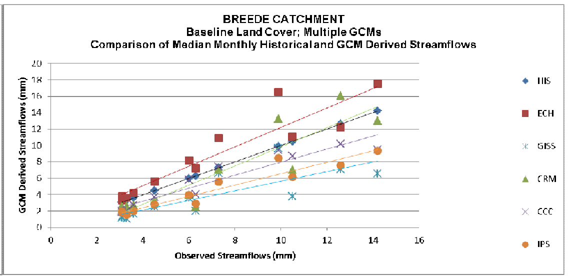
The scatter plots making up this Figure 5.4.3.1 illustrate that:

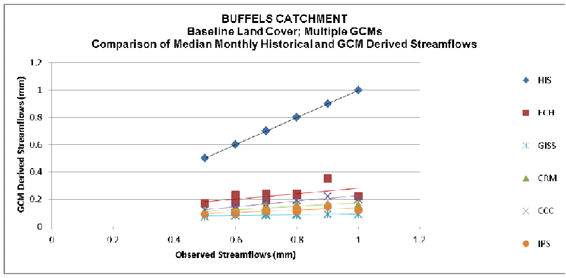
- streamflows are all under-simulated in the western regions (Berg, Buffels, Groen, Olifants),

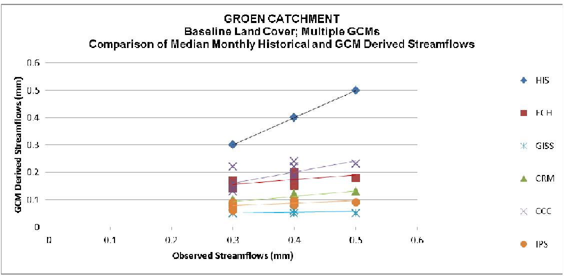
- streamflows are both under- and over-simulated in the southern regions (Breede, Klein, Krom), and
- streamflows are over-simulated in the eastern regions (Mdloti, Mlalazi, Thukela).

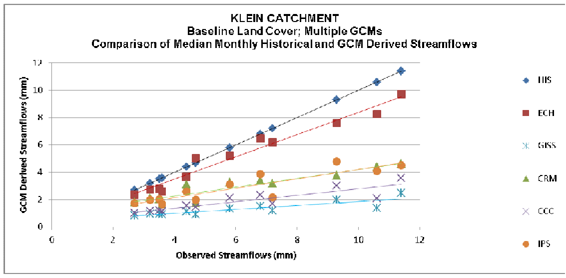
Additionally, these figures illustrate the signifcant over-simulation of streamflows when climate output from the GISS GCM is used in the eastern catchment where it is known to over-simulate rainfall (eg. Mdloti, Mlalazi and Thukela). As a consequence of this over-simulation, GISS was excluded from the more detailed simulations of the Klein catchment.

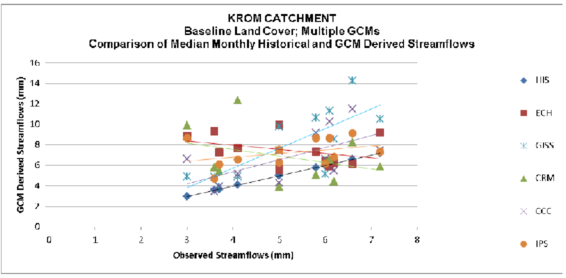












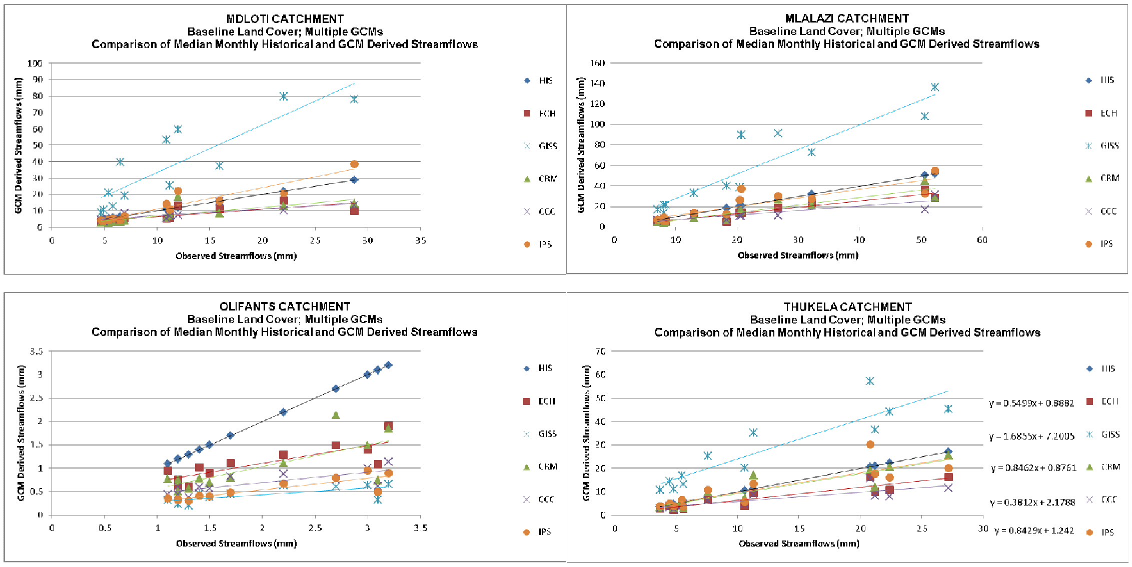


Figure 5.4.3.1: Scatter plots of streamflows at the exit Quinaries of the 10 selected catchments, with derived using outputs from 5 GCMs for the present period (1971 – 1990) and output using historical data for the same period

This validation study shows that the GCM output when used to generate streamflows show marked regional variation in accuracy. However, as the impact assessments in estuarine inflows in this study are all ratio based, many of the apparent errors will be self-correcting if it is assumed that GCM errors for the present period are transferred into future scenarios. Whether or not that is so remains untested.

5.5 Statistical Analysis of Streamflows

Streamflow output from each of the 10 catchments is obtained from the *ACRU* model in two forms:

- the frequency table, which shows monthly statistical values, and the
- daily streamflow output.

From the above output the possible effects of future climate changes on streamflow into estuaries can be assessed through changes in:

- mean flows,

- median flows
- 1 in 10 year annual low flows (10%),
- 1 in 10 year annual high flows (90%),
- pulses of high flow
- mean annual sediment yield, and
- breaching analysis.

5.5.1 Pulse Analysis

A pulse is defined as a marked increase in flow over a brief period of time. However, because a daily time step model was used in this research, it was decided that since the 10 selected catchments differ significantly in size, a pulse would be defined as an increase in freshwater flows into estuaries of ≥ 10 % from one day to the following day. Based on experimenting with different percentage increases and in consultation with estuary experts a ≥ 10 % increase over one day is considered realistic, particularly given the large area of some of the catchments. Furthermore, as a consequence of the vastly different flow magnitudes into each of the ten selected estuaries, a percentage value, rather than a volumetric value was used to define the magnitude of a pulse. Additionally, the highly variable nature of streamflow volumes during each season, and between seasons, would have resulted in constantly varying volumetric pulse values. Hence, a small volumetric shock during the low flow season may be a large percentage (i.e. relative) shock to the system at that time. Conversely, a volumetrically large shock during the high flow season may be a small shock in relative terms.

The macro written to process daily streamflow values obtained from each simulation, operated in the following sequence:

1. Sort daily streamflow values into monthly packages, considering also leap years.
2. The difference between each daily streamflow value in a given month was calculated, and from these values the percentage differences between each successive daily streamflow value was computed by using the following equation:

$$\frac{x-(x-1)}{(x-1)}\times 100$$

where x = daily flow.

3. All positive percentage differences between successive daily streamflows of ≥ 10 % were recognised as pulses, and were assigned a value of 1.
4. Similarly, all percentage differences, between successive daily streamflow values, of ≤ 10 % were not recognised as pulses, and were therefore assigned a value of zero.
5. The number of pulses occurring during each month and year was summed.
6. The median number of pulses occurring in each month was then calculated using pulse values obtained from hydrological simulations, which used climate input from each of the five selected GCMs, i.e. the median pulse value of the five selected GCMs was used.
7. The median number of pulses from multiple GCMs were then graphed.

The results of this analysis show median the number pulses occurring during each of the three GCM derived time periods and for each of the 10 selected catchments, thus showing changes that are projected to occur as a consequence of climate change in each catchment. If a change is apparent then this may indicate a change in the occurrence of runoff producing rainfall events above a critical threshold. An example of such a pulse analysis is shown in Figure 5.5.1.1, indicating that changes in pulses could affect the functioning of estuarine ecosystems.

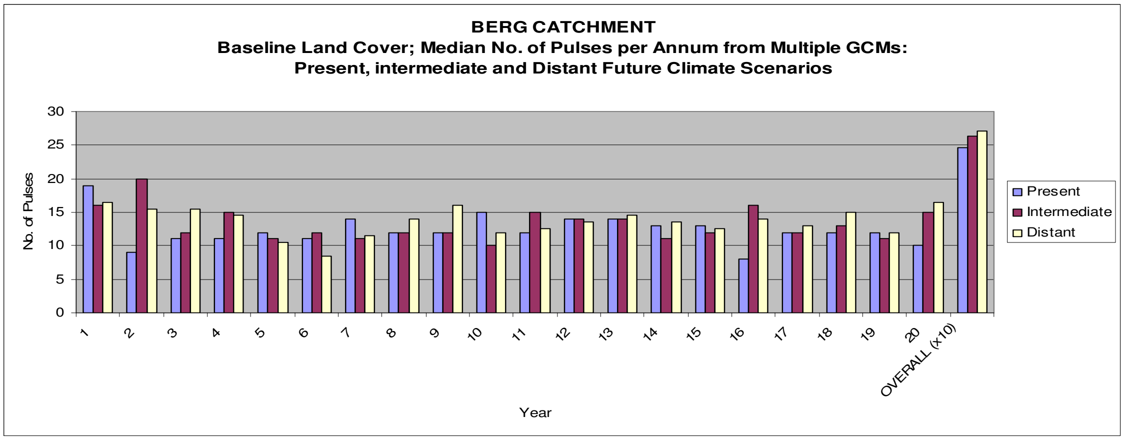


Figure 5.5.1.1: Demonstration of outputs of median annual pulses after macro processing

In order to determine the possible effects of changes in the seasonality of critical runoff producing rainfall events on streamflows into estuaries, the median monthly number of pulses was calculated as follows:

1. Calculate the number of pulses occurring during each seperate month of the 20 year period.
2. The median number of pulses for each month in the 20 year period is computed, eg. the median of January 1971, 1972 through to January 1990 must be calculated.

From this information graphs were created which highlight changes in numbers and magnitudes of median monthly pulses occurring, as shown in Figure 5.5.1.2

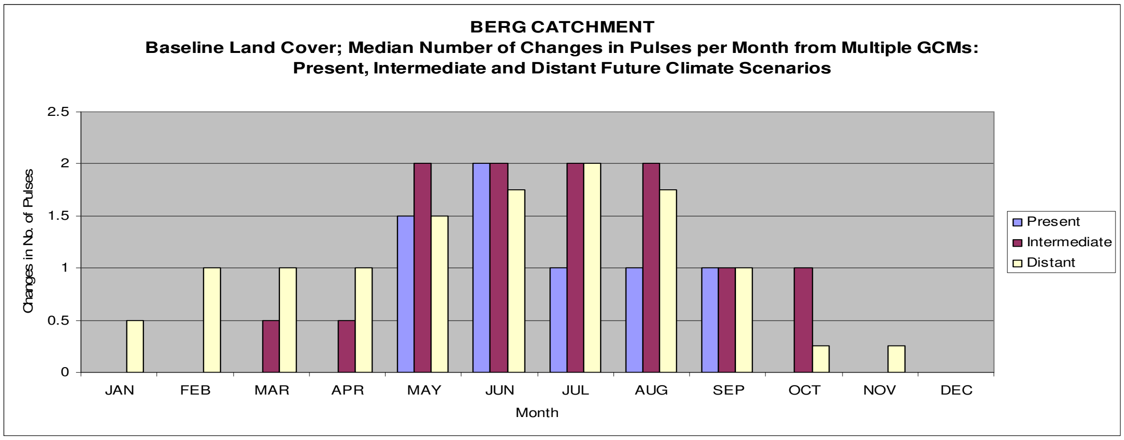


Figure 5.5.1.2: Demonstration of outputs of median annual pulses after macro processing

Hence, the possible effects of climate change on estuarine ecosystems in South Africa, through changes in the number of pulses which impact upon sedimentation and chemistry within these systems, may be determined. Interpretations of these graphs are provided in the results Chapter (Chapter 6).

5.5.2 Analysis of Information from Frequency Tables

Part of the output from the *ACRU* model is in the form of frequency tables which give monthly streamflow statistics for each hydrological simulation completed. From these frequency tables an overview of the monthly and annual streamflow regimes is provided for each of the 10 selected catchments and for each of the three GCM derived time periods. These frequency tables display, *inter alia*, the following monthly streamflow statistics:

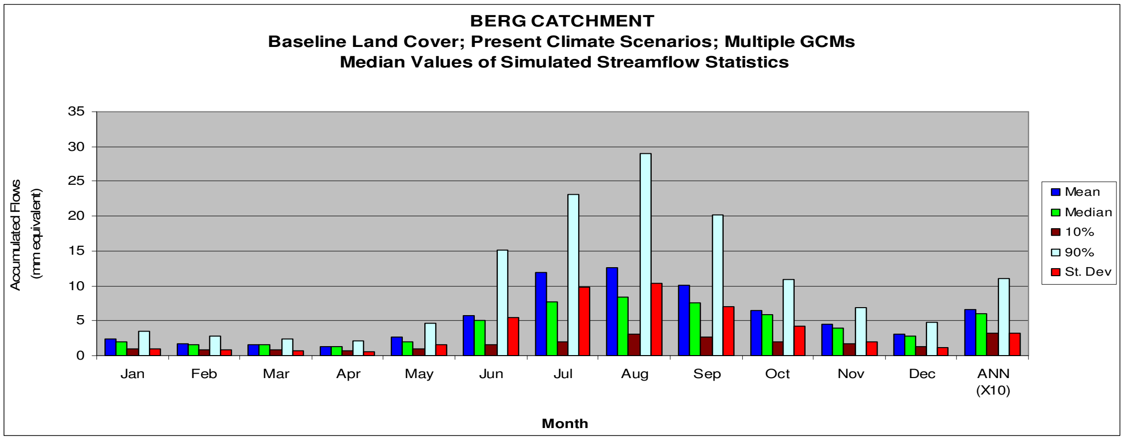
- the mean monthly streamflow,
- the median monthly streamflow,
- the standard deviation of the monthly streamflow,
- the 1 in 10 year high flow (90th percentile), and
- the 1 in 10 year low flow (10th percentile).

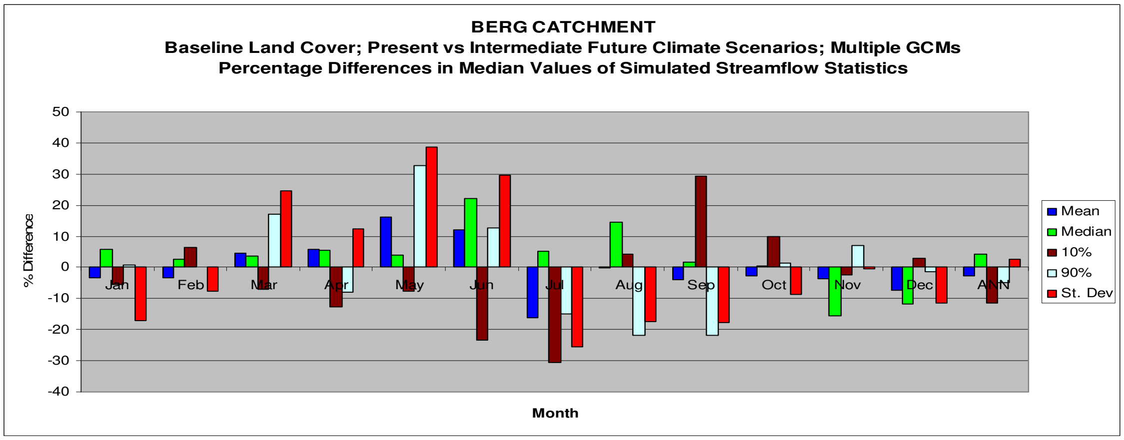
Using the monthly values from these tables, comparisons between flow regimes during the present, intermediate and distant future time periods have been undertaken. As with previous analyses, there is a considerable quantity of output to be processed. This is due to the completion of separate hydrological simulations for each of the 10 selected catchments, for each time period, and using climate output from each of the five selected GCMs. In order to process this information, the following computations were undertaken:

1. The median of the month-by-month streamflow statistics from the output of the five GCMs was determined for each of the 10 selected catchments for the present, intermediate and distant future time periods.
2. The percentage differences of monthly statistics between the intermediate and present, and the present and distant future time periods was computed for each of the 10 selected catchments and each of the five selected GCMs.
3. The median monthly values from the five GCMs were then calculated from the percentage values above.
4. The results were then graphed, with the example from one catchment shown in Figures 5.5.2.1a, b and c.

From these graphs changes in the streamflow regimes occurring between present and future time periods may be determined, using the present time period as the point of reference. A percentage value of zero indicates no change in streamflow regime, while a positive percentage value indicates an increase in streamflow into the future. The magnitude of increases in future streamflows can be calculated via the multiplication of actual flows values with the percentage increase. The same method applies to decreases in streamflow.

The comparison of these monthly median values will provide useful insight regarding the possible effects of climate change on streamflow regimes into estuaries. This, in turn, could aid conservation strategies regarding estuarine ecosystems, especially when abstractions for irrigation are accounted for. Results and interpretations of the above analyses are given in Chapter 6.





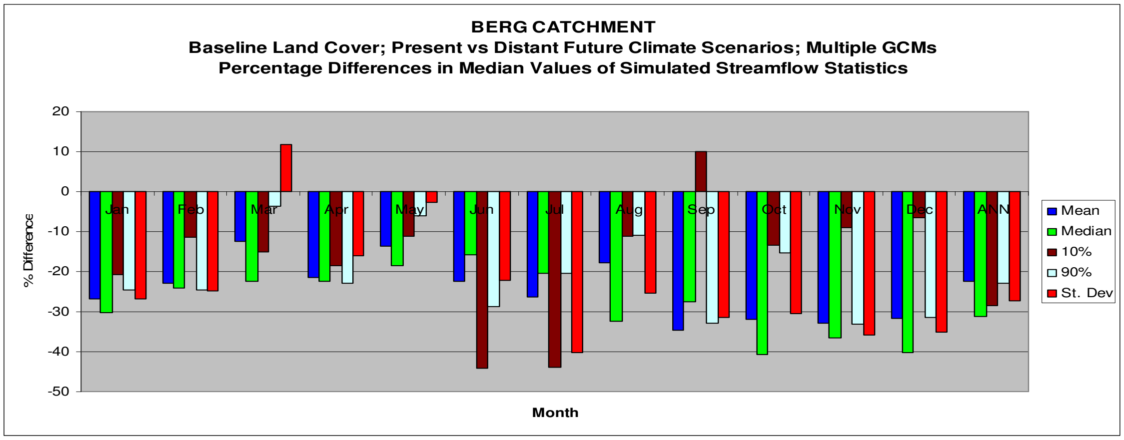


Figure 5.5.2.1: Flow regime from the Berg catchment into its estuary during the present climate period (top graph), providing a point of reference for simulations of future periods, and percentage changes in flow statistics into the intermediate (middle graph) and distant future (bottom graph) climate scenarios, derived from multiple GCMs

5.6 *ACRU* Streamflow Simulations under Actual Land Use Conditions, Including Irrigated Areas

The Klein catchment was selected for a detailed study of upstream changes in land uses on freshwater inflows into the estuary (cf. Sub-section 5.3.6). A considerable area of the Klein catchment consists of irrigated commercial crops, mainly winter wheat. The impacts of this irrigation could detrimentally affect daily streamflows into the Klein estuarine ecosystem. This is due to stored streamflows being utilised from dams in the Klein river system as a consequence of abstractions, and higher evapotranspiration from the irrigated fields. In this section the method for the assessment of the possible effects of irrigation on freshwater inflows into the Klein estuary is described.

Irrigation, where it occurs as stated in Sub-section 5.3.6, is configured to be simulated in the furthest downstream HRU of each Quinary catchment, the HRU into which crops and dams are also placed. Therefore, in order to determine the quantity of water lost from the river system, and pumped onto crops, an irrigation schedule must be selected from a number of options offered by the *ACRU* hydrological modelling system. In those HRUs with dams used for irrigation, the schedule in *ACRU* is set to a demand mode schedule, i.e. irrigation, and so also abstractions, begin when the soil water content in the zone of maximum rooting activity falls below half the plant available water. Irrigation fills the soil profile to its drained upper limit, i.e. to its field capacity. However, the irrigation schedule will differ if the water source is not from dams, but is pumped directly from a river.

Quinary catchments, such as 2764 and 2765, containing irrigated areas, but no dams, will then irrigate a fixed quantity of water in a fixed irrigation cycle, both determined by the user. For the purposes of this project, this cycle was set to deliver a net irrigation of 28 mm per 7 day cycle, in order to meet crop water requirements. However, if a daily rainfall event of 15 mm or more occurs during the irrigation cycle, the cycle resets itself.

Included in these irrigation simulations are water losses associated with different irrigation systems. In this region it was assumed that centre pivots were used. This assumption was based on images obtained from Google Earth, which show the circular irrigation pattern that is characteristic of centre pivot systems. Water losses from centre pivot systems are as a consequence of either:

- Conveyance losses .from water source to field, and
- Spray evaporation and wind drift losses which occur during the irrigation process.

In the Klein catchment the actual percentages of water losses is unknown, and hence default values of 10% were used for both conveyance and spray evaporation losses. For the irrigated crops interception losses of 1.5 mm per irrigation application were assumed. All water abstracted from the system is accounted for in these simulations.

Results from these simulations may be used to determine the effects of irrigation on present and future streamflows at daily, monthly and annual time steps. Hence, the possible effects of irrigation on estuarine ecosystems under future climate scenarios may be determined, especially during extreme droughts.

All alterations made to the baseline menus for each of the HRUs in order to accommodate hydrological simulations including irrigation and dams are given in Table 5.6.1, with reason given for each assumption made.

Table 5.6.1: Alterations made to the baseline menus in order to accommodate hydrological simulations including irrigation and dams

Variables	***ACRU* Variable Abbreviation, where (I) designates 12 monthly values**	**Reason for Alteration from Baseline Land Cover**	**Assumptions Made**
Option to specify if an irrigation simulation is to be performed	IRRIGN	Changed in accordance with the introduction of irrigation to this system	Set at 1 (1 = Yes)
Area (ha) to be irrigated in a given month	HAIRR (I = 1, 12)	Changed in accordance with the introduction of irrigation to this system	See Table 5.3.6.2 for irrigated areas
Soil water content (m/m) at permanent wilting point for soil being irrigated	WPIR	Changed in accordance with the introduction of irrigation to this system	Separate values were determined based on the soil texture in that area ranging between 0.068 and 0.159

Variables	***ACRU* Variable Abbreviation, where (I) designates 12 monthly values**	**Reason for Alteration from Baseline Land Cover**	**Assumptions Made**
Soil water content (m/m) at drained upper limit for soil being irrigated	FCIR	Changed in accordance with the introduction of irrigation to this system	Separate values were determined based on the soil texture in that area ranging between 0.143 and 0.254
Soil water content at saturation for soil being irrigated	POIR	Changed in accordance with the introduction of irrigation to this system	Because tillage practices changing the soil's bulk density, POIR is enhanced by a factor of 1.12 as per *ACRU* user Manual
Interception loss (mm/irrigation) for the crop under irrigation	DINTIR	Changed in accordance with the introduction of irrigation to this system	Interception loss of 1.5 mm/irrigation application user for winter wheat, as per *ACRU* User Manual

Variables	*ACRU* Variable Abbreviation, where (I) designates 12 monthly values	Reason for Alteration from Baseline Land Cover	Assumptions Made
Potential maximum rooting depth (m)for the crop irrigated	RDMAX	Changed in accordance with the introduction of irrigation to this system	Sum of thicknesses of topsoil and subsoil input
Crop coefficient of the irrigated crop when rooting depth reaches its maximum	CCOV	Changed in accordance with the introduction of irrigation to this system	Set at 0.7, i.e. the default for winter wheat as per *ACRU* User Manual
Crop coefficient of the irrigated crop when ground cover reaches its maximum	CCMAX	Changed in accordance with the introduction of irrigation to this system	Set at 0.7, i.e. the default values for winter wheat, as per *ACRU* User Manual
Mode of irrigation scheduling, input on a monthly basis	ISCHED (I = 1, 12)	Changed in accordance with the introduction of irrigation to this system	ISCHED = 1, i.e. demand irrigation from dams. ISCHED = 2, i.e. fixed amount/fixed cycle from rivers

Variables	***ACRU* Variable Abbreviation, where (I) designates 12 monthly values**	**Reason for Alteration from Baseline Land Cover**	**Assumptions Made**
Amount of irrigation water per application (mm)	IRAMT	Changed in accordance with the introduction of irrigation to this system	28 mm net irrigation per application, i.e. 4 mm per day
Irrigation cycle length in days	IRCYC	Changed in accordance with the introduction of irrigation to this system	7 day cycle assumed
Threshold amount of rainfall (mm) to be exceeded on a given day for irrigation cycle to be interrupted	RLIM	Changed in accordance with the introduction of irrigation to this system	15 mm per rainday
Fraction of irrigation water lost in conveyance from source to point of application	CONLOS	Changed in accordance with the introduction of irrigation to this system	0.1, i.e. the default for an efficient conveyance system

Variables	***ACRU* Variable Abbreviation, where (I) designates 12 monthly values**	**Reason for Alteration from Baseline Land Cover**	**Assumptions Made**
Fraction of spray evaporation and wind drift losses	EVWIN	Changed in accordance with the introduction of irrigation to this system	0.1, i.e. the default for centre pivots, as per *ACRU* User Manual
Source of water for irrigation purposes	IRRAPL	Changed in accordance with the introduction of irrigation to this system	IRRAPL = 1 when irrigating from a dam IRRAPL = 2, when irrigating from a river
Variable accounting for irrigation return flows into a dam, depending on whether irrigation is occurring upstream or downstream of a dam	UPSTIR	Changed in accordance with the introduction of irrigation from dams to this system	UPSTIR = 1, i.e. irrigation is assumed to be upstream of dam the, with return flows re-entering the dam

Variables	***ACRU* Variable Abbreviation, where (I) designates 12 monthly values**	**Reason for Alteration from Baseline Land Cover**	**Assumptions Made**
Option to request an analysis of reservoir yield	RESYLD	Changed in accordance with the introduction of dams to this system	RESYLD = 1, where dams are present
Full supply capacity of the dam (m^3) on which reservoir yield analysis is to be carried out	DAMCAP	Changed in accordance with the introduction of dams to this system	DAMCAP varies from case to case, computed from an equation using surface area as input, as per *ACRU* User Manual
Surface area (ha) of the dam at full capacity	SURFAR	Changed in accordance with the introduction of dams to this system	SURFAR varies from cases to case, determined from National Land Cover (2000)
Specifies if a surface area: storage volume relationship exists	ARCAP	Changed in accordance with the introduction of dams to this system	User determined ARCAP = 6, which calls up a general equation for dams irrespective of shape

Variables	***ACRU* Variable Abbreviation, where (I) designates 12 monthly values**	**Reason for Alteration from Baseline Land Cover**	**Assumptions Made**
Legal flows released (m^3/day)	QNORM	Changed in accordance with the introduction of dams to this system	Set to zero as no legal flow releases are assumed for small farm dams
Seepage through wall base (m^3/day)	SEEP	Changed in accordance with the introduction of dams to this system	SEEP is set to 1/1500 of full supply capacity per day, as per default in *ACRU* User Manual
Initial reservoir storage at the start of the simulation	PERDAM	Changed in accordance with the introduction of dams to this system	Assumed to be 50 %, i.e. dam is half full at commencement of simulation
Unusable portion of the reservoir, i.e. so-called 'dead storage'	DEDSTO	Changed in accordance with the introduction of dams to this system	10 %, i.e. the default used in South Africa

Variables	***ACRU* Variable Abbreviation, where (I) designates 12 monthly values**	**Reason for Alteration from Baseline Land Cover**	**Assumptions Made**
Monthly coefficient to adjust A-pan evaporation to an extensive water body (i.e. dam)	PANDAM	Changed in accordance with the introduction of agriculture to this system	Varies by month, with values given in the *ACRU* User Manual

5.7 Sediment Yield Analysis

Two important components of freshwater flows into estuarine ecosystems are the sediment and nutrient inputs. Although marine sediment contributions may be considerable in many estuarine systems, this dissertation is focused on freshwater inflows, and hence on sediment inputs from the catchment upstream of the estuary. Nutrient inputs were not considered.

Mean annual sediment yield values were obtained from daily estimates of sediment yields computed by the *ACRU* model (cf. Sub-section 5.3.3) for each Quinary in each of the 10 selected catchments in which baseline land cover was represented by Acocks' (1988) Veld Types. Only in the Klein catchment were sediment yields also computed for actual land uses. From these various results the differences in sediment yields between each time period and each GCM could be determined. Hence, possible effects of climate change on future sediment yields could be assessed.

In order to evaluate the effects of actual land use on sediment yields in the Klein catchment, land uses were determined from the National Land Cover (2000) database. In addition to the other changes made to the *ACRU* menus, as described in Sub-Section 5.6, adjustments to the cover factor, COVER (I), were made in these *ACRU* menus. This variable is one of the most sensitive in the Modified Universal Soil Loss Equation (MUSLE) which is embedded in *ACRU*, and represents the combined effects of surface cover and canopy cover characteristics. Simulations were completed with the monthly cover factors ranging from 0.36 to 0.01. These values were obtained from Table 5.17.8 in the *ACRU* User Manual, which provides cover factor values that may be applied to a range of land uses. The completed simulations provided the daily sediment yield from each of the HRUs in the Klein catchment.

The configuration of the *ACRU* hydrological modelling system does, at this stage, not compute the accumulation of sediments at the exit of the catchment with multiple sub-catchments. Instead, daily sediment yield values are given at the exit of each Quinary catchment, and do not include sediment yields from upstream Quinaries. Hence, in this project, daily sediment yield values were initially obtained for each HRU representing the

Klein catchment. These values were then summed, and the total quantity of sediment entering the Klein estuary on a daily basis was obtained. This approach assumes that no deposition or re-intrainment of sediments takes place in the channel. From these daily sediment values the mean annual sediment yield at the exit of a catchment could be calculated and graphed for each GCM derived time period and, thereby facilitating a comparison between results obtained from simulations using Acocks' (1988) Veld Types to represent baseline land cover, and the NLC (2000) database to represent actual land uses in the Klein catchment.

5.8 Estuarine Water Balance Model

Owing to the importance of freshwater inflows, into estuaries which, *inter alia*, control the breaching of berms at the exit of estuaries, it is imperative that the water balance of estuarine ecosystems be modelled. In this dissertation the water balance of the Klein estuary is modelled in order to demonstrate the possible effects of climate and land use changes on breaching events in this system.

Irrigation practices in the Klein catchment are the dominant cause of differences in streamflow between natural vegetation and actual land use (cf. Chapter 6.2). Median streamflow values from simulations in which irrigation was both included and excluded, were compared in order to show the possible effects that irrigated commercial agriculture may have on flows into estuaries, for each climate scenario. In order to make this comparison, a water balance model which was obtained by personal communication from an estuarine specialist (Van Niekerk, 2010b). Figure 5.8.1 illustrates the processes considered in a complex water balance model when all variables are taken into account. However, as a result of unavailability of certain data, the complex model was simplified by the candidate in consultation with the estuarine specialist.

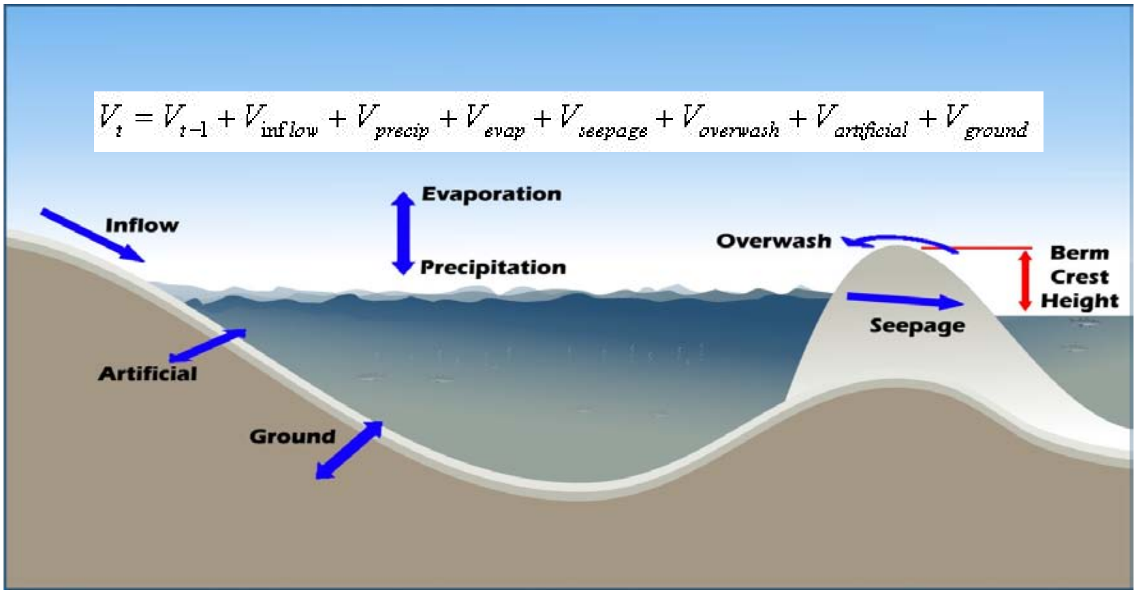


Figure 5.8.1: A schematic the inputs and losses affecting an estuarine water balance (Van Niekerk, 2010b)

The following equation was substituted for the more complex water balance model in Figure 5.8.1, while still maintaining the integrity of the output:

$$V_t = V_{t-1} + V_{inflow} + V_{precip} - V_{evap}$$

V_t = estuarine volume at end of day t (m^3),
V_{t-1} = estuarine volume of the previous day (m^3),
V_{inflow} = volume of inflow on day t (m^3),
V_{precip} = volume of precipitation falling directly onto the surface of the estuary (m^3), and
V_{evap} = volume of water lost as a result of evaporation from the surface of the estuary (m^3).

At the time of commencement of the simulation, the volume of the Klein estuary was set at 4 000 000 m^3 (Van Niekerk, 2010b). However, as a result of the variability of sediment deposits, which results in highly variable berm heights across the mouth of the estuary, considerable uncertainty exists regarding the volume of water in the estuary when it breaches. After consultation with Van Niekerk, (2010b), the volume of water in the Klein estuary at breaching was set at 24 000 000 m^3, or slightly less than that if the inflows on a given day, added to the volume of the previous day, would have exceeded the 24 000 000 m^3 volume. The 24 000 000 m^3 is the equivalent of a build up of water behind the berm of approximately 2.3 m above sea level and when the estuary surface area is approximately 11 km^2. Upon the breaching of the berm, the estuary was set to lose 20 000 000 m^3 over a 24 hour period, as would have occurred in reality, hence resulting in severe scouring of the mouth. This, in turn, prolongs the mouth's open state after breaching. As a result of continued entrainment, the open state of the mouth could be maintained for a considerable period of time. In the case of the Klein estuary the mouth remains open for approximately 150 days, or five months, before sediment deposits from tidal action and freshwater inputs result in mouth closure (Van Niekerk, 2010b). During this period the estuary will begin to fill, but the expert specified that the model be set so that the system would reach 4 000 000 m^3, and the water volume would remain static at this level for the entire five month period.

Additionally, a relationship between the volume and surface area of the Klein estuary was provided by Van Niekerk, (2010b), thereby allowing the calculation of the estuary's area for a certain volume, or vice versa (Figure 5.8.2). Hence, the calculation of the volume of water lost and gained, via evaporation and precipitation respectively, could be completed using the equations given below for the volume lost by evaporation lost from the surface of the estuary.

$$V_{evap} = K_{cm} \text{ x } E_r \text{ x } A_{est}$$

V_{evap} = volume of water lost by evaporation from the estuary on a given day (m^3),

K_{cm} = monthly pan adjustment coefficient for a particular region in South Africa, in this case Zone 1,

E_r = evaporation rate on a given day (mm), computed with the Penman-Monteith equation,

A_{est} = surface are of the estuary (m^3) on a given day.

The volume gained by the estuary is given as:

$$V_{input} = Ppt \text{ x } A_{est} + V_{inflow}$$

V_{input} = volume of water gained by the estuary on a given day (m^3),

Ppt = precipitation occurring over the surface of the estuary (mm)

A_{est} = surface area of the estuary on a given day (m^2),

V_{inflow} = volume of streamflow entering the estuary on a given day (m^3).

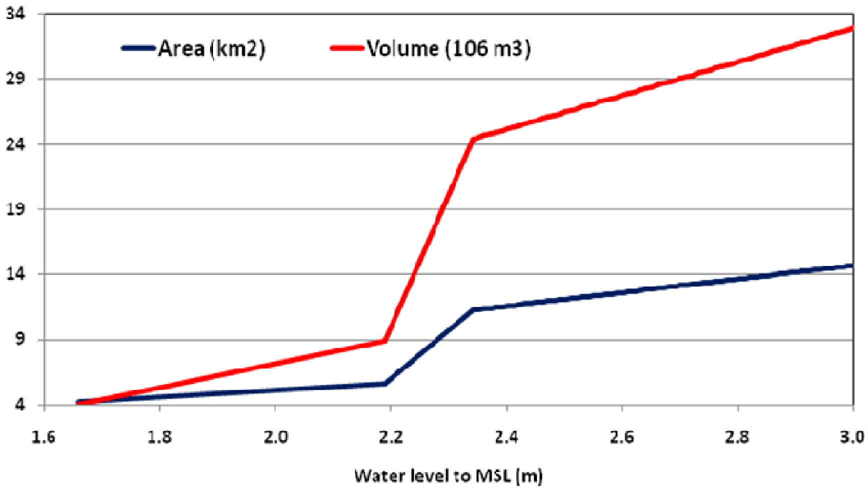


Figure 5.8.2: Relationship between the volume and surface area of the Klein estuary (Van Niekerk, 2010b)

From these equations, the occurrence of breaching and closure of the Klein estuary mouth could be evaluated for the different climate scenarios on the Klein catchment, based on volume of water contained in the estuary. Therefore, with the breaching information provided, the occurrence of tidal interaction with the marine system could be determined, thereby facilitating the assessment of estuarine integrity. The latter has, however, not been covered explicitly in the dissertation, but is discussed in Chapter 7 from a literature review perspective.

6 RESULTS

6.1 Results and Discussion 1: A General Assessment of Climate Change on Hydrological Responses into Estuaries Under Baseline Land Cover Conditions

In South Africa, climate change is projected to have different effects from region to region. Hence, it is highly probable that the catchments selected for this study will be impacted upon differently. Additionally, upstream anthropogenically influenced land use change is one of the major drivers of hydrological responses. This change from natural land cover to actual land use could affect the quantity and quality of streamflows from catchments. In combination, climate and land use changes could impact upon flows into estuaries, thereby affecting considerably the ecological and economic contributions of these systems.

For this study on possible impacts of climate change on responses of freshwater inflows, 10 estuaries in differing climate regimes (cf. Figure 4.1) and with differing catchment areas were selected, as shown in Figure 4.2 and, for the sake of clarity, below in Figure 6.1.1. Results in the following sub-sections will be presented starting one the west coast (i.e. Buffels catchment) and moving along south to the east coast (i.e. Mlalazi catchment). It should be noted that the graphs in the following sections are do not have the same scales on the y-axis. This is due to the extreme differences in catchment size, location, land cover and climatic region which result in flows from each of the catchments which are significantly different. Owing to this difference in the magnitude of flows, it is not practical to display the results obtained for all the catchments using a single scale on the axes, as the variation in some results may not be detected.

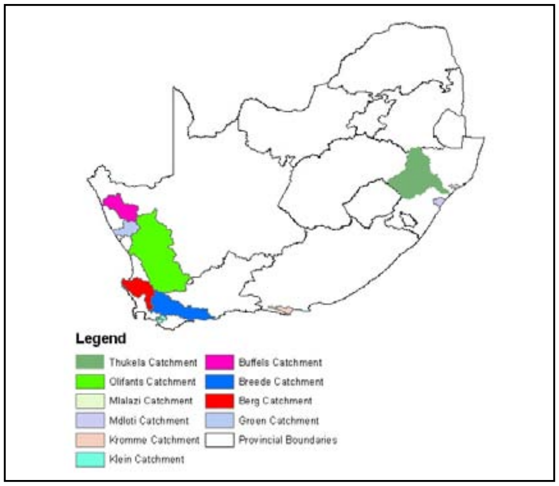


Figure 6.1.1: Location of the ten estuaries and their catchments which were selected for this study

As a point of reference to the discussion on the analysis of monthly statistics of streamflows entering the 10 selected catchments, maps of projected changes in annual rainfall for the whole of South Africa, derived from multiple GCMs, are shown in Figure 6.1.2. This series of maps shows that rainfalls are projected to increase in the east, but that in the latter part of this century a marked drying is projected for the west of South Africa.

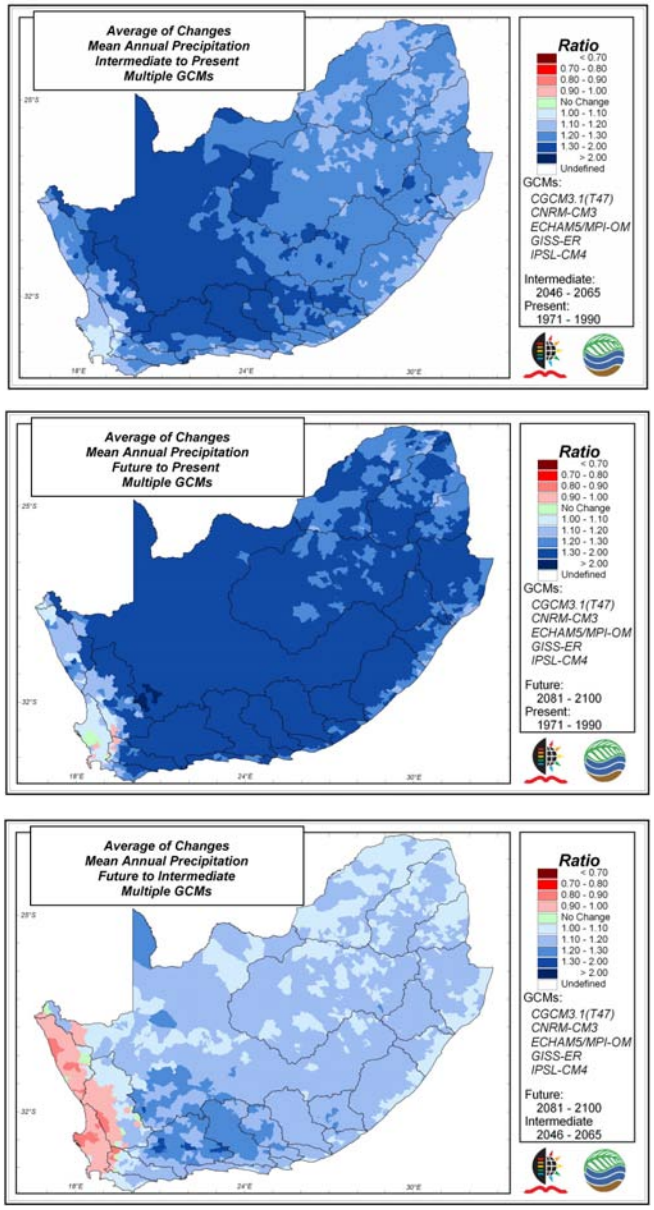


Figure 6.1.2: Average of ratio of changes of mean annual precipitation between intermediate and present (top graph), distant future and present (middle graph) and distant and intermediate future climate scenarios (bottom graph), multiple GCMs (Schulze, 2011a).

6.1.1 Analysis of Monthly Statistics of Streamflows Entering the Ten Selected Estuaries

a. Buffels Catchment

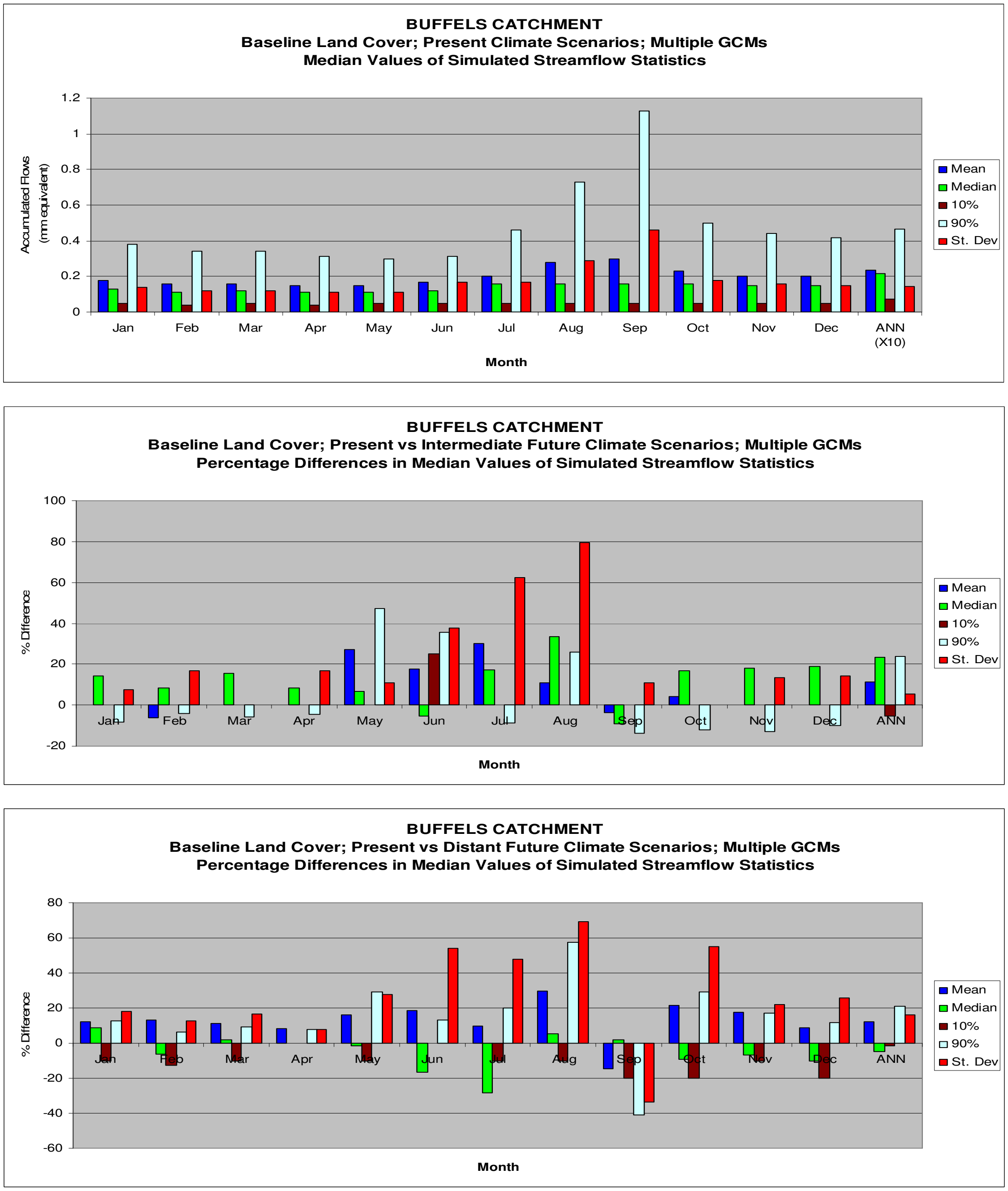
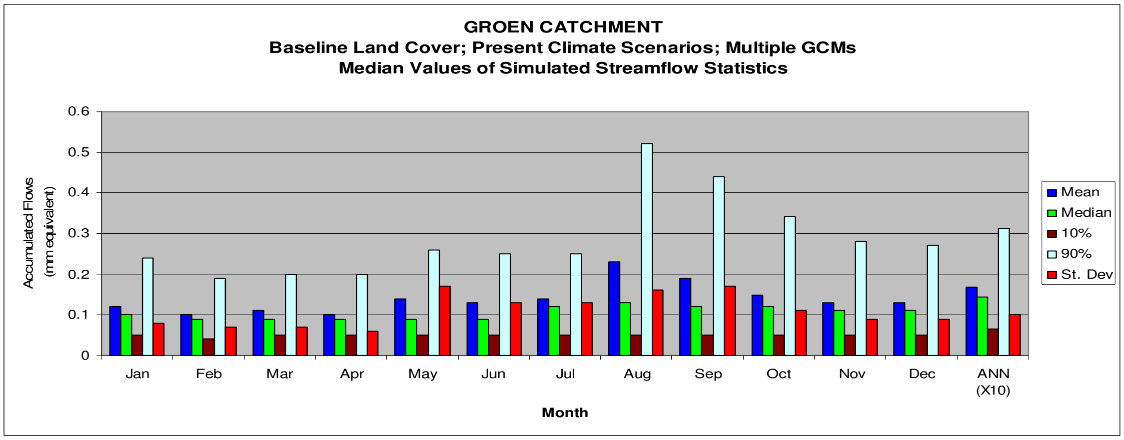


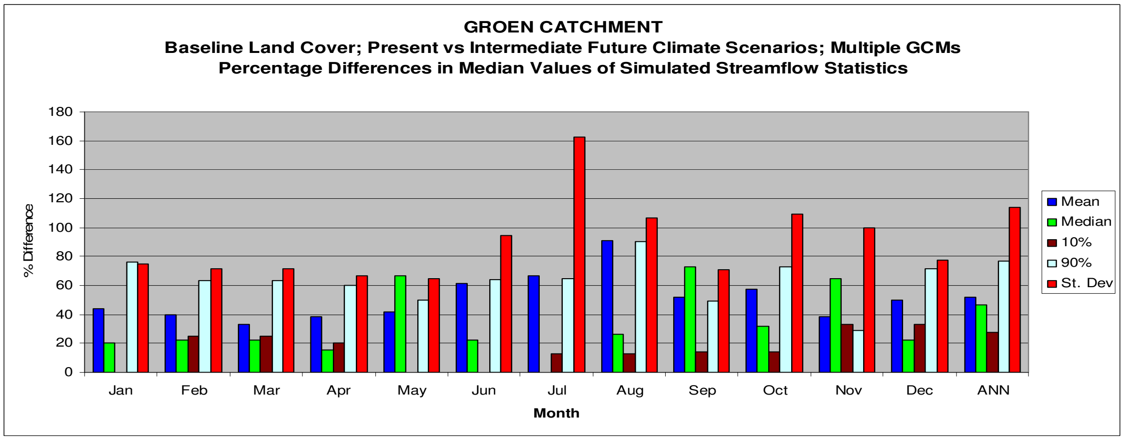
Figure 6.1.1.1: Flow regime from the Buffels catchment into its estuary during the present climate period (top graph), providing a point of reference for simulations of future periods, and percentage changes in flow statistics into the intermediate (middle graph) and distant future (bottom graph) periods, derived from multiple GCMs

From the flow regime exhibited in Figure 6.1.1.1 (top) the Buffels catchment has low overall flows occurring throughout the year, but a late winter/early spring peak. Mean flows are greater than medians during most months, indicating high flow events in those months in certain years, which influence the monthly means. This is supported by the high flow analysis (90 %) which mimics mean monthly flow patterns, but at ~ twice the magnitude. Figure 6.1.1.1 (middle) exhibits considerable increases in streamflows in the intermediate future, with a flow shift towards mid-winter. This may be due to a shift in the occurrence of rainfall over this region. Additionally, the magnitude of high (90 %) and low flows (10 %) increase considerably into the future, indicating also a slight increase in rainfall during late autumn, which increases the magnitude of high flows during this period. Into the distant future there are slight increases in mean flows, with a peak occurring during August (Figure 6.1.1.1, bottom). However, as a consequence of the highly variable rainfall over this catchment, increases in mean flows may be as a result of increases over some portions of this catchment, while no increases occur over other portions.

b. Groen Catchment

The Groen catchment displays all year flows at low magnitudes with a late winter maximum. High flows illustrated in Figure 6.1.1.2 (top) mimic the pattern of the mean flows and are ~ twice the magnitude of the mean flows throughout the year. Owing to occasional very high flow years, mean flows exceed the medians in every month of the year. Low flow magnitudes (10 %) remain consistent throughout the year, and indicate that during drought years flows may virtually cease. Figure 6.1.1.2 (middle) illustrates an overall increase into the intermediate future in all streamflow statistics presented, especially the winter mean flows, thus indicating that there may be an increase in rainfall during the winter , i.e. the wet season, over the west coast and adjacent interior. Into the distant future there is negligible change in mean flows from this system (Figure 6.1.1.2, bottom). However, there are increases in the magnitude of flows in high flow years, which may be as a result of increased extreme rainfall events over this catchment.





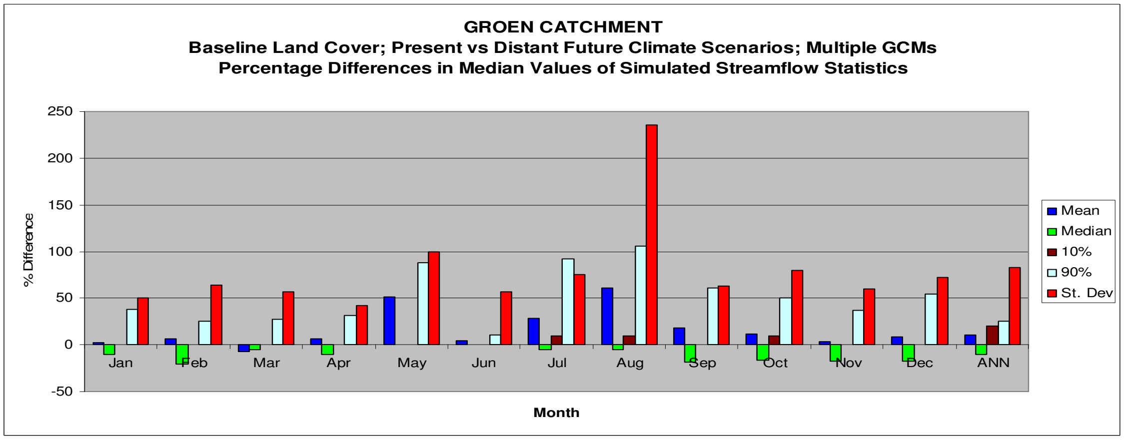
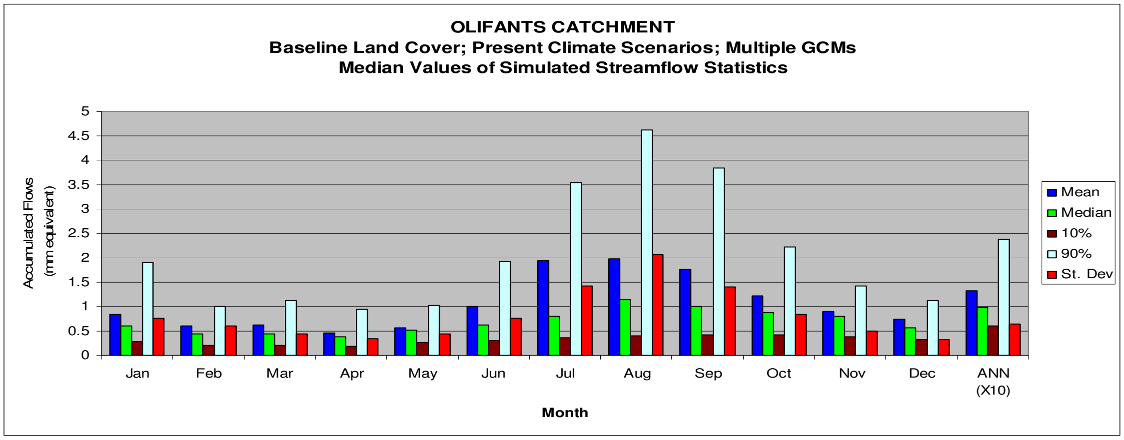
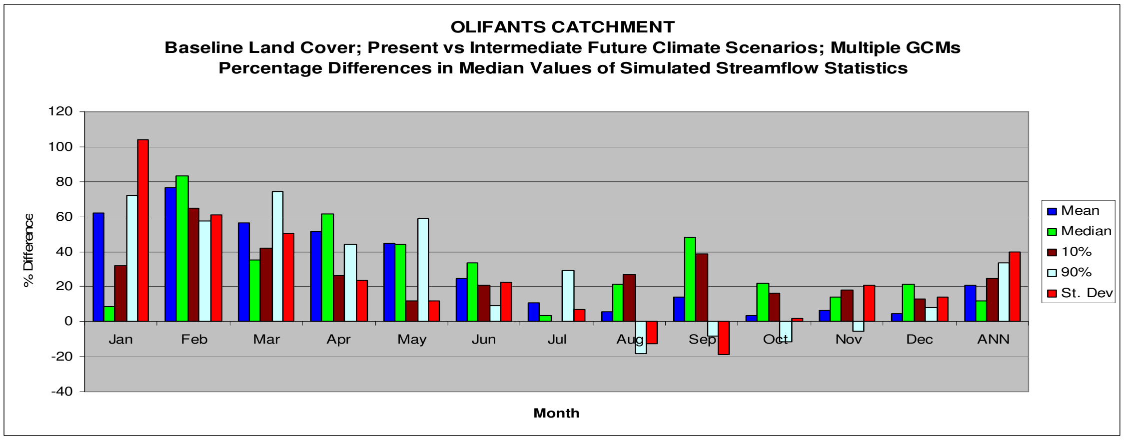


Figure 6.1.1.2: Flow regime from the Groen catchment into its estuary during the present climate period (top graph), providing a point of reference for simulations of future periods, and percentage changes in flow statistics into the intermediate (middle graph) and distant future (bottom graph) periods, derived from multiple GCMs

c. *Olifants Catchment*





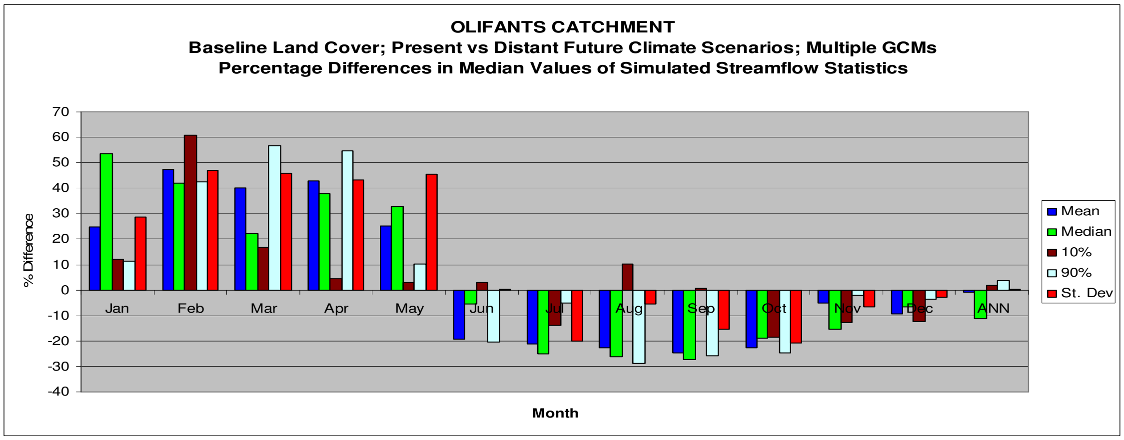
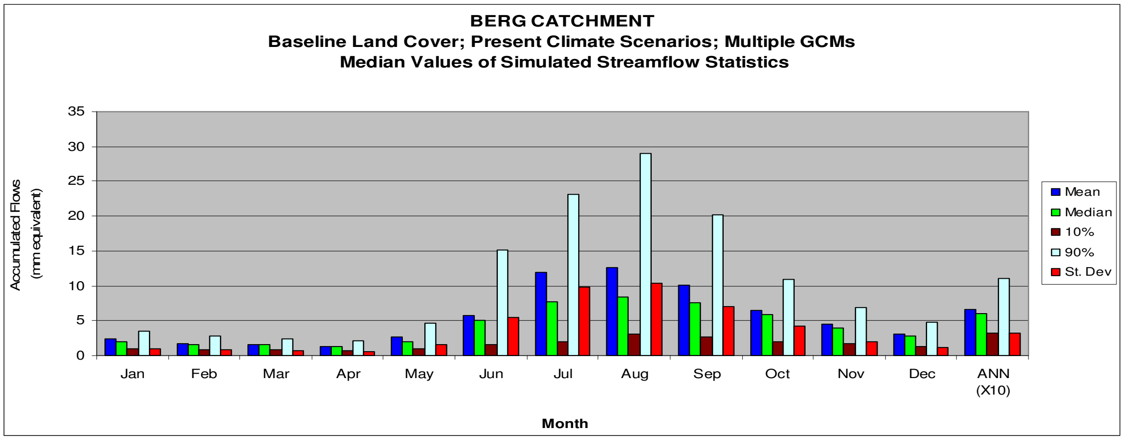


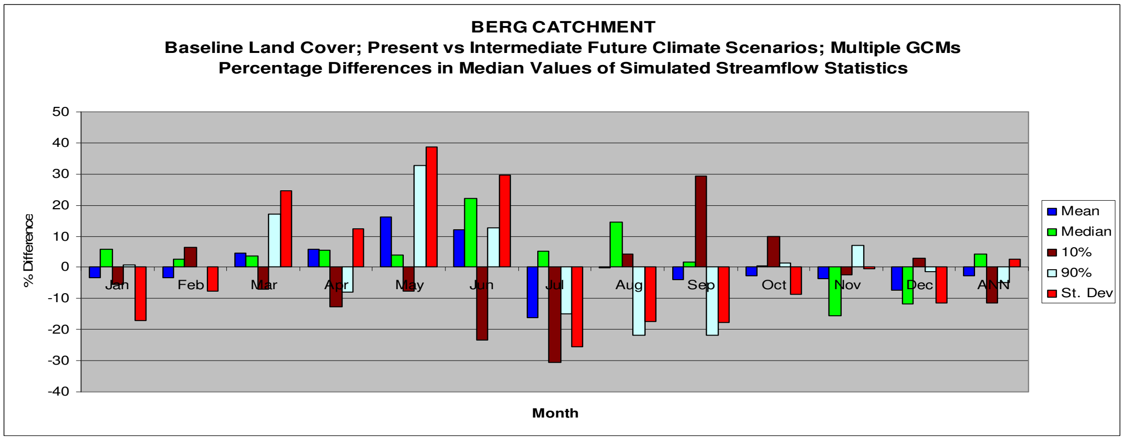
Figure 6.1.1.3: Flow regime from the Olifants catchment into its estuary during the present climate period (top graph), providing a point of reference for simulations of future periods, and percentage changes in flow statistics into the intermediate (middle graph) and distant future (bottom graph) periods, derived from multiple GCMs

Figure 6.1.1.3 (top) illustrates the seasonal nature of the flow regime of the Olifants catchment, which is dominated by late winter/early spring runoff. Throughout the year mean monthly flows exceed median flows, indicating the occurrence of occasional years with high flows. The highest mean monthly flow and the greatest 1:10 year high flow both occur in August. This implies that the highest rainfall occurs during this period. The magnitude of the monthly low flows varies with season, the highest occurring during winter, which indicates the occurrence of significant recharge into the groundwater zone. Figure 6.1.1.3 (middle) illustrates increases in magnitude into the intermediate future, of both mean and median flows during the summer period, indicating a significant temporal shift in the occurrence of rainfall over this region. This shift is seen also for both the low and high flows. Into the distant future the distinction between period of increases vs decreases become far more pronounced (Figure 6.1.1.3, bottom). Decreases in flows occur during the winter and spring period, while increases occur during the summer and autumn period. This illustrates the possible temporal shift in rainfall from winter to summer over some portions of this catchment, which results in changes in the temporal flow regime.

d. Berg Catchment

The flow regime of the Berg catchment in the winter rainfall region is dominated by late winter flows, with the highest mean flows occurring during August. Figure 6.1.1.4 (top) illustrates the exceedance of median flows by mean flows, thus highlighting the occurrence of occassional high flow periods which influence the means. High flows (90 %) are ~ twice the magnitude of mean flows during winter. However, during summer the high flows are ≈ to mean flows. Figure 6.1.1.4 (middle) illustrates the decrease in mean flows, but an increase in median flows into the intermediate future. Flows in high (90 %) and low (10 %) flow years decrease into the intermediate future period, illustrating an increase in the severity of hydrological droughts over this region. Figure 6.1.1.4 (bottom) illustrates marked decreases in flows into the distant future period, which is probably due to the decreases in rainfall over the Berg catchment. The greatest decreases occur during the spring and summer, indicating that seasonal droughts could become more severe.





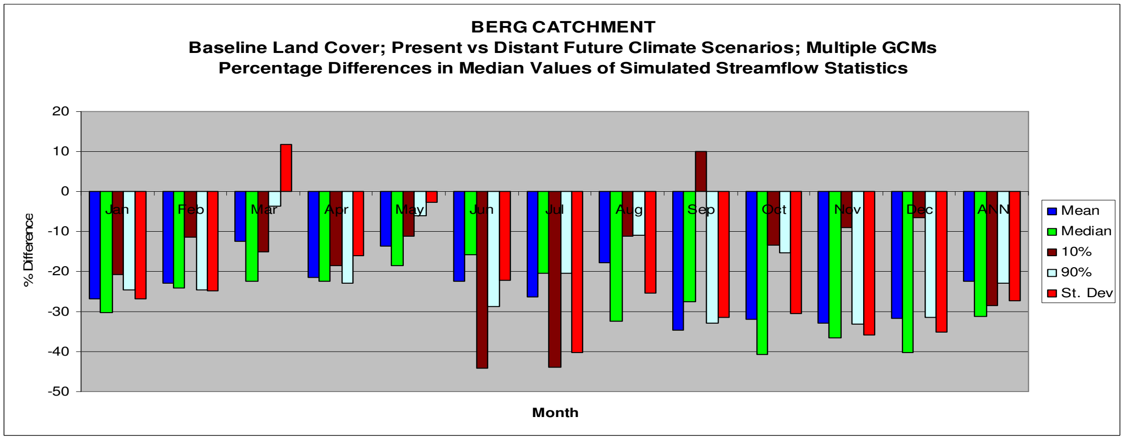
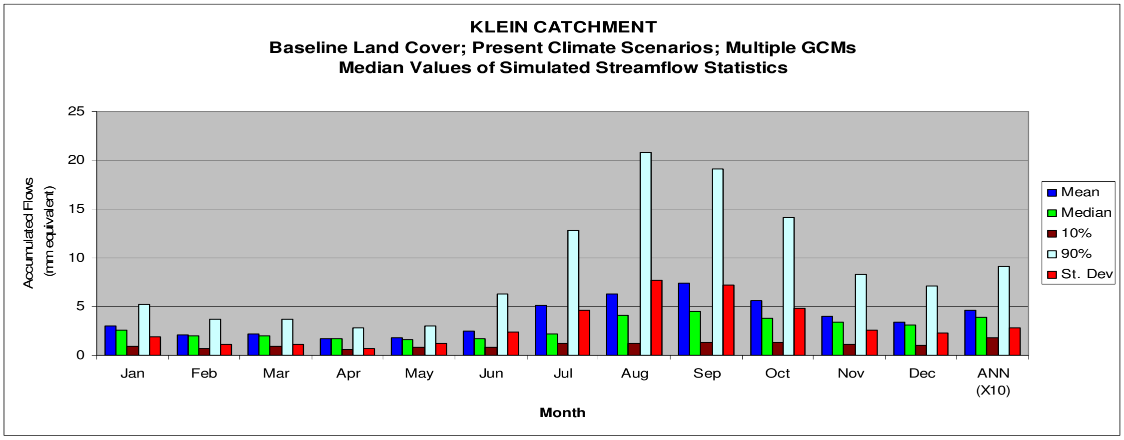
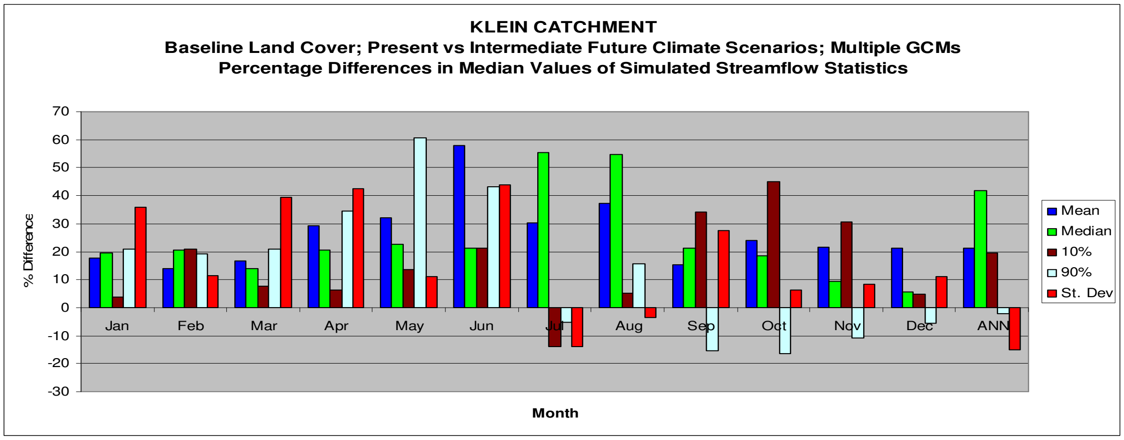


Figure 6.1.1.4: Flow regime from the Berg catchment into its estuary during the present climate period (top graph), providing a point of reference for simulations of future periods, and percentage changes in flow statistics into the intermediate (middle graph) and distant future (bottom graph) periods, derived from multiple GCMs

e. Klein Catchment





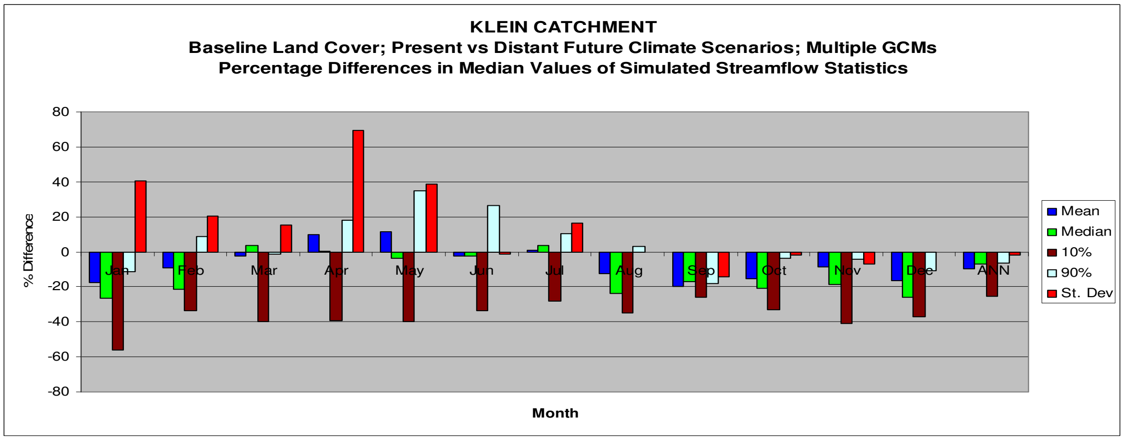


Figure 6.1.1.5: Flow regime from the Klein catchment into its estuary during the present climate period (top graph), providing a point of reference for simulations of future periods, and percentage changes in flow statistics into the intermediate (middle graph) and distant future (bottom graph) periods, derived from multiple GCMs

The flow regime of the Klein catchment is highly seasonal and dominated by winter streamflows, with the highest mean flows occurring during August - September. Figure 6.1.1. (top) illustrates the exceedance of the median flows by the mean flows, thus highlighting again the occurrence of high flow periods in certain years which influence the mean flows. High flows (90 %) are generally > twice the magnitude of mean flows. Low flows (10 %) increase only slightly during winter. Figure 6.1.1.5 (middle) illustrates the increase in mean and median flow in all months into the intermediate future, with some increases in the magnitude of median flows being greater than the increases in mean flows. High (90 %) flows shift ~two months earlier, illustrating a possible shift in the occurrence of rainfall. Low flows (10 %) increase in magnitude during most months. Figure 6.1.1.5 (bottom) illustrates negligible increases in flows into the distant future, indicating a decrease in rainfall from the intermediate period into the distant future. Additionally, low flow years become more severe as rainfall decreases, which results in decreased groundwater recharge and so lower baseflows.

f. Breede Catchment

The flow regime of the Breede catchment is dominated by winter rainfall, with the highest mean flows occurring from July to September. Figure 6.1.1.6 (top) illustrates the exceedance of the median flows by the mean flows during most months, highlighting again the occurrence of years with high flows which influence the means. High flows (90 %) are ~ twice the magnitude of mean flows during winter; however, during summer the high flows are ≈ to mean flows. Figure 6.1.1.6 (middle graph) illustrates an increase in mean and median flows into the intermediate future. High (90 %) and low (10 %) flows also increase into the intermediate future, illustrating a decrease in the occurrence of low flow years over this region relative to the present. Additionally, a projected increase in the magnitude of mean and median flows during the summer months indicates a temporal shift in rainfall into the intermediate future. Figure 6.1.1.6 (bottom graph) illustrates that increases into the distant future occur during the summer period. However, these increases are not as pronounced as during the intermediate future. This indicates that rainfall increases during the intermediate period and then decreases slightly during the distant future. Additionally, mean flows decrease slightly during the winter period, indicating a possible temporal shift in rainfall into the distant future period.

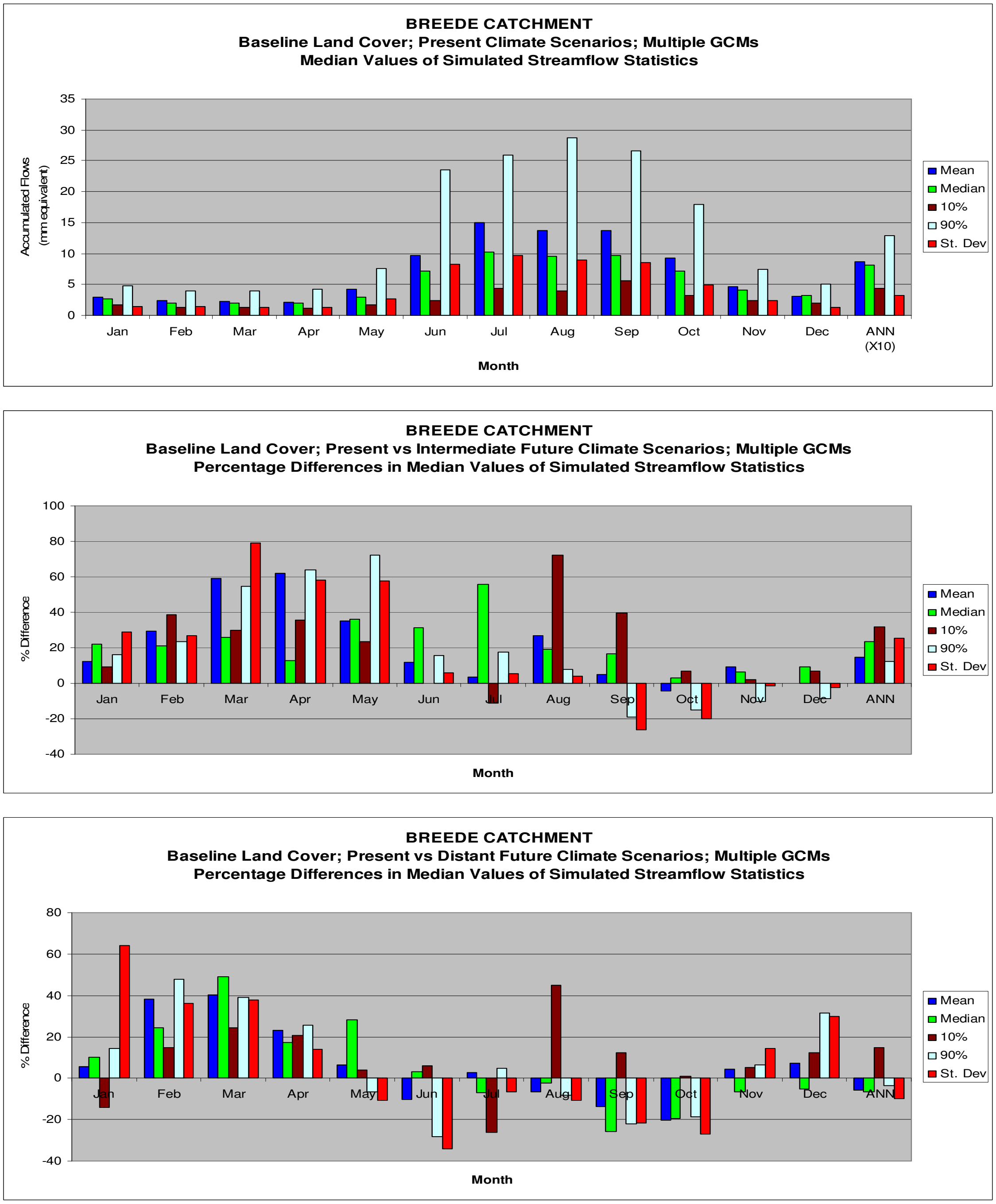
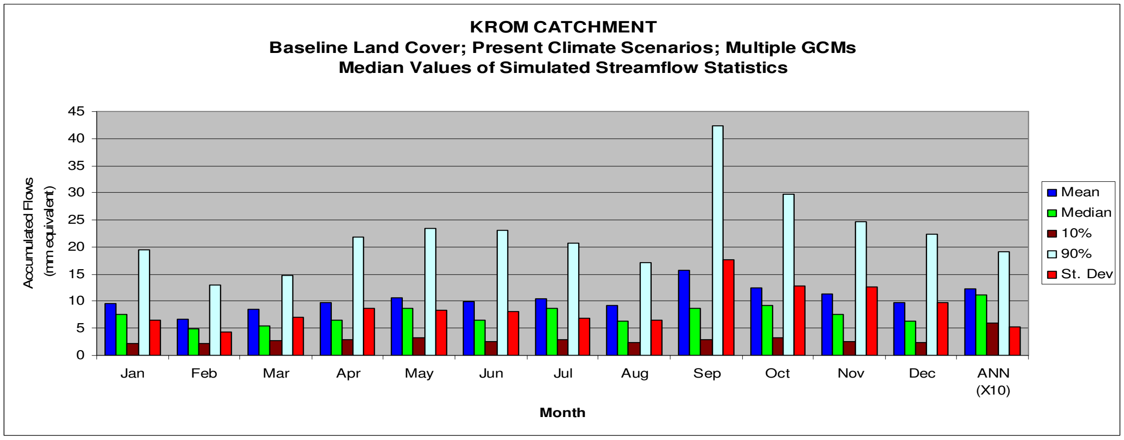
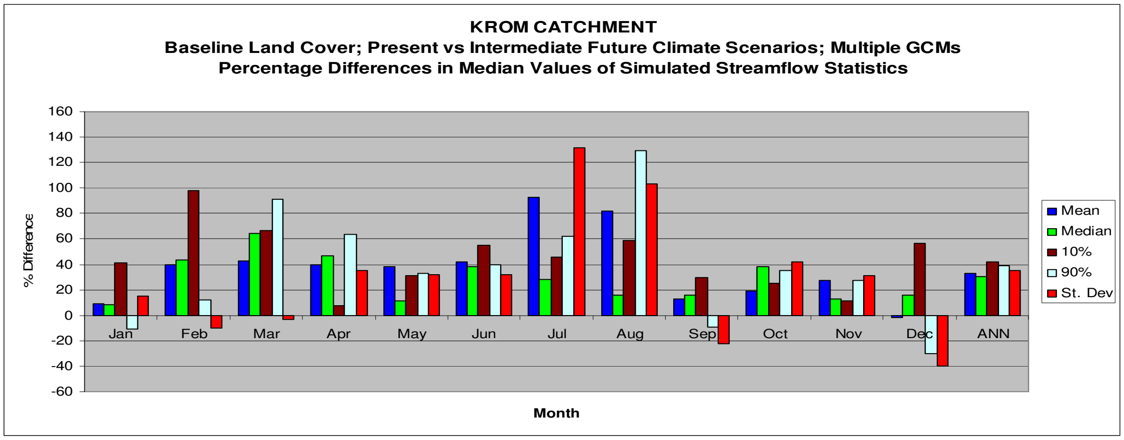


Figure 6.1.1.6: Flow regime from the Breede catchment into its estuary during the present climate period (top graph), providing a point of reference for simulations of future periods, and percentage changes in flow statistics into the intermediate (middle graph) and distant future (bottom graph) periods, derived from multiple GCMs

g. Krom Catchment





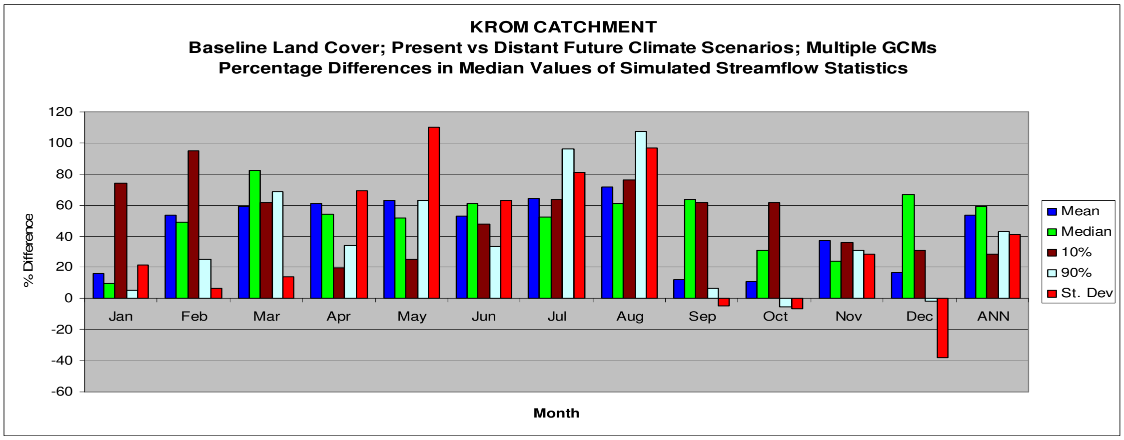


Figure 6.1.1.7: Flow regime from the Krom catchment into its estuary during the present climate period (top graph), providing a point of reference for simulations of future periods, and percentage changes in flow statistics into the intermediate (middle graph) and distant future (bottom graph) periods, derived from multiple GCMs

Figure 6.1.1.7 (top) illustrates that mean in flows into the Krom estuary are high and relatively consistent throughout the year, with a slight peak in early spring. For each month of the year, mean flows exceed medians, which is indicative of the occurrence of occasional years with high flows (90 %). High flows in most months are ~ twice the magnitude of means, except in spring when they are more than double the means. Low flows (10 %) vary only slightly throughout the year. Figure 6.1.1.7 (middle) illustrates an increase in mean and median flows into the intermediate future during the winter period. The majority of increases in the magnitude of low (10 %) and high (90 %) flow events occur during the first eight months the year, illustrating a possible shift in rainfall to the late summer/early winter period. Therefore, this presently all year rainfall region is projected to becoming more seasonal. Figure 6.1.1.7 (bottom) illustrates a significant increase in mean and median flows in the first half of the year, which is likely to be due to the temporal shift in rainfall from all year to summer and autumn. Low flows during summer and winter show considerable increases, which probably result from greater groundwater recharge due to the increases in rainfall during the afore-mentioned periods.

h. Mdloti Catchment

Figure 6.1.1.8 (top) illustrates the seasonal nature of flows from the Mdloti catchment, which is dominated by late summer streamflows, with the highest means occurring from February to April. Mean flows consistently exceed median flows. Throughout the year high flows (90 %) are ~ 2 - 3 times the magnitude of the mean flows, and low flows (10 %) fluctuate in accordance with seasonal changes. This indicates that even during drought years the baseflow store is sufficient to sustain flows. Into intermediate future, increases in mean and median flows, especially between autumn and early summer, are projected (Figure 6.1.1.8, middle). However, there is no trend in the magnitude of these increases. There is an increase in the high flows (90 %) into the intermediate future, illustrating a possible increase in rainfall occurrence during late autumn and early spring. Into the distant future the mean flows increase during the autumn, winter and spring periods, which may indicate a temporal shift in rainfall over this region (Figure 6.1.1.8, bottom). The magnitudes of high flows increase during same period as mean flows, which may be as a consequence of an increase in high intensity rainfall events. Low flows increase slightly, but show negligible variation. This indicates possibly slight increases in groundwater recharge.

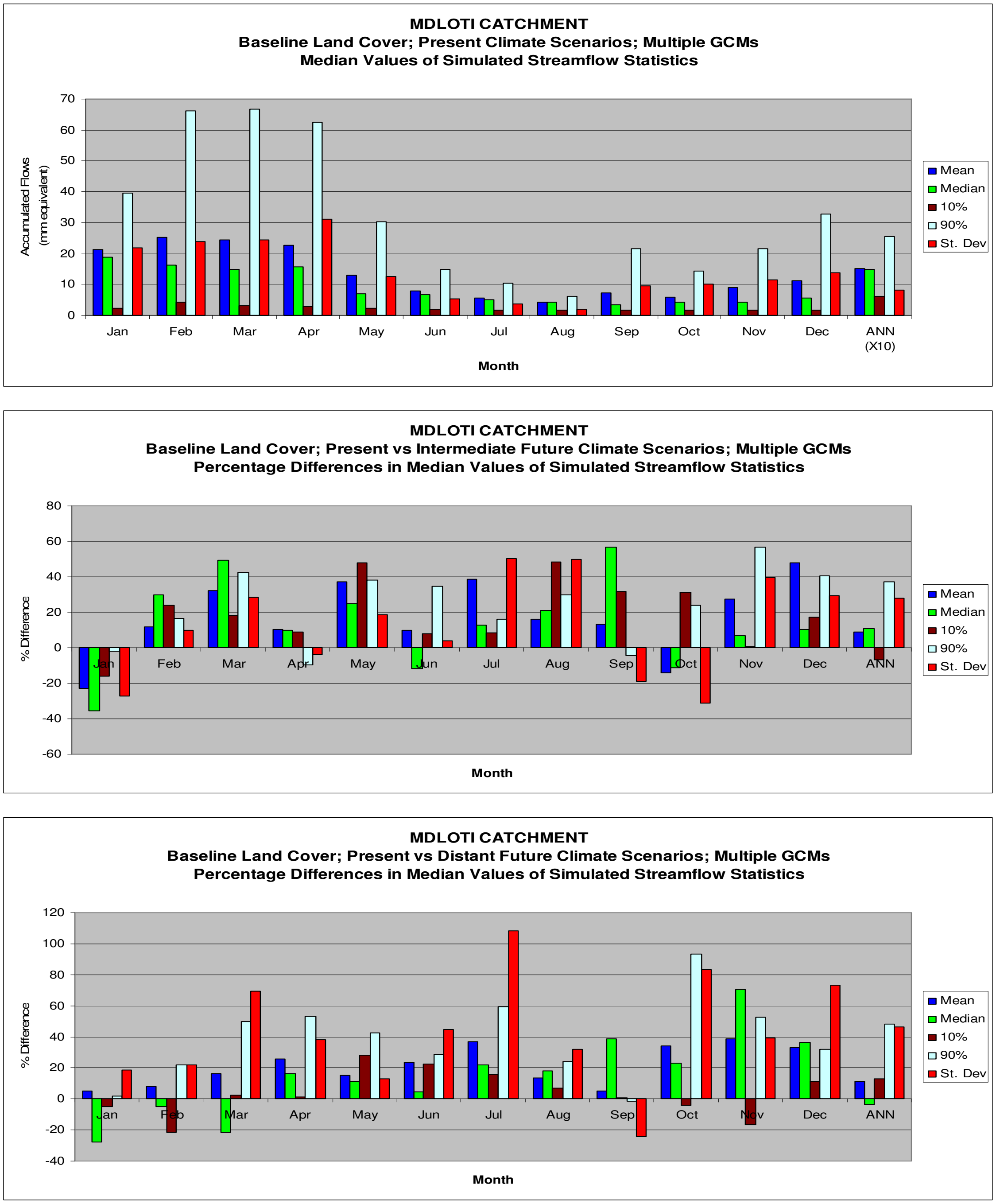


Figure 6.1.1.8: Flow regime from the Mdloti catchment into its estuary during the present climate period (top graph), providing a point of reference for simulations of future periods, and percentage changes in flow statistics into the intermediate (middle graph) and distant future (bottom graph) periods, derived from multiple GCMs

i. Thukela Catchment

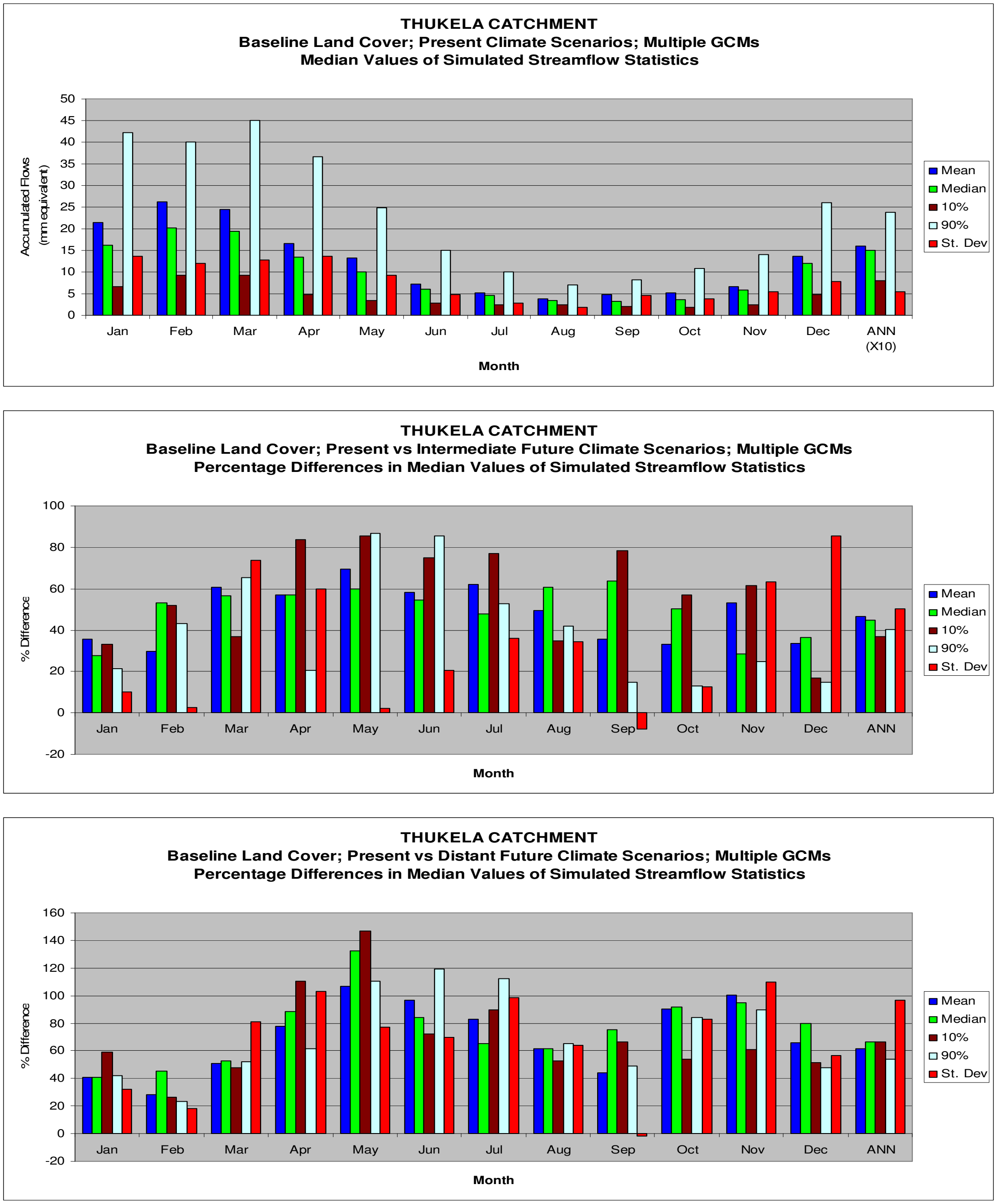
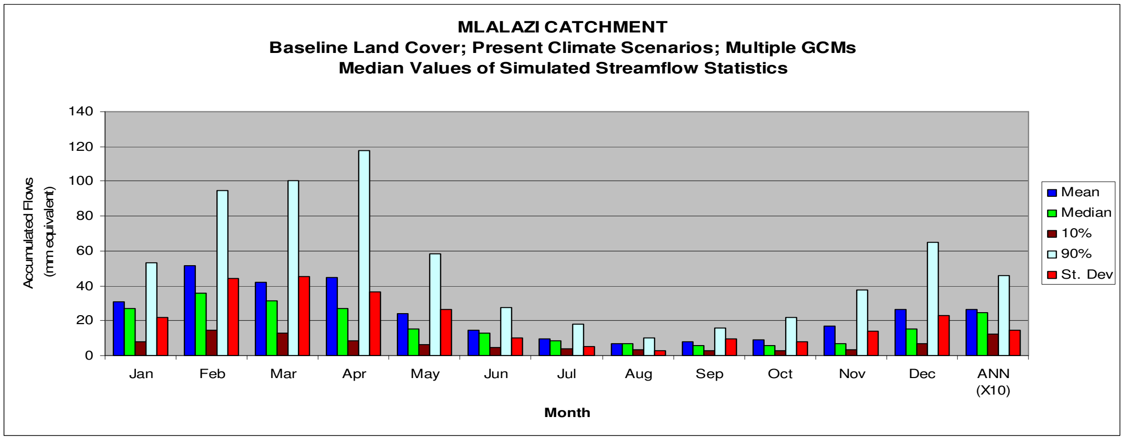


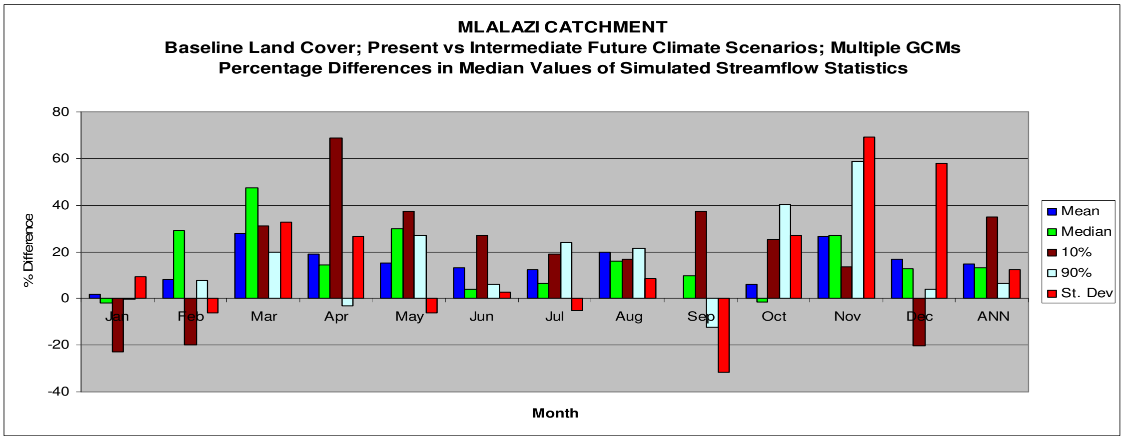
Figure 6.1.1.9: Flow regime from the Thukela catchment into its estuary during the present climate period (top graph), providing a point of reference for simulations of future periods, and percentage changes in flow statistics into the intermediate (middle graph) and distant future (bottom graph) periods, derived from multiple GCMs

The flow regime of the Thukela catchment is dominated by late summer streamflows, as illustrated in Figure 6.1.1.9 (top). Mean monthly flows are greatest during February and exceed median monthly flows in all months, indicating that years with high flows influence the means. Additionally, both high (90 %) and low (10 %) flows are influenced by the highly seasonal rainfall in this region, with high flows being ~ 1.5 - 2 times greater than mean monthly flows. Figure 6.1.1.9 (middle) illustrates the increases in magnitude in all monthly flow statistics. In addition to increasing, rainfall may be undergoing a temporal shift to a month or two later than at present. Low flows increase markedly, thus indicating a significant increase in groundwater recharge. Figure 6.1.1.9 (bottom) illustrates a distinct bimodal increase in mean flows, with peaks occurring during May and November. The greatest increases in low flow years occurs in the first half of the year, with a peak during May. This future flow pattern may be an indication that rainfall may undergo a temporal shift so that rainfall occurs two to three months later than during the present period.

j. Mlalazi Catchment

Figure 6.1.1.10 (top) illustrates the strong seasonality of the Mlalazi catchment, which is dominated by late summer streamflows, with the highest mean flows occurring during February. Mean flows consistently exceed median flows. Throughout the year 1:10 year high flows (90 %) are ~ 2 – 2.5 times the magnitude of the mean flows. Low flows (10 %) increase during summer and decrease during winter, in accordance with seasonal rainfall. Into the intermediate future, increases in mean, median and low flows are illustrated in Figure 6.1.1.10 (middle). These increases in magnitude occur during late autumn and spring, with medians exceeding means in some months. There is an increase in the high flows (90 %) into the intermediate future, illustrating a possible increase in rainfall during late autumn and early spring. Low flows increase in magnitude, indicating an increase in groundwater zone recharge. Into the distant future low flows during the late autumn/early winter period increase (Figure 6.1.1.10, bottom). Additionally, mean flows during winter and spring increase, possibly indicating increased rainfall during these periods, which accounts for greater groundwater recharge, and therefore increases in baseflow.





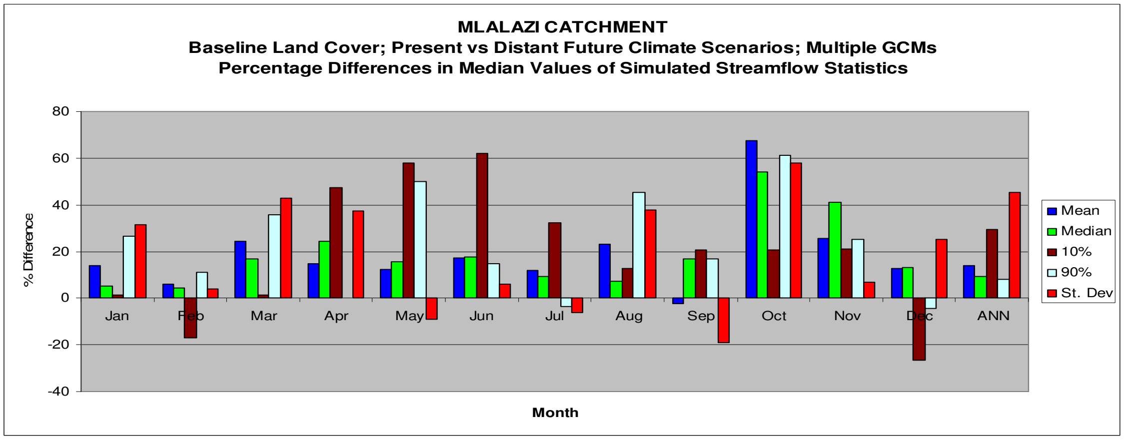


Figure 6.1.1.10: Flow regime from the Mlalazi catchment into its estuary during the present climate period (top graph), providing a point of reference for simulations of future periods, and percentage changes in flow statistics into the intermediate (middle graph) and distant future (bottom graph) periods, derived from multiple GCMs

6.1.2 Analysis of Pulses of Flow into Ten Selected Estuaries

In this dissertation a pulse is defined as a step increase in flows above a specified threshold over a short period of time, in the case of the daily time step *ACRU* model from one day to the next. As the 10 selected catchments differ significantly in size, it was decided for this study that a pulse would be defined as an increase in freshwater flows into estuaries of ≥ 10 % from one day to the next.

As a consequence of the vastly different flow magnitudes into each of the 10 selected estuaries, a relative percentage value was used to define the threshold for a pulse to be recognised, instead of a volumetric value (cf. Sub-section 5.5.1). Another reason for using a percentage value is the highly variable nature of streamflow in the course of a year and between years, which would have resulted in constantly varying volumetric pulse values, had a volumetric approach been used (cf. Sub-section 5.5.1). Hence, a small volumetric shock during the low flow season may be a relatively large shock to an estuarine ecosystem at that time. Alternatively, a volumetrically large change from one day to the next during the high flow season may only be a small ecological shock in relative terms.

Additionally, it must be noted that the scales on the graphs of pulse frequency are not standardised, as a result of various catchment and climatic factors. For a more detailed explanation cf. Sub-section 6.1.

Over the next pages a catchment-by-catchment analysis of the median number of pulses per annum is made for present, intermediate and distant future climate scenarios, calculated from multiple GCMs, followed by a month-by-month analysis of the projected changes in the number of pulses per month for the different climate scenarios. Again the sequence of catchments for this pulse analysis is from the west coast to the east coast.

a. Buffels Catchment

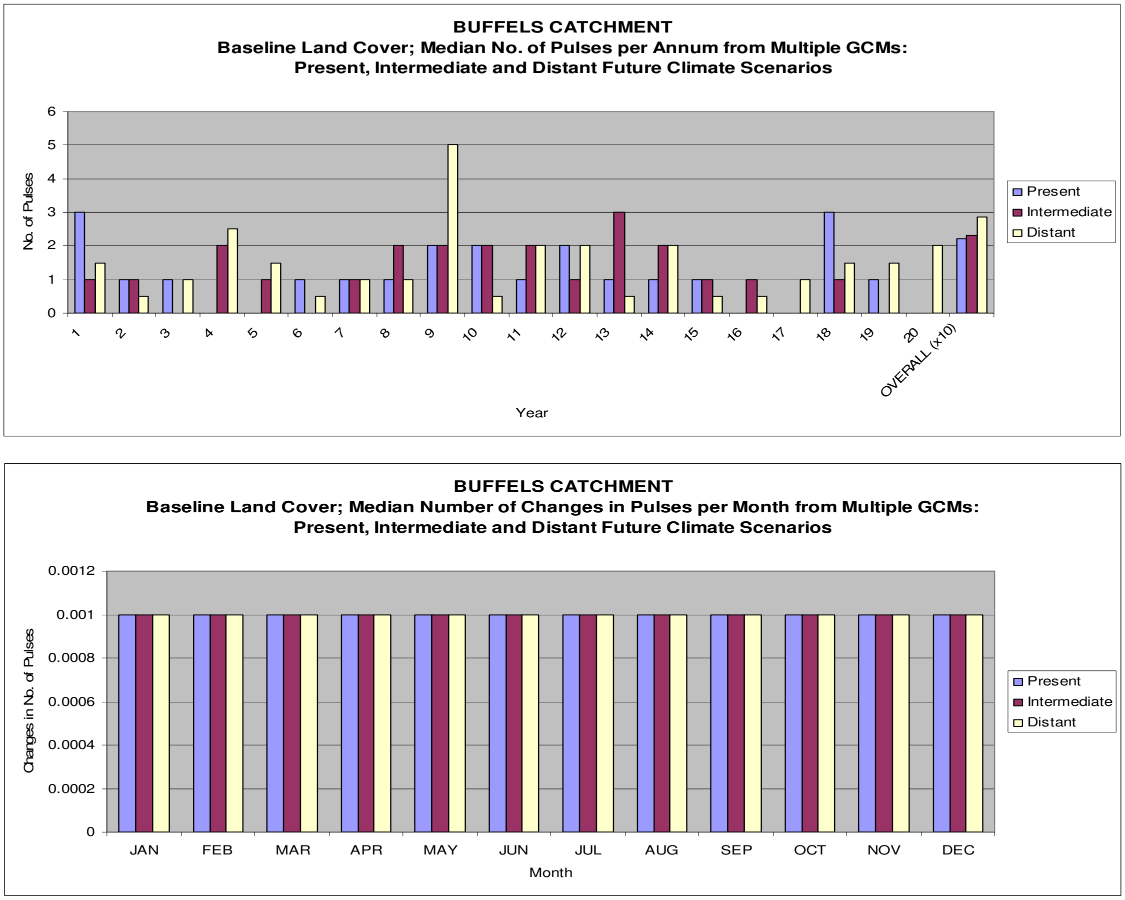


Figure 6.1.2.1: Median of the annual number of pulses (top graph), and changes in median monthly numbers of pulses (bottom graph) entering the Buffels estuary during the present, intermediate and distant future time periods derived from multiple GCMs

Figure 6.1.2.1 (top) illustrates no time trend within the 20 year period, in the number of pulses occurring into the Buffels estuary. However, there is a slight increase in the number of pulses into the intermediate and then a greater increase into the distant future periods, implying an increase in the occurrence of high intensity runoff events over the Buffels. From Figure 6.1.2.1 (bottom) it would appear that there are no pulses occurring in this system. The reason for this is that median monthly pulse values were utilised instead of mean monthly pulse values, in order to exclude outlier values. Hence, in arid regions in which runoff events are rare, it is unlikely that the median monthly value would register a pulse. This is unfortunate as the attempt to increase the representativeness by utilising medians instead of means, has inadvertently reduced the sensitivity to pulses at a monthly level. However, this only applies to arid systems such as the Buffels and Groen in which flows cease on a regular basis.

b. Groen Catchment

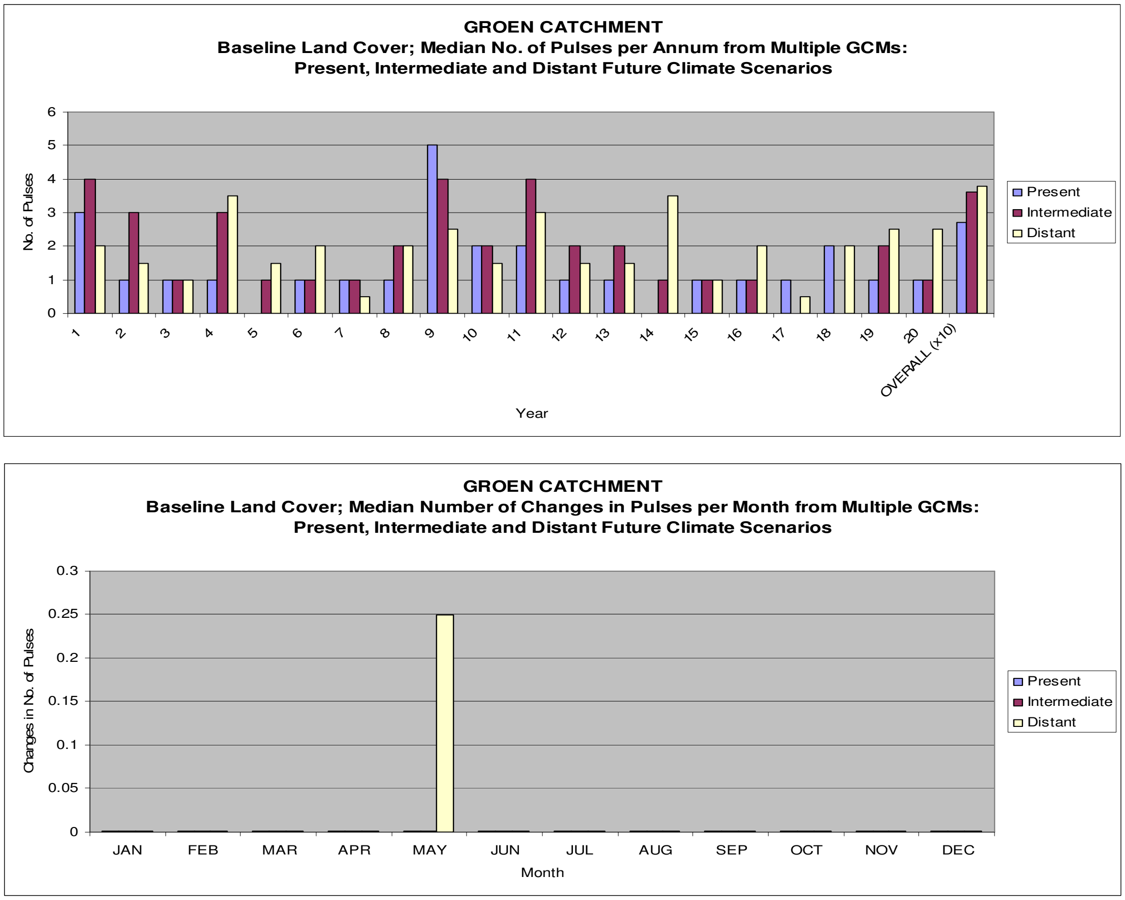
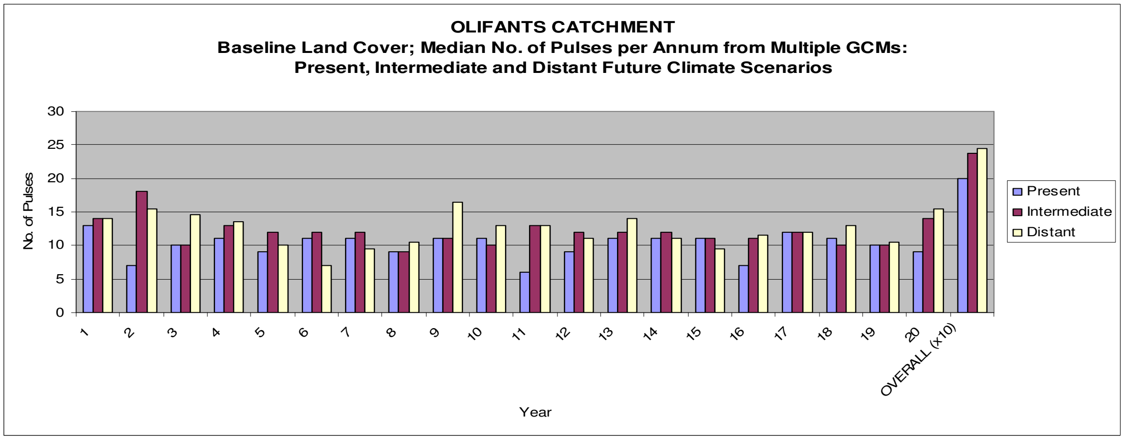


Figure 6.1.2.2: Median of the annual number of pulses (top graph), and changes in median monthly numbers of pulses (bottom graph) entering the Groen estuary during the present, intermediate and distant future time periods, derived from multiple GCMs

Figure 6.1.2.2 (top) illustrates that an increase in the number of annual pulses occurs in the Groen catchment into the intermediate and distant future time periods. This may be as a consequence of increases in the frequency of heavy rainfall events over this catchment. In the Groen system these would register as pulses, especially during periods of very low or zero, flows when small volumetric increases would be registered as marked percentage increases. From Figure 6.1.2.2 (bottom) it would appear that a number of pulses, on average once in four years, occurred during May in this system.

c. Olifants Catchment



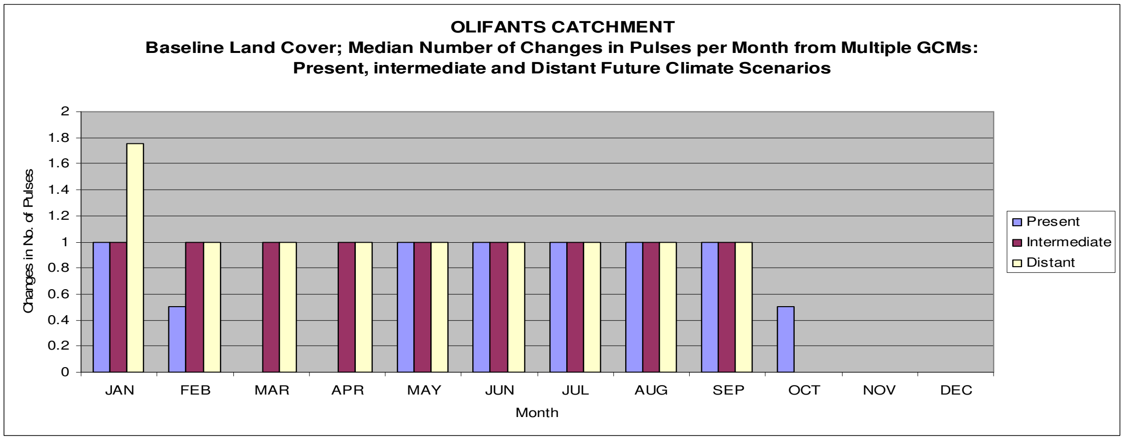


Figure 6.1.2.3: Median of the annual number of pulses (top graph), and changes in median monthly numbers of pulses (bottom graph) entering the Olifants estuary during the present, intermediate and distant future time periods, derived from multiple GCMs

Figure 6.1.2.3 (top) illustrates a considerable increase in the number of pulses occurring into the intermediate and a slight increase into the distant future. This may be due to the projected increases in the frequency of high runoff producing rainfall events over the Cedarberg Mountains, which are included in the Olifants catchment, hence resulting in an increase in the number of pulses. Figure 6.1.2.3 (bottom) illustrates that during the present period the highest number of pulses occurs in late summer and then again in the winter/early spring months. However, into the intermediate future the distribution of pulses from mid-summer through to early spring increases, which may be due to a temporal shift in rainfall over significant portions of the Olifants catchment. This is also supported by the frequency analysis graphs in Sub-section 6.1.1 which show considerable increases in the magnitude of flows during summer.

d. Berg Catchment

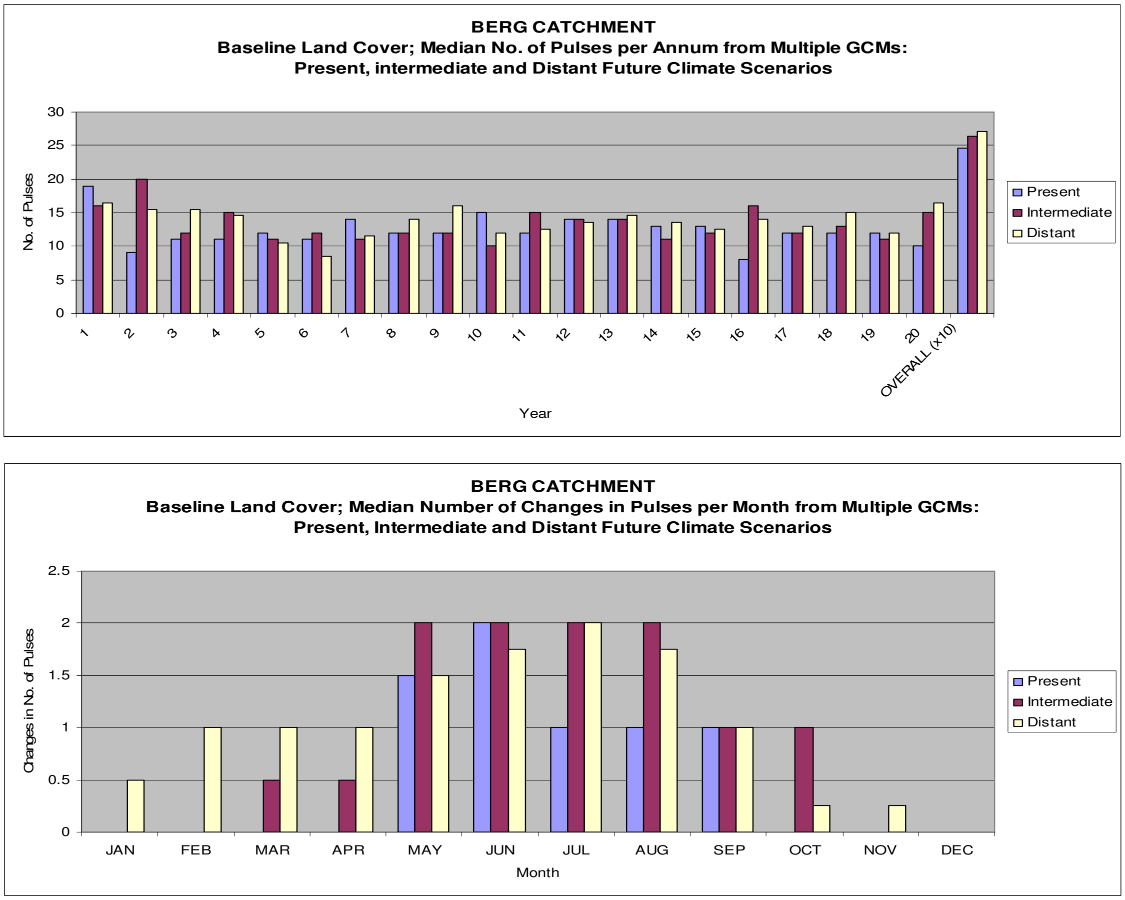


Figure 6.1.2.4: Median of the annual number of pulses (top graph), and changes in median monthly numbers of pulses (bottom graph) entering the Berg estuary during the present, intermediate and distant future time periods, derived from multiple GCMs

Figure 6.1.2.4 (top) illustrates that the number of pulses occurring during the present and into projected future climates is relatively consistent; however, there is a slight overall increase in the occurrence of pulses into the future, which implies that either the intensity or the frequency of rainfall events over the catchment may increase during the future periods. Figure 6.1.2.4 (bottom) illustrates that the highest number of pulses in the present period occurs during June, but that the temporal distribution of the highest number of pulses increases from a single to four months into the intermediate future. The temporal distribution of the highest number of pulses then decreases into the distant future, so that a peak of the number of pulses occurs only during July. This indicates a possible temporal shift in rainfall between present, intermediate and distant future periods.

e. Klein Catchment

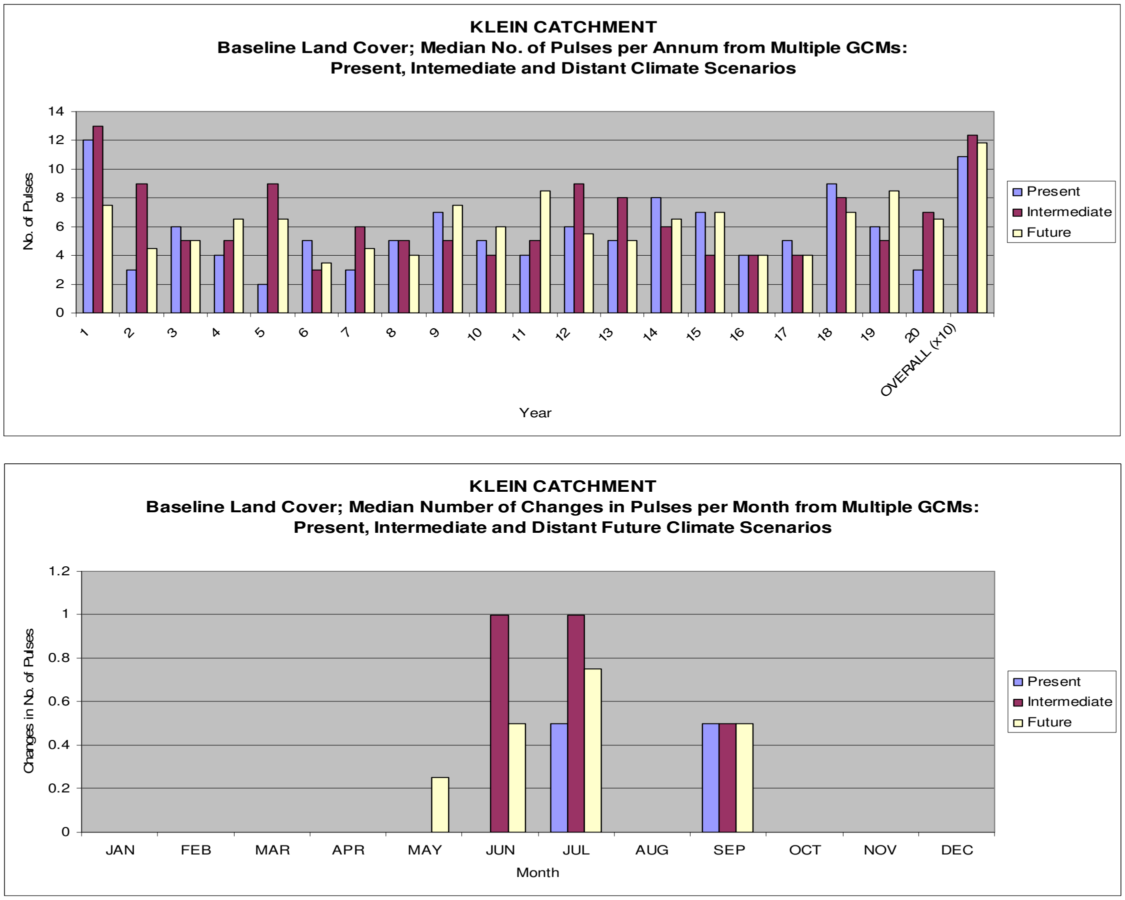
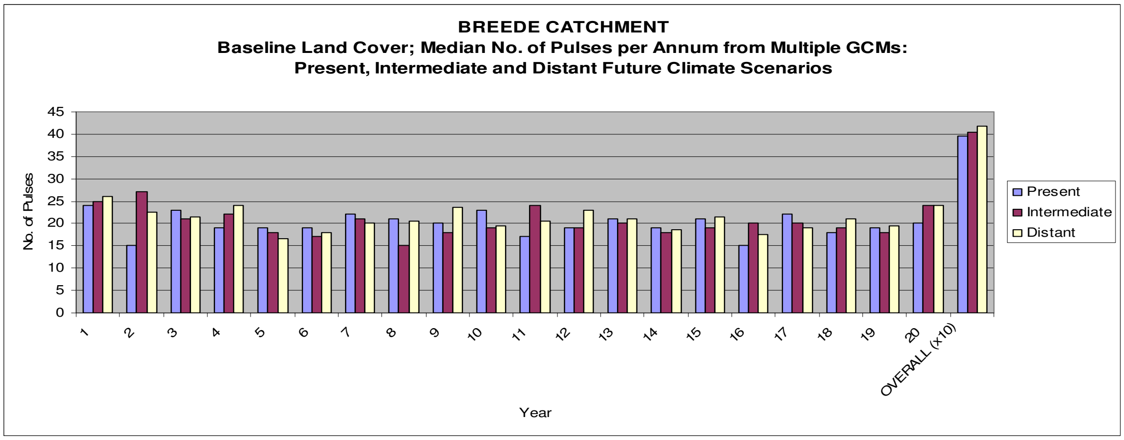


Figure 6.1.2.5: Median of the annual number of pulses (top graph), and changes in median monthly numbers of pulses (bottom graph) entering the Klein estuary during the present, intermediate and distant future time periods, derived from multiple GCMs

Figure 6.1.2.5 (top) illustrates increases in the occurrence of pulses from the present into the intermediate future in the Klein catchment. From the intermediate period into the distant future there is a slight decrease in the occurrence of pulses. Hence, it is possible that the occurrence of high runoff events over this region increases into the intermediate future and then decreases into the distant future. Figure 6.1.2.5 (bottom) illustrates an increase in the occurrence and distribution of pulses into the intermediate future during the winter months.

Into the distant future there is slightly wider time distribution in the occurrence of pulses; however, the number of pulses is not as high.

f. Breede Catchment



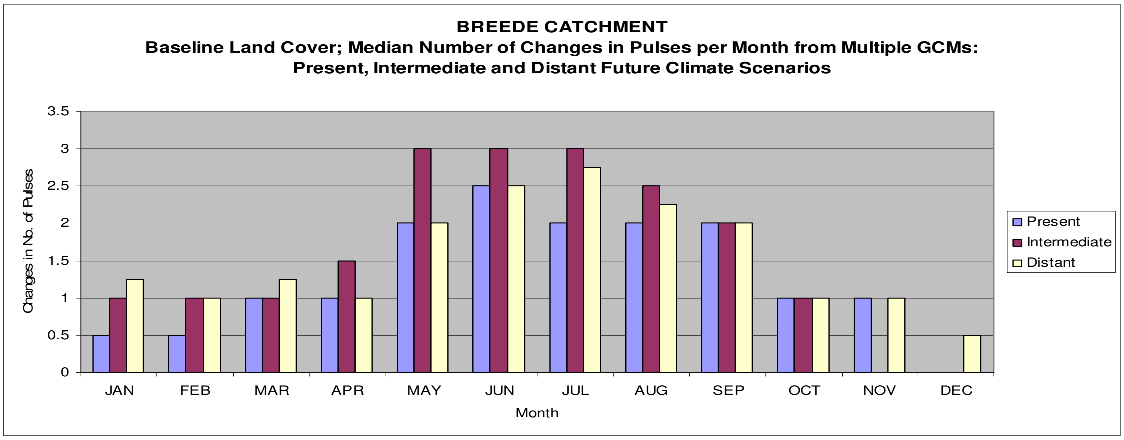


Figure 6.1.2.6: Median of the annual number of pulses (top graph), and changes in median monthly numbers of pulses (bottom graph) entering the Breede estuary during the present, intermediate and distant future time periods, derived from multiple GCMs

Figure 6.1.2.6 (top) illustrates the number of pulses into the estuary occurring annually during each of the three time periods from the Breede catchment. It is apparent that there is no distinct pattern between the present and future climate scenarios. While increases in streamflows are projected for this system (cf. Figure 6.1.1.6), there are only slight increases in the occurrence of pulses in the future. Figure 6.1.2.6 (bottom) illustrates that the highest number of pulses occurs in June during the present period. Into the intermediate future the number of pulses increases in winter and decreases in early summer, and distribution of the peak number of pulses is extended from one month to three, i.e May to July. Into the distant future this peak period contracts back to one month, and the number of pulses occurring is reduced, in the winter months and increases in summer, indicating a possible temporal shift in the occurrence of high intensity runoff events, and a more even distribution of rainfall throughout the year.

g. Krom Catchment

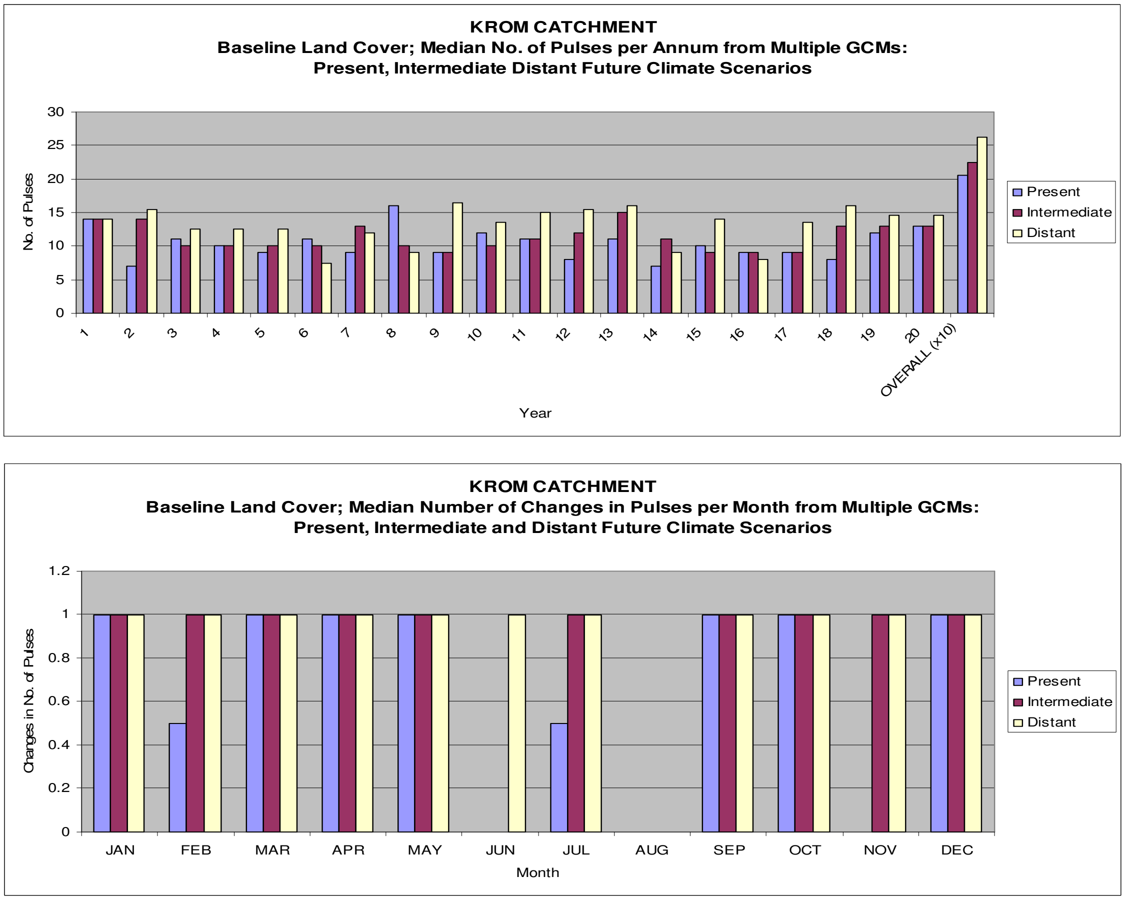
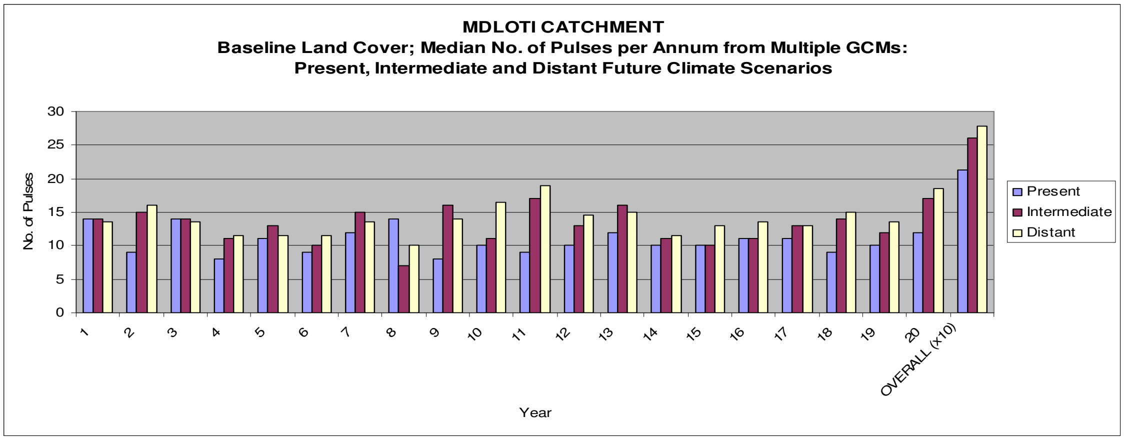


Figure 6.1.2.7: Median of the annual number of pulses (top graph), and changes in median monthly numbers of pulses (bottom graph) entering the Krom estuary during the present, intermediate and distant future time periods, derived from multiple GCMs

Figure 6.1.2.7 (top) illustrates the slight increase in the occurrence of pulses from the present into the intermediate future. Into the distant future period there is a slightly more marked increase in the number of pulses. This is most likely due to increases the in frequency of high runoff events over this region. The number of monthly pulses fluctuates during the present time period, as is shown in Figure 6.1.2.7 (bottom). However, into both the intermediate and distant future, the median number of pulses per month increases to one pulse per month, except during June and August in the intermediate period, and August in the distant future.

h. Mdloti Catchment



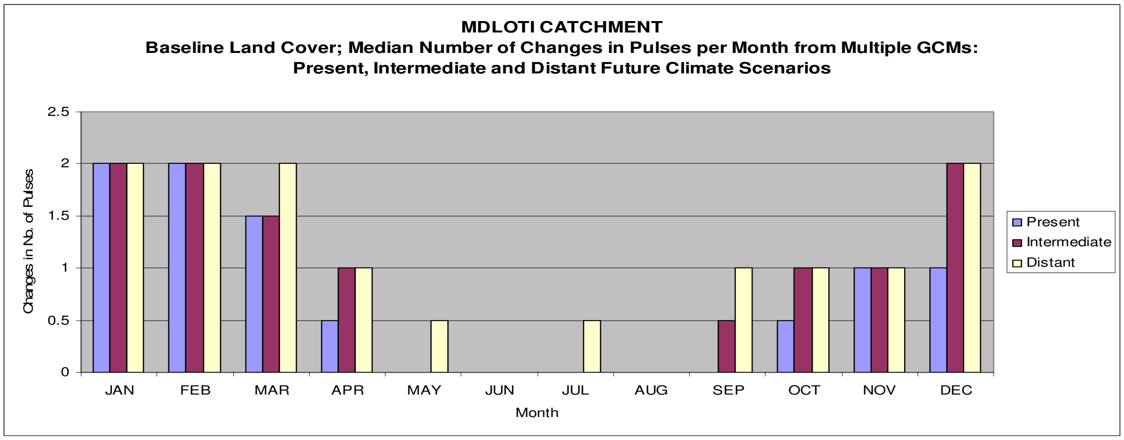
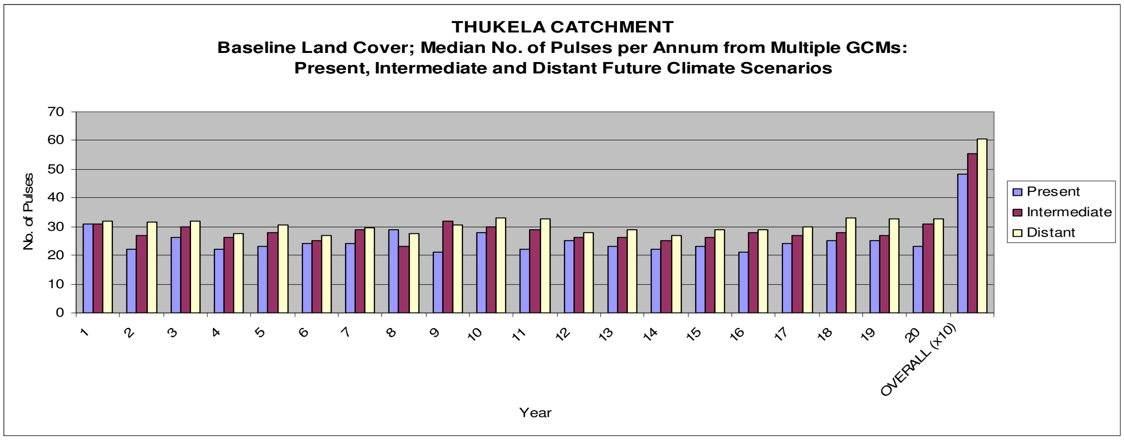


Figure 6.1.2.8: Median of the annual number of pulses (top graph), and changes in median monthly numbers of pulses (bottom graph) entering the Mdloti estuary during the present, intermediate and distant future time periods, derived from multiple GCMs

Figure 6.1.2.8 (top) shows an overall increase in the occurrence of pulses into the intermediate and distant future climate scenarios. As the Mdloti catchment is located in a region over which rainfall is projected to increase in both quantity and frequency of events, (Schulze, 2011a), it is highly probable that there could be an increase in the occurrence of pulses. The intra-annual pulses at monthly time steps in the Mdloti system are highly seasonal, and the highest number of pulses occurring in the summer months with an increase into the intermediate period during April and early spring. Into the distant future pulses also occur during the late autumn and winter period, when previously no pulses were simulated (Figure 6.1.2.8, bottom). This may be due to the increases in large runoff producing rainfall events during future summer periods, as corroborated by the frequency analyses in Sub-section 6.1.1.

i. Thukela Catchment



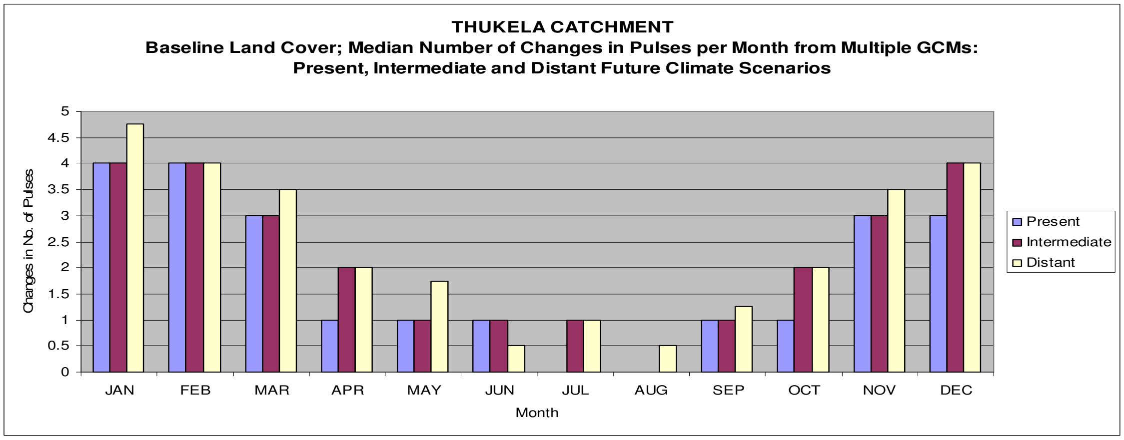
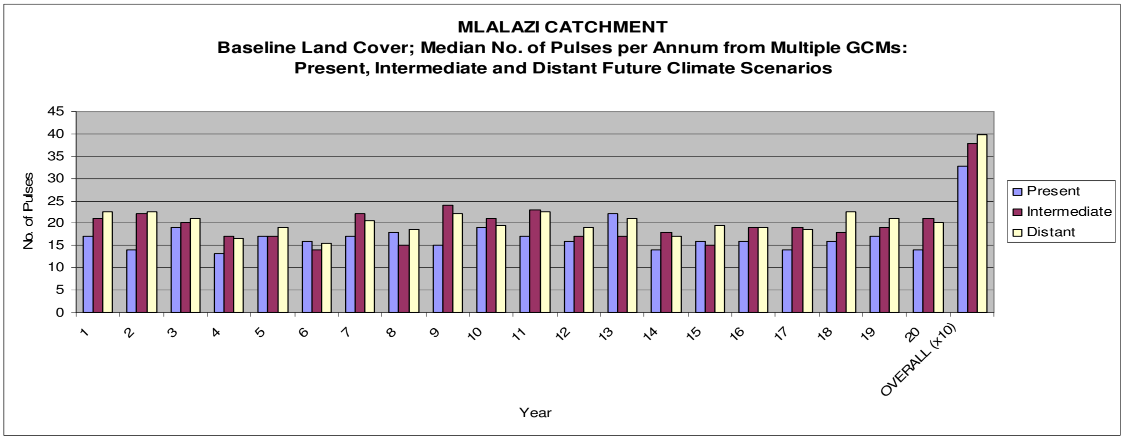


Figure 6.1.2.9: Median of the annual number of pulses (top graph), and changes in median monthly numbers of pulses (bottom graph) entering the Thukela estuary during the present, intermediate and distant future time periods, derived from multiple GCMs

Figure 6.1.2.9 (top) illustrates almost uniform increases in the occurrence of pulses into the intermediate and distant future periods in the Thukela catchment. This statement is supported by increases in the magnitude of flows entering the Thukela estuary into the intermediate and distant future, as shown in Sub-section 6.1.1. Figure 6.1.2.9 (bottom) illustrates increases in the median number of pulses into the intermediate future in 4 months and into the distant future in 10 month of the year. Additionally, pulses in future climate scenarios now occur during the winter period, when previously no pulses occurred. This is possibly a consequence of the Thukela catchment being located in the summer rainfall region over which increases are projected to occur in future. Owing the size of the Thukela catchment, rainfall events must be of significant size and/or must cover a significant area simultaneously before the increases in the magnitude of streamflow may be classified as a pulse.

j. Mlalazi Catchment



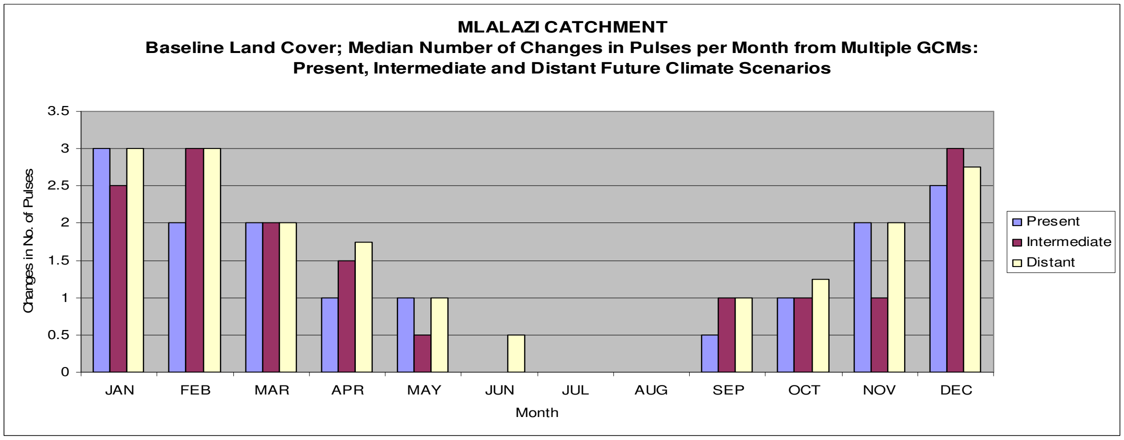


Figure 6.1.2.10: Median of the annual number of pulses (top graph), and changes in median monthly numbers of pulses (bottom graph) entering the Mlalazi estuary during the present, intermediate and distant future time periods, derived from multiple GCMs

Figure 6.1.2.10 (top) illustrates an overall increase in the occurrence of pulses in the Mlalazi catchment into the intermediate and distant future. This is possibly due to the location of the

Mlalazi catchment along the east coast, over which rainfall is projected to increase in both quantity and number of large events (Schulze, 2011a), consequently resulting in an increase in the occurrence of pulses. The intra-annual pulses at monthly level in the Mlalazi system are highly seasonal, with the highest number of pulses occurring the summer months. Additionally, the number of pulses occurring on a monthly basis increases into the intermediate future in three months, but also decreasing in three months, while into the distant future pulses increase in six months of the year, and also occurs during June when previously no pulses occurred, as shown in Figure 61.2.10 (bottom). As in the case of the Mdloti catchment, this is hypothesized to be due to the projected increases in rainfall concentration and intensity during future summer periods, as corroborated in Sub-section 6.1.1.

6.1.3 Analysis of Annual Sediment Loads Entering Ten Selected Estuaries

Freshwater sediment inputs into estuaries form a major physical component on which the productivity of estuarine ecosystems rely (Van Niekerk, 2007b). Sediments entering estuaries contain organic nutrients in the form of detritus derived from fauna and flora upstream of the estuary which add to the nutrient supply for micro-organisms in these ecosystems (McLusky, 1981; Kennish, 1986; Bonner *et al.*, 1990; Autenrieth *et al.*, 1991). Hence, it is important that freshwater inflows into estuaries be maintained, as marine sediments contain negligible quantities of nutrients.

It should be explained that in a non-linear system such as the hydrological system, any errors in rainfall are amplified when streamflows are simulated. These errors are usually further amplified in higher order hydrological responses in which the equations used contain exponents and multipliers (Schulze, 2003b), as in the case of sediment yield calculations (cf. Chapter 5, Sub-section 5.3.3).

In this study, as stated previously, all five GCMs were used in simulations of climate scenarios for the present (1971 – 1990), the intermediate (2046 – 2065) and distant future (2081 – 2100) periods. However, as the CCC GCM is not capable of simulating distant future climate scenarios, the four remaining GCMs were used for these simulations.

Additionally, unlike the monthly streamflow statistics and pulse analyses, the sediment yield analysis does not make use of median values. The reason for this is that in order to determine the annual sediment yield for each catchment, the resultant value for the 20 year period was divided by 20 in order to determine a mean annual sediment yield. These mean values were then used in these. Note again that the *ACRU* model outputs sediment yield on an event basis and per sub-catchment, in this instance, Quinary catchments. On a day-by-day basis the sediment yields entering an estuary were the sum of that day's sediment yield from all Quinaries making up that catchment, with cognisance taken of the shortcomings of this approach as discussed in Sub-section 5.7. What follows is a catchment-by-catchment assessment of the sediment yields entering the estuaries.

a. Buffels Catchment

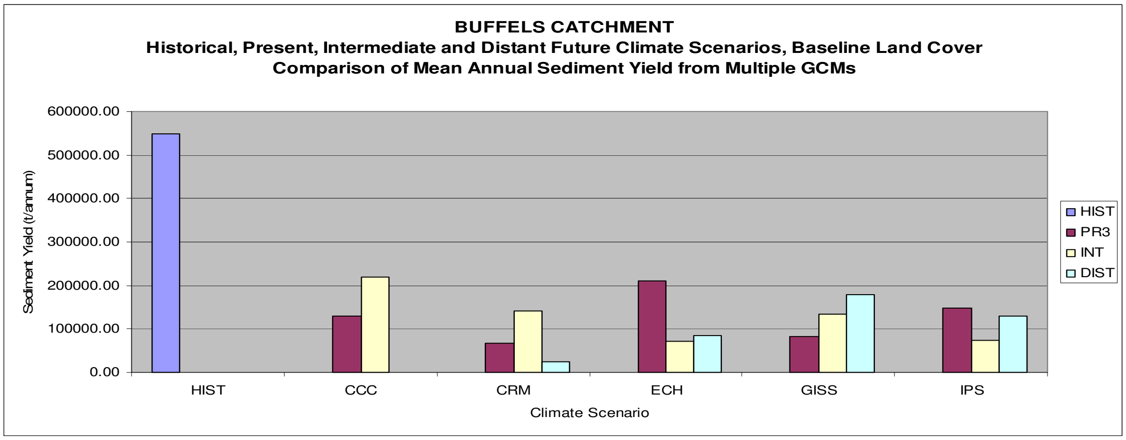


Figure 6.1.3.1: Comparison of simulated mean annual sediment yields entering the Buffels estuary, derived from historical climate as well as from present, intermediate and distant future climate scenarios from five GCMs

The results from the Buffels catchment display the well known hydrological phenomenon that simulations in semi-arid and arid regions generally yield inconsistent results. The reasons for this are the highly localised and infrequent runoff producing events over large catchments, which the coarse scaled GCMs do not capture, and that sediment yield estimates amplify any errors there may be in runoff generating events (cf. Appendix A). The inconsistencies also manifest themselves in differences in results between GCMs and results between the three climate scenarios of individual GCMs, with some displaying increases in future sediment yields into the future (CCC, CRM) while others show decreases (ECH, IPS).

b. Groen Catchment

Figure 6.1.3.2 illustrates the under-simulation of sediment yield entering the Groen estuary in all instances analysed. Additionally, like the Buffels catchment, the simulations of sediment yields from this catchment are inconsistent, further illustrating the local nature of rainfall:runoff events occurring in arid regions. Compared to the present, all five GCMs show an increase in the sediment yields into the intermediate future. Three of the four qualifying GCMs indicate a slight decrease in sediment yields from the intermediate into the distant future period. The increase and then decrease in the magnitude of sediment loads entering the Groen estuary is supported by fluctuations in streamflow that exhibit a similar pattern (cf. Sub-section 6.1.1).

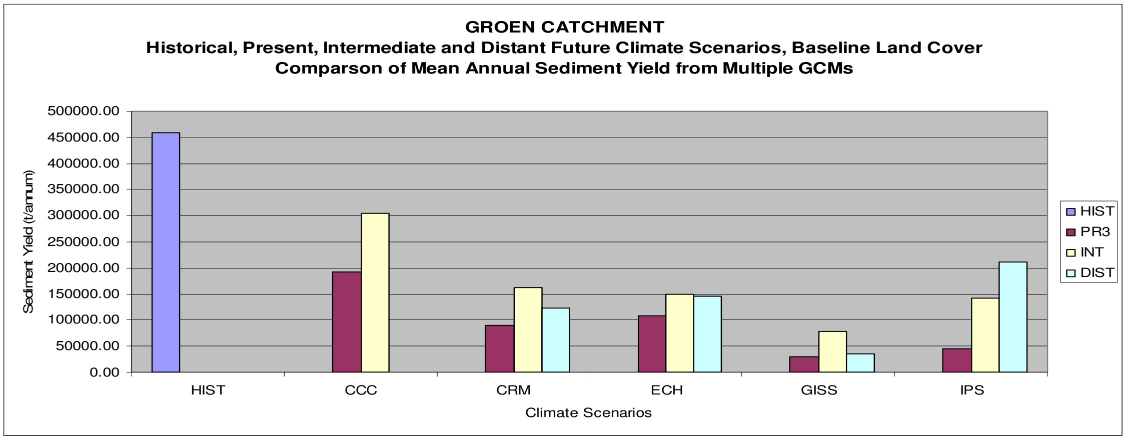


Figure 6.1.3.2: Comparison of simulated mean annual sediment yields entering the Groen estuary, derived from historical climate as well as from present, intermediate and distant future climate scenarios from 5 GCMs

c. Olifants Catchment

Figure 6.1.3.3 illustrates that three of the five GCMs show increases in the sediment load entering the Olifants estuary from the present into the intermediate future. Two of the four GCMs show further increases in sediment yield into the distant future. These increases in sediment yield from this catchment may be due to increases in stormflow events (cf. Figure 6.1.1.3). These result in increased sediment yields, which may decrease the primary productivity of this estuary as a consequence of higher turbidity levels (cf. Sub-section 3.1.2).

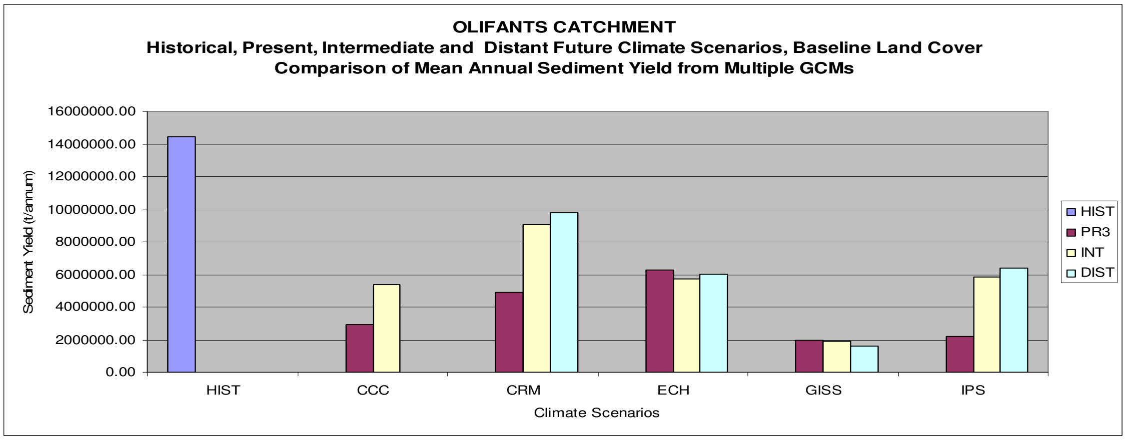


Figure 6.1.3.3: Comparison of simulated mean annual sediment yields entering the Olifants estuary, derived from historical climate as well as from present, intermediate and distant future climate scenarios from 5 GCMs

d. Berg Catchment

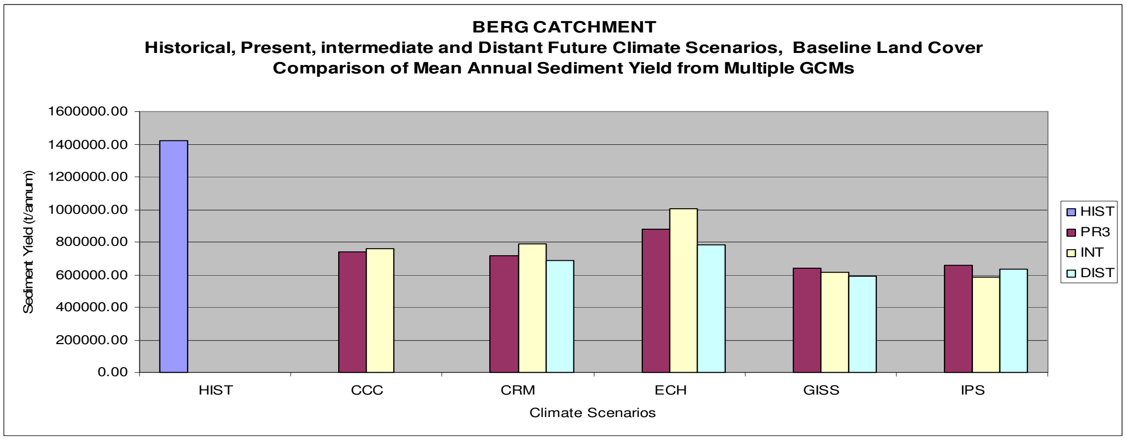


Figure 6.1.3.4: Comparison of simulated mean annual sediment yields entering the Berg estuary, derived from historical climate as well as from present, intermediate and distant future climate scenarios from 5 GCMs

Sediment entering the Berg estuary is projected to increase slightly from the present into the intermediate future, according to three out of the five GCMs, as shown in Figure 6.1.3.4 This possible increase may be a consequence of an increase in the magnitude of stormflow events over some regions of this catchment, which can result in higher sediment yields (cf. Figure 6.1.2.4). The quantity of sediments lost decreases into the distant future according to the results from three of the four GCMs that are capable of simulating this period. This is likely to be a consequence of decreased streamflows in the winter rainfall region.

e. Klein catchment

Figure 6.1.3.5 illustrates the under-simulation of sediment yields entering the Klein estuary when using climate input from all the GCMs used. Sediment simulations that are using climate input from the ECH GCM during the present period are reasonably accurate when compared with those simulated with historical climate data. Despite the variation in sediment yield between the GCMs, four of the five GCMs indicate an increase in the sediment load entering the Klein estuary into the intermediate future. This is likely a consequence of the increase in stormflow events occurring over this region (cf. Figure 6.1.1.5), thereby increasing the sediment yield. Three of the four GCMs indicate an increase in sediment yield between the intermediate and the distant future.

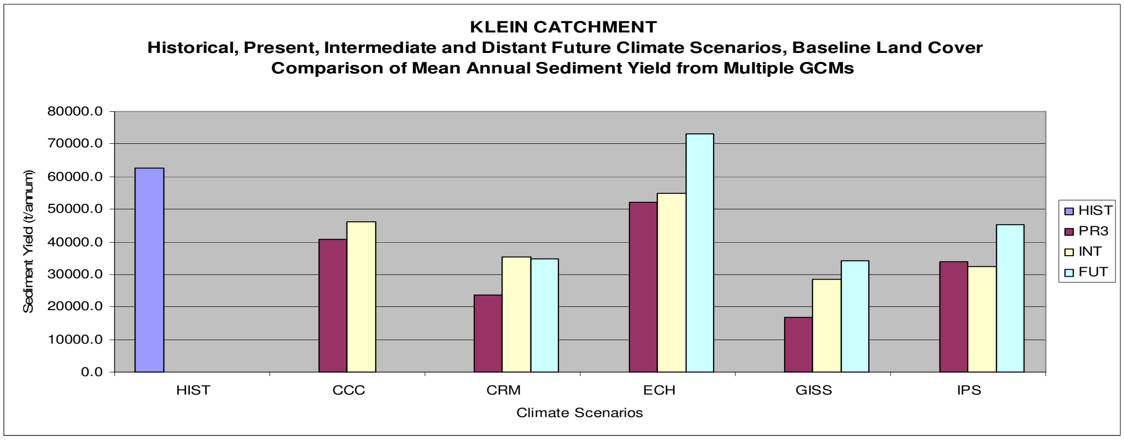


Figure 6.1.3.5: Comparison of simulated mean annual sediment yields entering the Klein estuary, derived from historical climate as well as from present, intermediate and distant future climate scenarios from 5 GCMs

f. Breede Catchment

From the comparison of sediment yield results derived from historical and present climate scenarios for the Breede estuary, sediment yields in Figure 6.1.3.6 indicate overall good results with a slight over-estimation in one GCM and slight under-estimations in the other four. Future projections indicate an increase in sediment yields from the present into the intermediate period from four out of the five GCMs. Supporting this result is the increase in simulated streamflow which was found into the intermediate future (cf. Figure 6.1.1.6). Decreases in sediments entering the estuary into the distant future are indicated by three of the four qualifying GCMs, and this finding concurs with decreases in simulated streamflows in the future for the Breede, as illustrated in Figure 6.1.1.6.

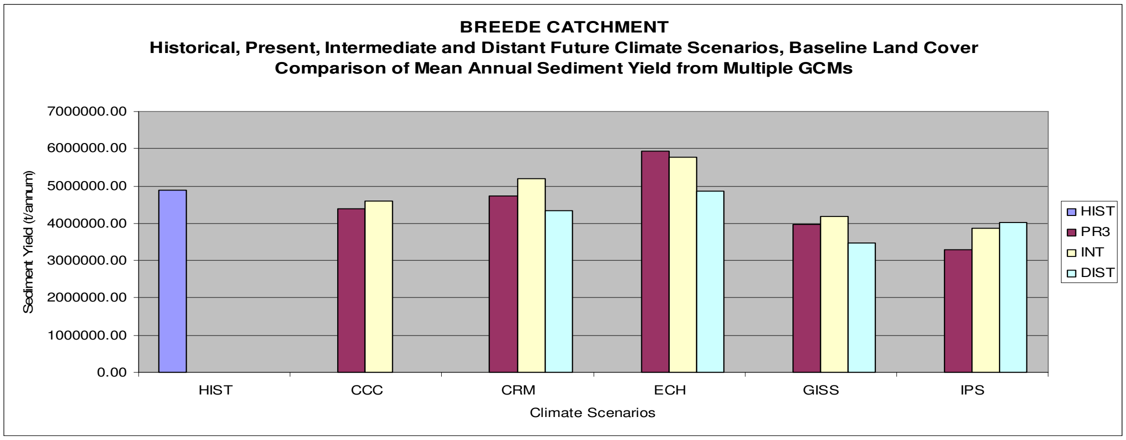


Figure 6.1.3.6: Comparison of simulated mean annual sediment yields entering the Breede estuary, derived from historical climate as well as from present, intermediate and distant future climate scenarios from 5 GCMs

g. Krom Catchment

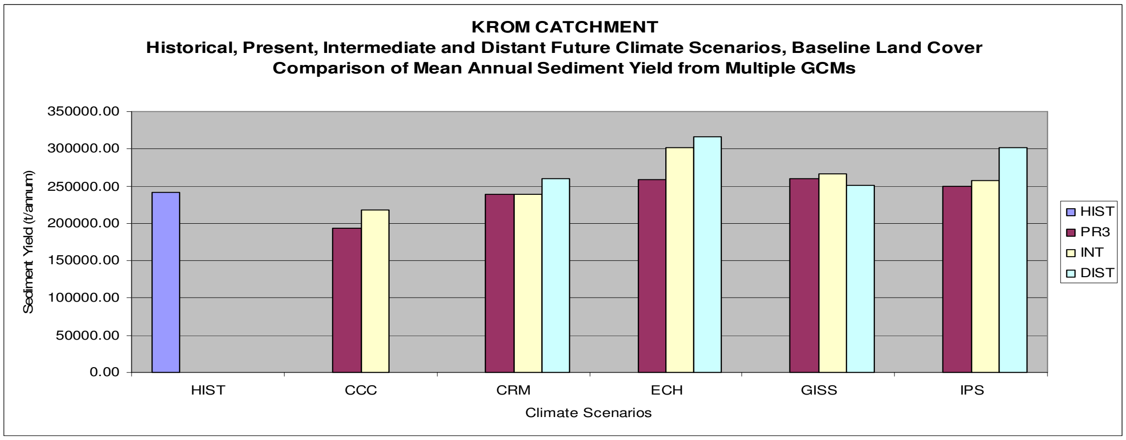


Figure 6.1.3.7: Comparison of simulated mean annual sediment yields entering the Krom estuary, derived from historical climate as well as from present, intermediate and distant future climate scenarios from 5 GCMs

Figure 6.1.3.7 illustrates that sediment yields from the Krom catchment, derived from the present climate scenarios of GCMs, generally match those from the historical record well. All GCMs show increases in sediment yield from the present into the intermediate future, which may occur as a result of increases in the magnitude of streamflows between these two periods (cf. Figure 6.1.1.7). Three of the four qualifying GCMs show an increase in sediment yield into the distant future.

h. Mdloti Catchment

Figure 6.1.3.8 illustrates an under-simulation of sediment yield in four of the five GCMs, the exception being GISS, for which it is well documented that rainfalls have been over-simulated (Schulze, 2011a). Four of the five GCMs indicate decreases in sediment yield from the present into the intermediate future. Into the distant future three of the four qualifying GCMs show increases in sediment yield. This may be a consequence of the projected increases in rainfall over this region, which could result in considerable increases in the magnitude of stormflow events as was shown in Figure 6.1.1.8.

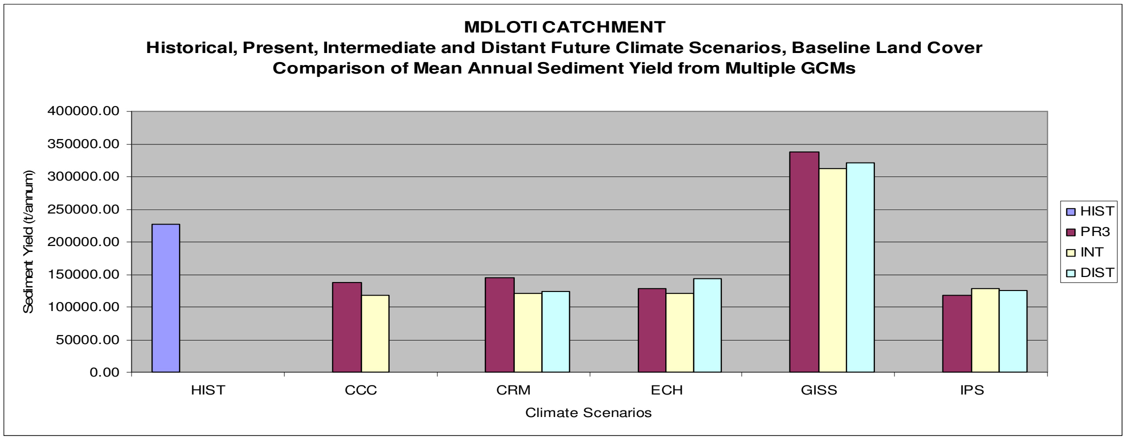


Figure 6.1.3.8: Comparison of simulated mean annual sediment yields entering the Mdloti estuary, derived from historical climate as well as from present, intermediate and distant future climate scenarios from 5 GCMs

i. Thukela Catchment

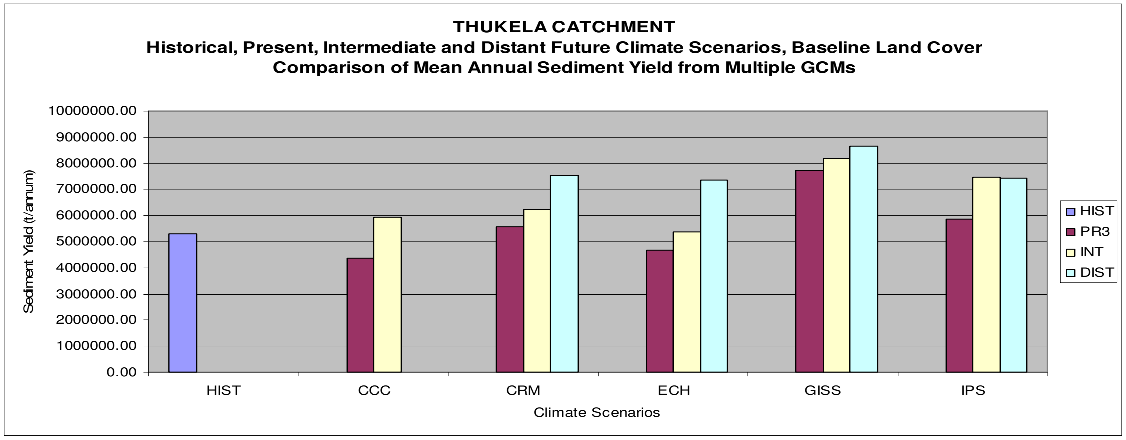


Figure 6.1.3.9: Comparison of simulated mean annual sediment yields entering the Thukela estuary, derived from historical climate as well as from present, intermediate and distant future climate scenarios from 5 GCMs

With the exception of sediment yields derived from the GISS GCM, the other GCMs display relatively similar results for the Thukela catchment for the results from the present climate scenarios when compared with results derived from the historical climate record. All GCMs show increases in sediment yield from the Thukela catchment from the present into the intermediate future. Three of the four qualifying GCMs indicate an increase in sediment yields from the intermediate into the distant future. The increase in sediment yield into the intermediate and distant future periods is supported by considerable increases in streamflow magnitudes (cf. Figure 6.1.1.9).

j. Mlalazi Catchment

Sediment yields entering the Mlalazi estuary have been under-simulated by all five GCMs. Four of the five GCMs indicate an increase (sometimes very small) in sediment yield from the present into the intermediate future, while one of the four qualifying GCMs illustrates a decrease in sediment yield into the distant future. The increase in streamflow magnitudes (cf. Figure 6.1.1.10) is likely to be the cause of increases in sediment yields.

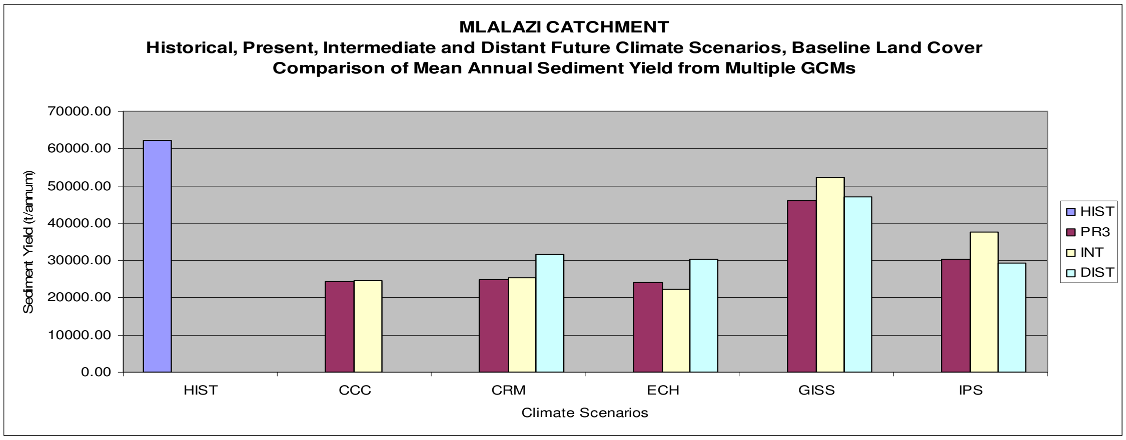


Figure 6.1.3.10: Comparison of simulated mean annual sediment yields entering the Mlalazi estuary, derived from historical climate as well as from present, intermediate and distant future climate scenarios from 5 GCMs

6.1.4 Discussion and Summary of Above Results

The results of simulations presented in Sub-sections 6.1.1 to 6.1.3 illustrate the effects of the:

- climate change scenarios used, the
- climate region in which each catchment is located, and the
- catchment size

on flows entering each of the ten selected estuaries. This Sub-section will provide a brief summary and discussion of the afore-going results.

The examination of flows from GCMs for the present period (1971 to 1990) from the catchments located in the eastern regions, i.e. in the summer rainfall region, highlights the seasonality of these systems, with peak mean flows occurring during summer. In contrast, peaks of mean flows for the present period in those catchments located in the western and southern regions occur during winter/early spring and all year, respectively. This is a direct consequence of the climate region in which each system is located. East coast regions may be broadly defined as summer rainfall regions, and west coast regions may be defined as winter rainfall regions, while south to south eastern coastal regions may be defined as all year rainfall regions. However, according to future projections made using the five downscaled GCMs available to this study, the occurrence of rainfall into the intermediate and distant future is projected to undergo temporal changes in places.

From the graphs presented in previous sub-sections, major temporal changes in the occurrence of rainfall are implied mainly over the southern and south western regions, eg. the Olifants and Breede catchments. This statement is supported by significant increases in flow magnitudes occurring during the summer period and decreases during the winter period when using outputs from future climate scenarios. However, the temporal shift in rainfall does not occur over the whole of South Africa; it appears to impact differently on each climate region.

In the summer rainfall region no significant temporal changes in the occurrence of rainfall are implied when changes in streamflows are analysed projected. However, there is a marked increase in the magnitude of flows into intermediate and distant future periods from catchments located in this region, especially in the Thukela catchment. These increases vary considerably and have different manifestations on streamflows into estuaries due to the differing catchment characteristics (cf. Tables 4.3 to 4.12).

Considerable increases in future streamflows are projected for the Thukela catchment (29 200 km^2), while the increases into the intermediate and distant future in the smaller Mdloti (602 km^2) and Mlalazi (503 km^2) systems are not as distinct. A similar pattern is illustrated in the southern regions with large catchments, such as the Breede (12 500 km^2), exhibiting increases in flows of a much greater magnitude than either the smaller Krom (1 018 km^2) or Klein (989 km^2) river systems. A likely reason for the large catchments responding relatively more than the smaller ones is that the headwaters of the large catchments tend to be in mountainous high rainfall (hence very high runoff) areas, while the smaller catchments generally do not experience the altitudinal influence on rainfall as much.

Evidence for changes in flows is provided by the annual changes in sediment yield and the changes in the number of annual pulses occurring from the 10 selected catchments. Both variables imply an increase in rainfall during the intermediate and distant future periods in the eastern regions. However, the southern (all year) and western (winter) rainfall regions show a much greater uncertainty in changes in sediment yield and numbers of pulses. This may be due to the uncertainty in projections of rainfall over these regions.

6.2 Results and Discussion 2: A Case Study on Simulated Impacts of Upstream Land Uses and Channel Changes on Hydrological Responses into the Klein River Estuary, Excluding and Including Effects of Irrigation

Land cover is defined as the bio-physical state of the earth's surface and its sub-surface in terms of broad categories such as cropland, grassland and man-made forests. Land use, on the other hand, is defined as the conversion of land cover, through anthropogenic alteration, for many purposes, but mainly for agricultural was and human settlement.

The magnitude of alteration to natural ecosystems through anthropogenic activities may be categorized by their effects on water resources. In the case study of the Klein catchment the baseline land cover has been converted to the following categories of ecosystems recognised by Hobbs and Hopkins (1990):

- *Utilised ecosystems*, which is the exploitation of a natural system <u>without</u> impacting on the hydrological system, e.g. recreation land uses (Hobbs and Hopkins, 1990; Schulze, 2003a), and
- *Replaced ecosystems*, which is the replacement of an indigenous ecosystem with a simpler system designed for a single purpose, such as forestry, <u>with</u> an impact on the partitioning of rain water flows in the catchment, thereby affecting hydrological responses (Hobbs and Hopkins, 1990).

6.2.1 Analysis of Monthly Streamflows entering the Klein Estuary

a. Klein – Monthly Streamflow Statistics under Present Climate Scenarios

Figure 6.2.1.1 shows monthly statistics of flows entering the estuary of the Klein during the present period, with statistics derived for baseline land use (top) and actual land use. Because the extent of replaced rainfed ecosystems in the Klein catchment is not large (cf Chapter 5, Table 5.3.6.2), the magnitude of impacts on the Klein estuary are likely not be exceptional. The reasoning here is that where the land cover in the Klein catchment has been changed to rainfed agricultural uses, these still provide adequate canopy cover and soil surface cover (Table 5.3.6.3), as does the baseline land cover. Therefore, stormflows and sediment yields are not expected to change significantly from those under baseline land cover conditions. This is illustrated in Figure 6.2.1.1 (middle) by comparing the differences between monthly streamflow statistics derived from baseline land cover and actual land use (excluding irrigation). However, when irrigation is included in simulations, differences in flow entering the Klein estuary become more pronounced because with irrigation water is abstracted directly from either a dam or a river. This bigger difference is illustrated in Figure 6.2.1.1 (bottom). A more detailed interpretation of Figure 6.2.1.1 is given below.

Figures 6.2.1.1 (top and middle) illustrate slight increases in mean flows when a comparison between flow statistics baseline land cover and actual land use, but excluding irrigation. When simulations of the effects of upstream irrigation are included, Figure 6.2.1.1 (bottom) illustrates a decrease in the magnitude of flows when compared with the increase when irrigation is excluded Figure 6.2.1.1 (top and middle). This is especially apparent during the dry summer period, as the highest irrigation abstractions are most likely to occur during this period. Figure 6.2.1.1 (bottom) illustrates this by the significant decrease in flows in the driest year in 10, because of higher irrigation demands under dry conditions.

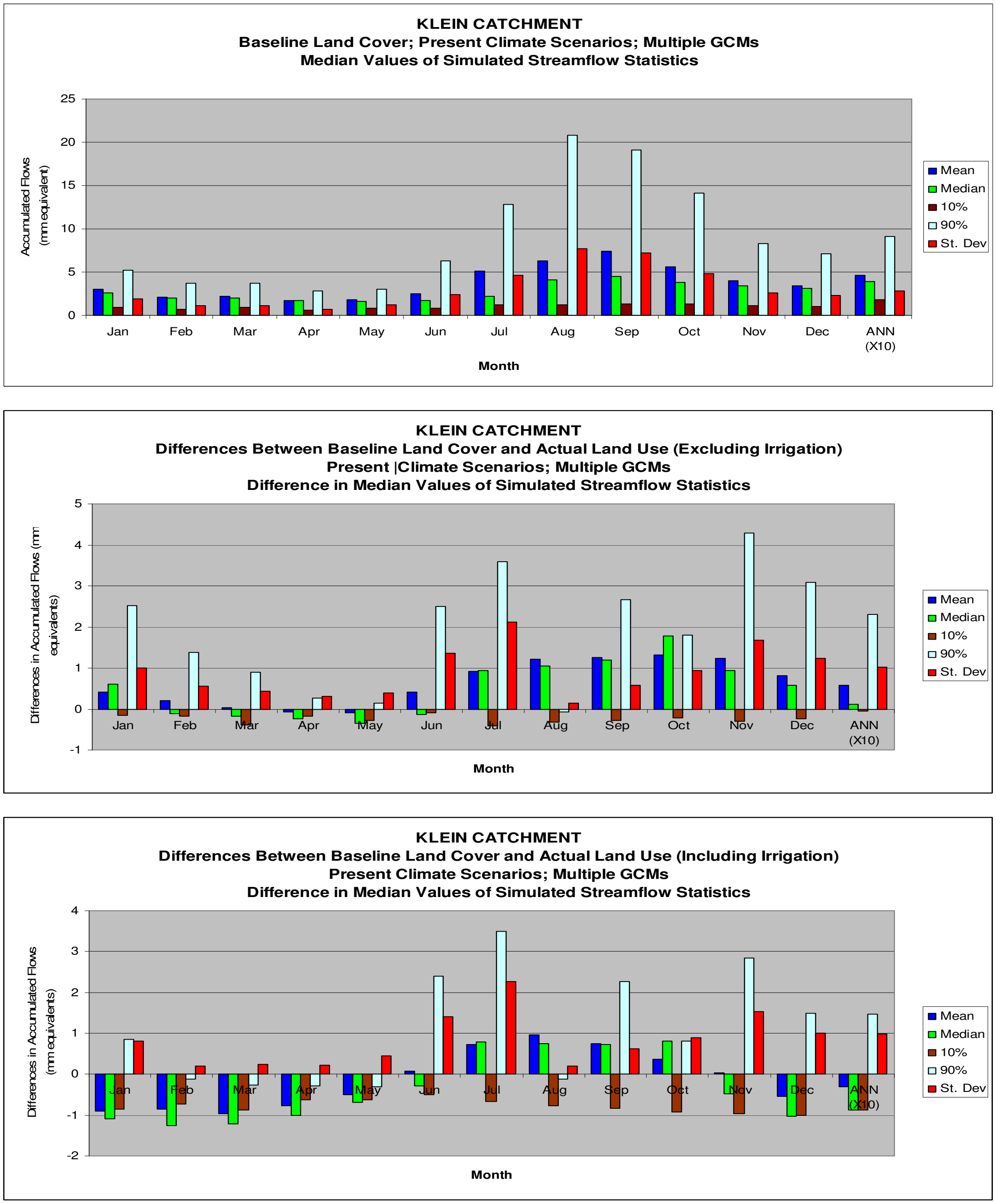


Figure 6.2.1.1: Monthly statistics of flows into the Klein estuary derived from multiple GCMs for the present period, assuming baseline land cover (top), and differences in flow statistics between baseline land cover and actual land use excluding irrigation effects (middle), and actual land use including irrigation effects (bottom)

b. *Klein – Changes in Monthly Streamflow Statistics Between the Intermediate and Present Climate Scenarios*

Figures 6.2.1.2 (top) and (middle) illustrate an increase in flows from the present into the intermediate future. However, increases in mean flows are more evenly distributed throughout the year under baseline land cover simulations. Additionally, the results from actual land use simulations excluding irrigation (cf. Figure 6.2.1.2, middle graph) show that the increases in flow magnitudes are not as significant as those illustrated from baseline land cover results. Flows in the driest year in 10 increase significantly when actual land use is included in simulations. However, this is a consequence of the increases being expressed in relative terms rather than being expressed volumetrically (cf. Sub-section 6.1.2). Figure 6.2.1.2 (bottom) illustrates significant increases in the magnitude of flows in dry years when irrigation abstractions are included, especially during the dry summer period, when compared with the results shown in Figures 6.2.1.2 (top) and 6.2.1.2 (middle). This is again due to the graph showing relative rather than volumetric changes. In addition, changes in mean flows are projected to increase more during the dry summer period. This is surmised again to be a consequence of the use of relative changes appearing much greater than they are volumetrically.

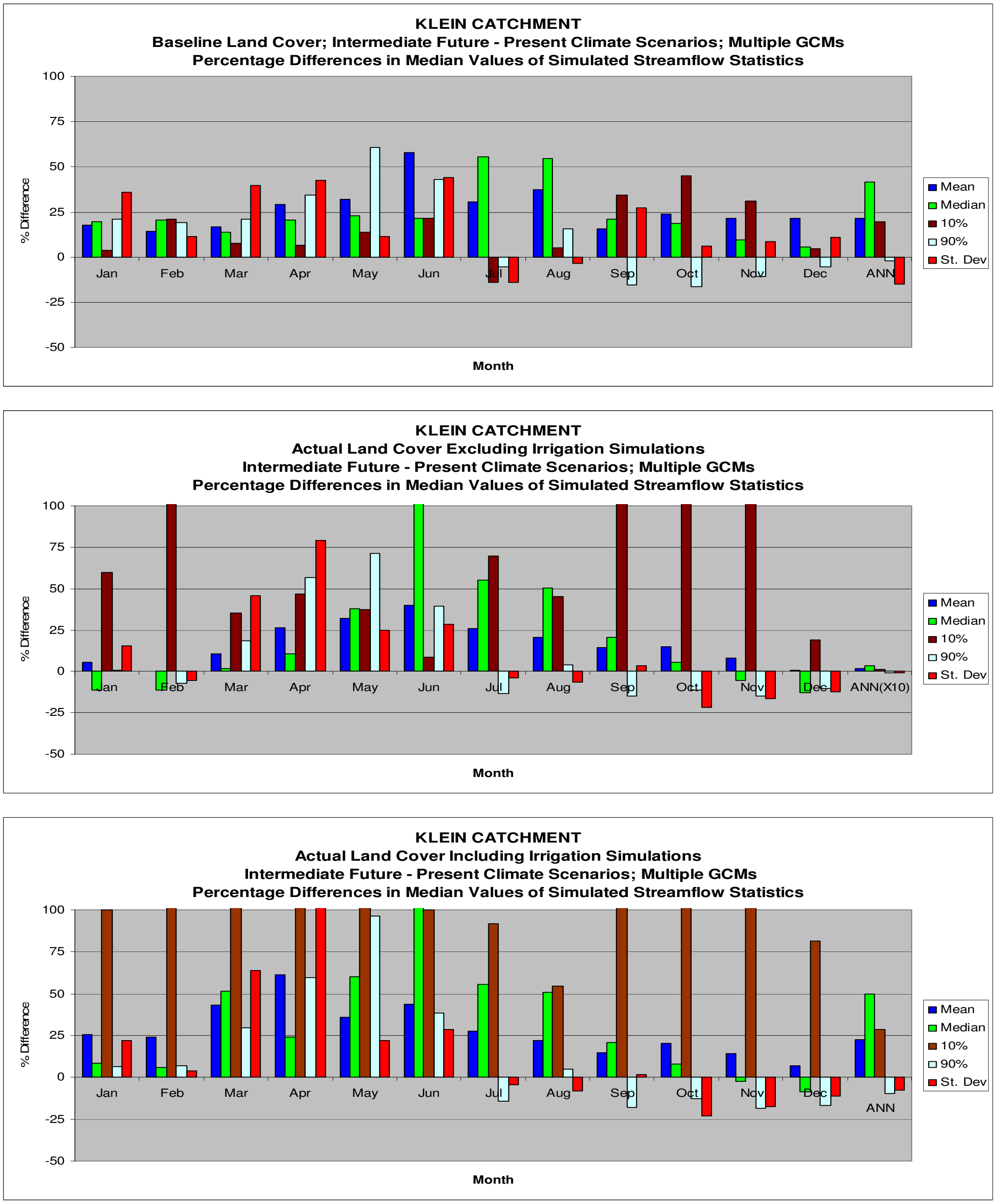


Figure 6.2.1.2: Changes in monthly statistics of flows into the Klein estuary between the intermediate future and present climate scenarios, derived from multiple GCMs, assuming baseline land cover (top), actual land use excluding irrigation (middle), and actual land use including irrigation (bottom)

c. Klein – Changes in Monthly Streamflow Statistics Between the Distant Future and Present Climate Scenarios

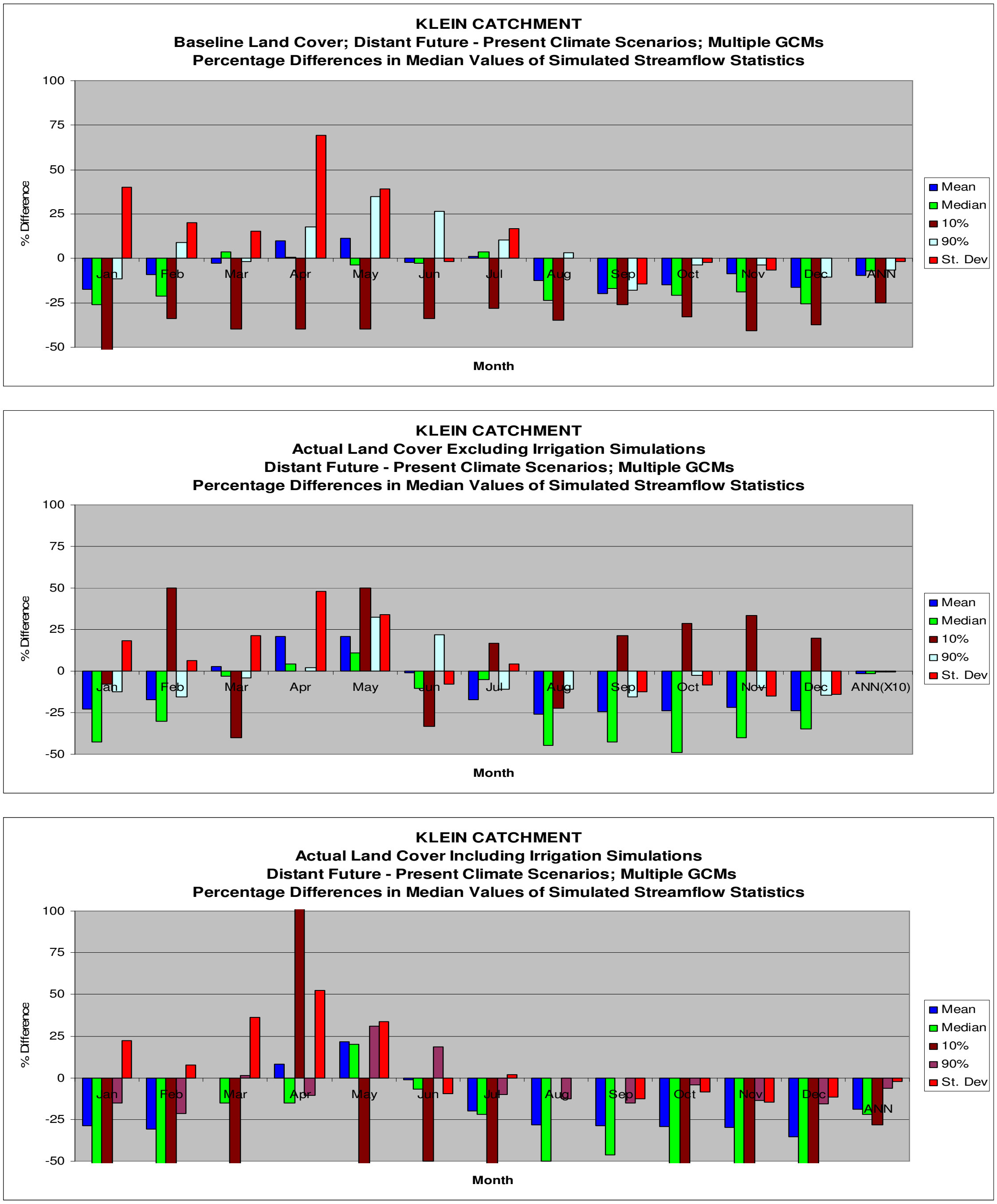


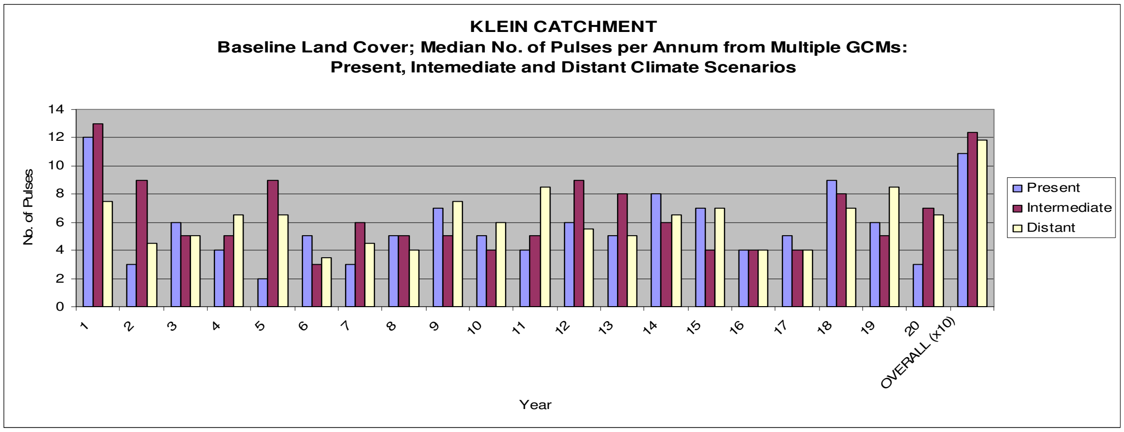
Figure 6.2.1.3: Changes in monthly statistics of flows into the Klein estuary between the distant future and present climate scenarios, derived from multiple GCMs, assuming baseline land cover (top), actual land use excluding irrigation (middle), and actual land use including irrigation (bottom)

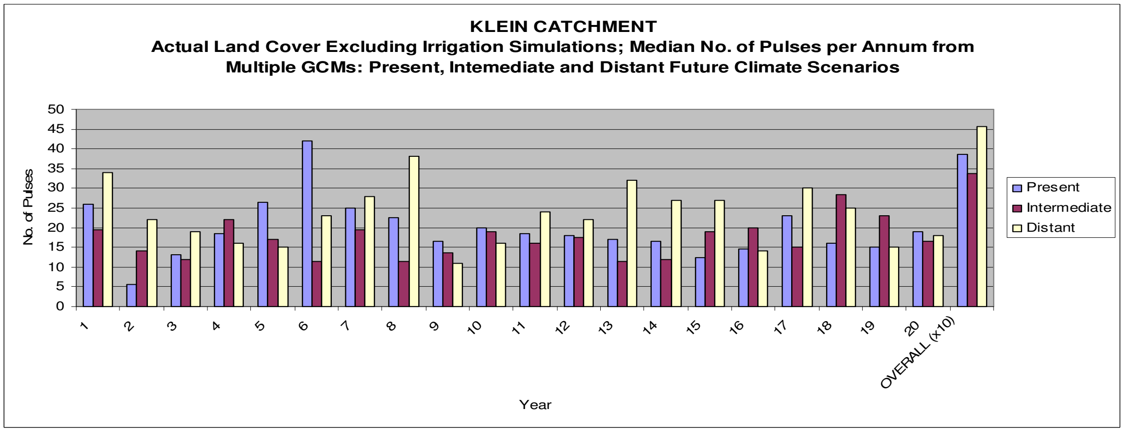
The comparison of Figure 6.2.1.3 (top and middle) illustrates a decrease in changes of the magnitudes of flows between the distant future and present climate scenarios during the dry summer and wet winter periods. However, when actual land use (excluding irrigation) is included in these simulations (cf. Figure 6.2.1.3 middle) the decreases in means become much greater. A comparison of Figure 6.2.1.3 (bottom) with Figure 6.2.1.3 (top and middle) illustrates that irrigation will impact negatively on the magnitude of future flows during both the dry summer and the wet winter, the former as a consequence of additional abstractions during the dry summer and the latter as a consequence of a temporal shift in rainfall over this region (cf. Figure 6.1.1.5). Hence, it appears that from this comparison, the inclusions of both actual land use without irrigation and with irrigation in streamflow simulations result in the amplification of the result of baseline simulations (cf. Figure 6.2.1.3 top).

6.2.2 Analysis of Pulses of Flows into the Klein Estuary

a. Klein – Median Number of Pulses per Annum under Different Climate Scenarios

In this analysis it is important to note the differences in the y-axis scales between the three figures representing baseline land cover conditions (cf. Figure 6.2.2.1 top), actual land uses excluding irrigation effects (cf. Figure 6.2.2.1 middle) and actual land uses including upstream irrigation effects (cf. Figure 6.2.2.1 bottom). These scale differences arise out of pulses into estuaries being defined as relative (i.e. percentage) changes from one day to the next rather than volumetric changes. The inclusion of actual land use in simulations shows an increase in the number of pulses when results of baseline land cover (cf. Figure 6.2.2.1 top) and actual land use (cf. Figure 6.2.2.1 middle) simulations are compared. Figure 6.2.2.1 bottom, which includes effects of upstream irrigation, illustrates an increase in the number of pulses into the intermediate future and then a decrease in the number of pulses into the distant future. This is similar to the results from the baseline land cover simulations (cf. Figure 6.2.2.1 top). However, the overall number of pulses is considerable at, between 160 and 180, compared to between 10 and 14 from the baseline simulations. Therefore, this comparison illustrates a decrease in the overall magnitudes of flows entering the Klein estuary when irrigation abstractions are factored in. This statement highlights once again the fact that the increase in the number of pulses is relative, and therefore a volumetrically smaller flow as a consequence of upstream abstractions will, in turn, imply that the flow increases do not have to be as great to qualify as a pulse.





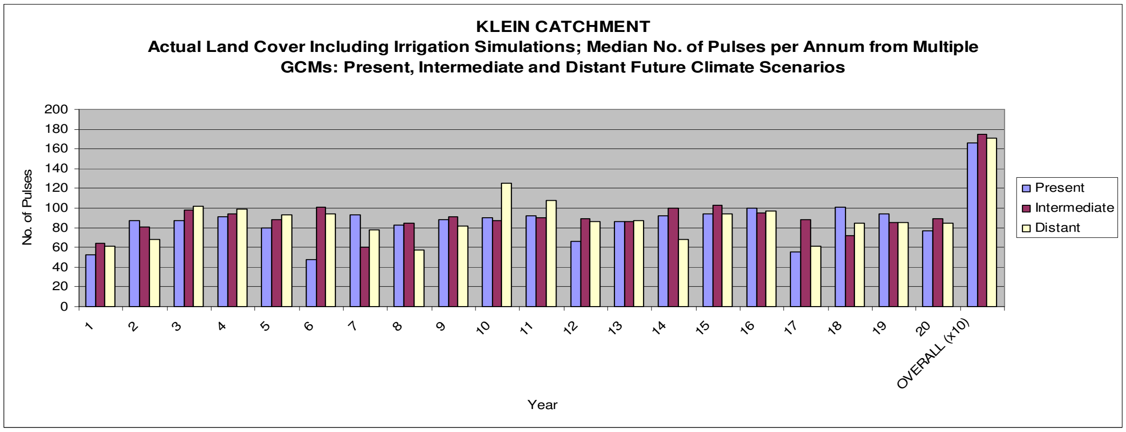
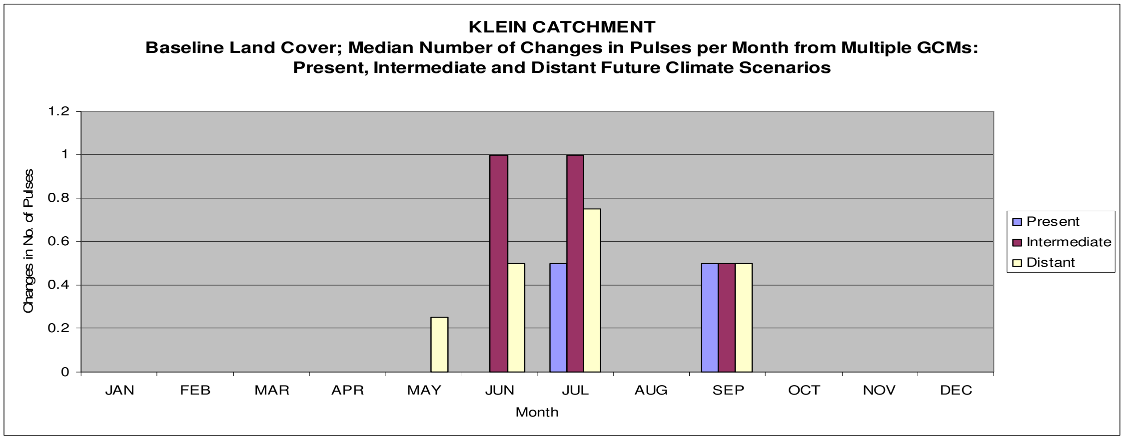
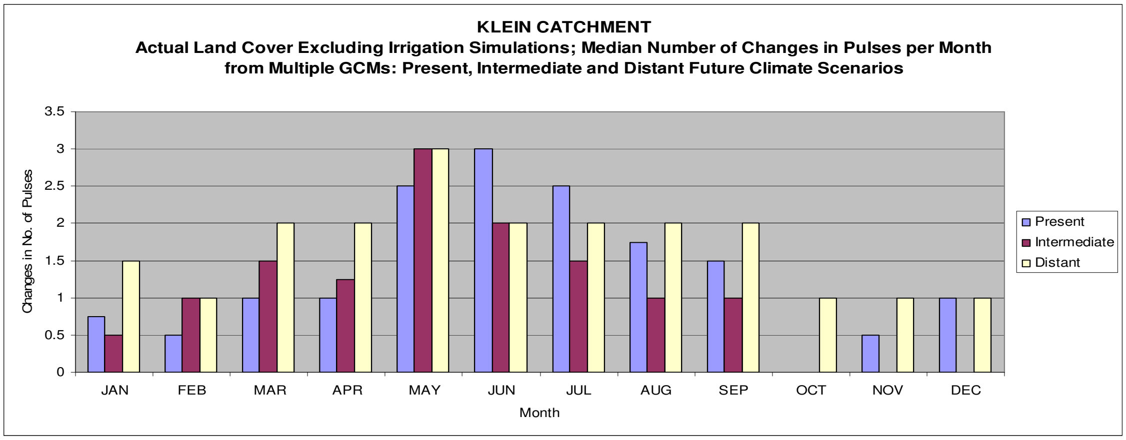


Figure 6.2.2.1: Annual numbers of pulses into the Klein estuary, derived from multiple GCMs for present, intermediate and distant future climate scenarios, assuming baseline land cover (top), actual land use excluding upstream irrigation (middle), and actual land use including upstream irrigation (bottom)

b. Klein – Median Number of Changes in Pulses per Month





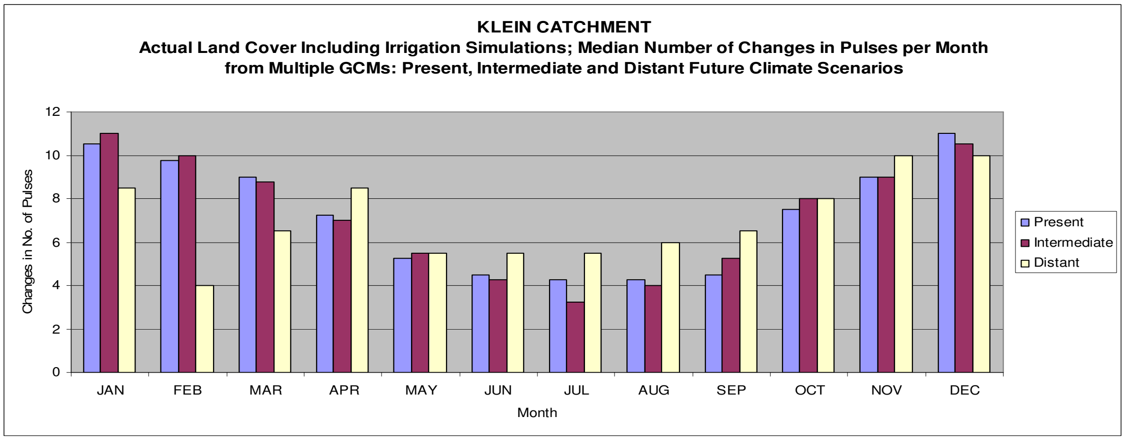


Figure 6.2.2.2: Monthly numbers of pulses into the Klein estuary, derived from multiple GCMs for present, intermediate and distant future climate scenarios, assuming baseline land cover (top), actual land use excluding upstream irrigation (middle), and actual land use including upstream irrigation (bottom)

In this analysis it needs to be re-iterated that it is critical to note the differences in y-axis scales between the three figures representing baseline land cover conditions (Figure 6.2.2.2 top), actual land use excluding upstream irrigation effects (Figure 6.2.2.2 middle), and actual land use including upstream irrigation effects (Figure 6.2.2.2 bottom). These scale differences arise out of pulses into estuaries being defined as relative (i.e. percentage) changes from one day to the next, rather than as volumetric changes. Under baseline land cover conditions pulses occur only in the wet winter season for all three climate scenarios (Figure 6.2.2.2 top). Figure 6.2.2.2 (middle) on pulses from actual land use, but excluding irrigation, illustrates a considerable increase in the number of pulses occurring on a monthly basis when compared with results from simulations using baseline land cover (cf. Figure 6.2.2.2 top). Figure 6.2.2.2 (middle) illustrates an increase in the number of pulses during winter and then during the summer period, which is due to the decreases in flows, and the use of relative values rather than volumetric values. When results of simulations including irrigation (cf. Figure 6.2.2.2 bottom) are compared with those from baseline land cover (cf. Figure 6.2.2.2 top) and actual land uses excluding irrigation effects (cf. Figure 6.2.2.2, middle), it is found that the number pulses occurring increases markedly. For this land use scenario the increase in the number of pulses is most pronounced during the dry summer period, when most irrigation abstractions occur, which was not the case when irrigation impacts were omitted. Additionally, the number of pulses occurring during winter does not increase to the same extent, as a consequence of greater flows during this wet period when irrigation abstractions occur less frequently.

6.2.3 Analysis of Annual Sediment Loads entering the Klein Estuary

For the annual sediment yield analysis, no simulations were performed for the actual land use scenarios including irrigation effects, as all irrigation abstractions were out of dams (cf. Chapter 5) and the *ACRU* Model does not yet include routines for sediment yield trapping in reservoirs and nor for sediments in suspensions from overflows out of the dams. The comparison of Figures 6.2.3.1 (top and bottom) illustrates a relatively small change in the pattern of results of sediment yields obtained from each of the GCMs. However, it may be stated that there is a considerable increase (~ 15%) in sediment yield when the quantity of sediments, obtained from baseline (cf. Figure 6.2.3.1 top) simulations is compared with the quantity of sediment obtained from simulations including actual land use (cf. Figure 6.2.3.1, bottom). In general, sediment yields derived from show an increase into the future.

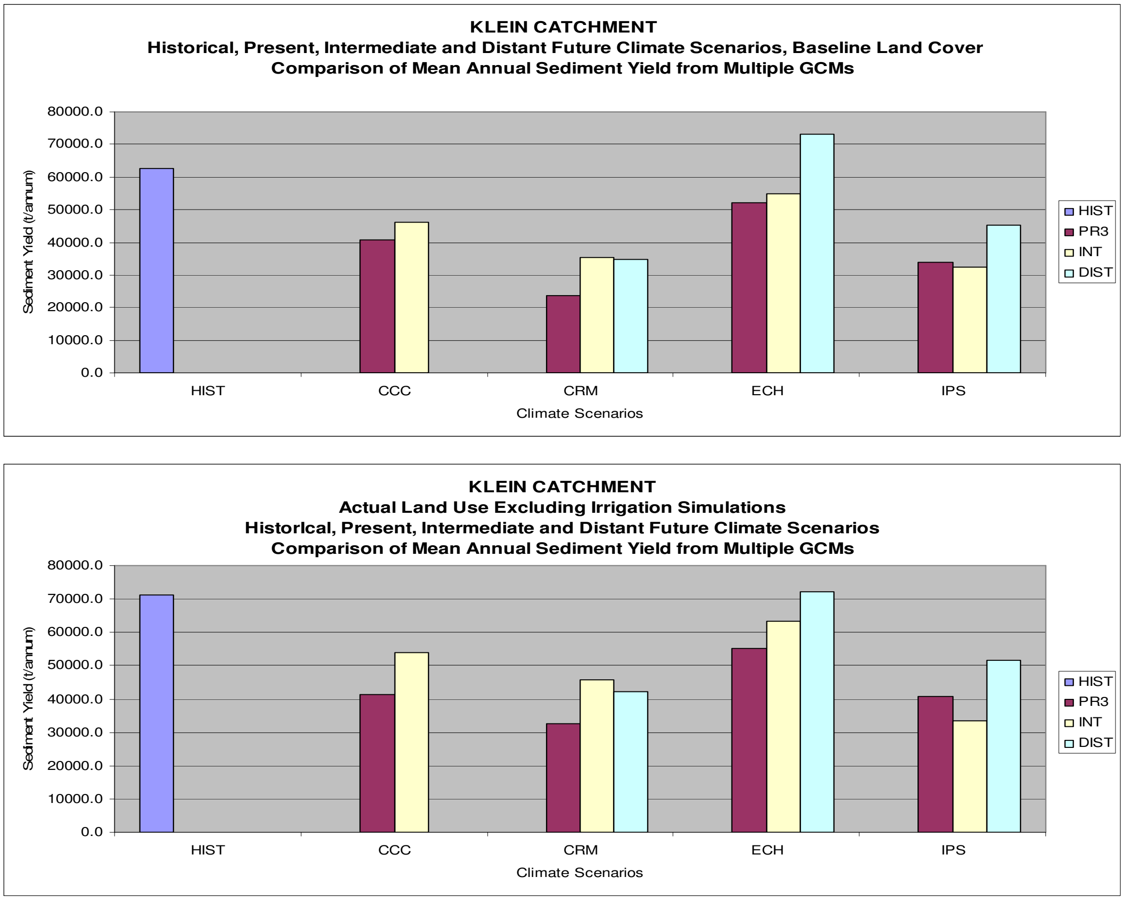


Figure 6.2.3.1: Comparison of simulated mean annual sediment yields entering the Klein estuary under baseline land cover conditions (top) and actual land use (excluding irrigation; bottom), derived from historical climate as well as from present, intermediate and distant future climate scenarios from four GCMs

6.2.4 Analysis of Breaching Events of the Klein Estuary

Methodology for the calculation of Breaching Events of the Klein Estuary Re-Visited

At the time of commencement of the simulation the volume of the Klein estuary was set at 4 000 000 m^3, and the volume at which the estuary was set to breach was, after consultation with Van Niekerk, (2010b), set at a threshold of 24 000 000 m^3. Upon the breaching of the berm, the estuary was set to lose 20 000 000 m^3 over a 24 hour period, as would have occurred in reality, resulting in severe scouring of the mouth. In this case the Klein estuary mouth was set to remain open for approximately 150 days or 5 months, as a consequence of continued entrainment, before sediment deposits result in mouth closure. During this period the estuary would normally fill, but in the model the volume was set to remain static at 4 000 000 m^3, before filling was allowed to occur.

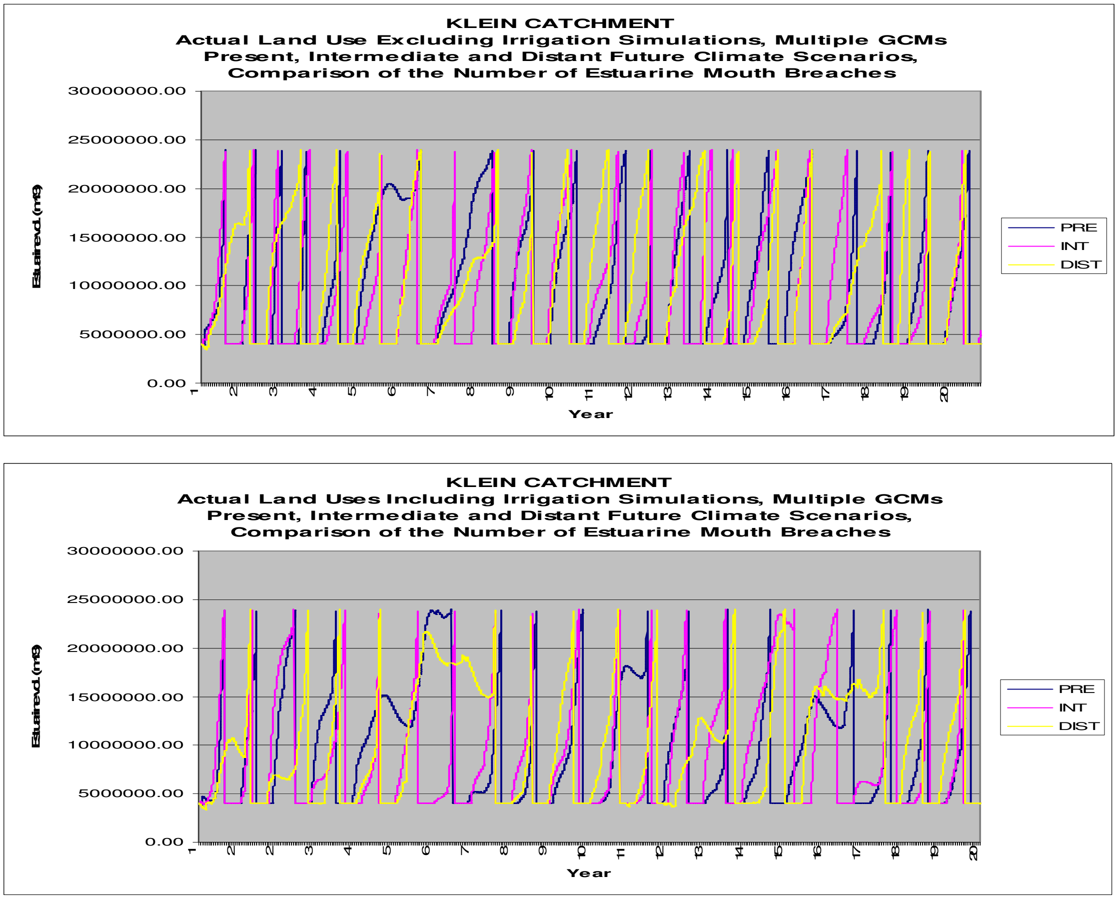


Figure 6.2.4.1: Simulated breaching events of the Klein estuary occurring during the 20 year periods constituting the present, intermediate and distant future climate scenarios for actual land use conditions excluding irrigation simulations (top) and including irrigation simulations (bottom)

Figure 6.2.4.1 (top) illustrates that breaching events occur almost every year during the present period, when irrigation simulations are excluded. Into the intermediate future the number of breaching events increases to occur regularly on an annual basis. In contrast, the number of breaching events into the distant future decreases, as a consequence of decreased streamflows (cf. Figure 6.2.1.3 middle). When compared with simulations including irrigation, the number of breaching events decreases from occurring regularly on an annual basis during the present period (cf. Figure 6.2.4.1 bottom).

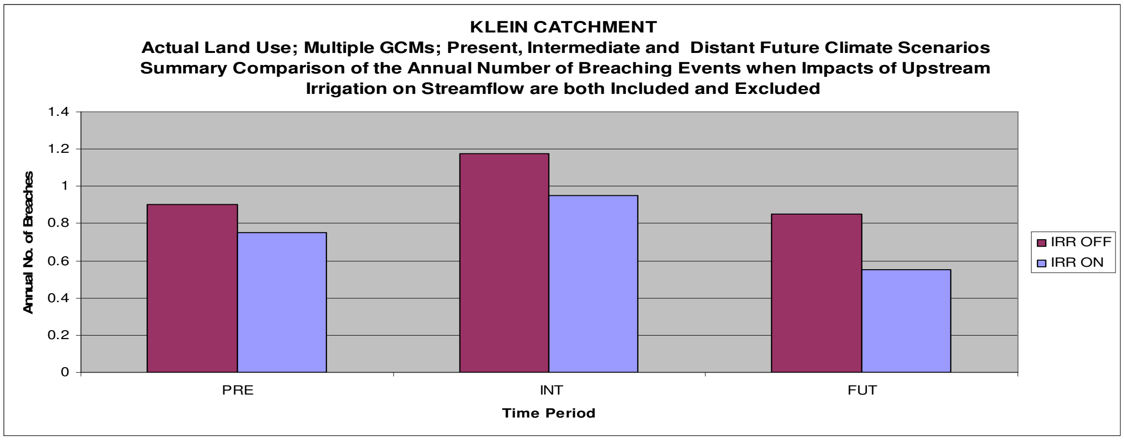


Figure 6.2.4.2: Summary of simulated annual number of berm breaching events of the Klein estuary occurring during the present, intermediate and distant future periods, excluding upstream irrigation (red) and including upstream irrigation (blue)

Regarding Figure 6.2.4.2 it should be noted that when the number of annual breaching events is below one, there will not be a breaching event every year, and when the number of breaches exceeds one, then there will be more than one breach in a year. Figure 6.2.4.2 illustrates that during the present period, when irrigation simulations are excluded, breaching events occur on an almost annual basis. When irrigation simulations are included, there is a decrease in the frequency of breaching events, which is due to the decrease in streamflows entering this system because of upstream irrigation abstractions (cf. Figure 6.2.1.1 bottom). Into the intermediate future the number breaching events increases to more than one event annually, as a consequence of an increase in streamflows (cf. Figure 6.2.1.2 middle). When abstractions for upstream irrigation are included there is a significant decrease in the number of annual breaching events. Into the distant future the number of breaching events decreases and, when abstractions for irrigation are included, breaching events decrease to occur almost once every two years only. Fluctuations in the number of breaching events may have an effect on the ecology of the Klein estuary, and these effects will be discussed further in Sub-section 6.3.

7 DISCUSSION OF RESULTS AND CONCLUSIONS

The effects of climate change on the catchments upstream of the 10 selected estuaries is demonstrated by comparing flows during the present and into the intermediate and distant future periods, as shown in Sub-sections 6.1 and 6.2. Factors which alter projected effects of climate change from one region to the next include local topography, local soils and local land use (cf. Literature Review Chapter 2 to Chapter 4). Therefore, as a consequence of differing locations, the possible effects of climate change on streamflow into each of the 10 selected estuaries can vary even more than through the effects of climate change by itself (cf. Results Sub-section 6.1.1). Hence, as estuarine ecosystems rely on freshwater and marine inputs in order to maintain their unique environments, these systems may become threatened as a consequence of future climate changes (cf. Literature review Chapter 3). In addition to the possible direct effects of climate change on streamflows, are the possible effects of anthropogenic interference which, in the case of the Klein catchment, consists of the conversion of baseline land cover to dryland and irrigated agricultural uses, with a small percentage of urban areas (cf. Introduction Chapter 1 and Results Sub-section 6.2). Hence, in order to meet the objectives of this project, a case study of the Klein catchment was completed and the results will be discussed in more detail in order to illustrate the effects of land cover conversion on streamflow, and the effects that this, in combination with climate change, could have on the functioning of estuarine ecosystems.

Estuarine circulation is based on the inputs of both fresh and saline water, and is one of the main determinants of habitat availability which, in turn, determines the distribution of floral and faunal species in estuarine ecosystems (cf. Literature Review Chapter 3).

7.1 Discussion on Regional Differences of Hydrological Responses to Climate Change

The systems located along the ***east coast region*** (summer rainfall) display distinct increases in the magnitude of flows, and number of pulses into estuaries, into the intermediate future period. This is particularly true for the Thukela system (cf. Result Sub-section 6.1.1). Estuaries along the east coast range from being moderately stratified to highly stratified, based on flow characteristics. An increase in freshwater inputs along east coast estuaries may result in the halocline, which is often located in the lower reaches of such systems, being forced out of the estuary mouth (cf. Literature Review Sub-section 3.1.1). This may occur more frequently during high flow years and as a result of the increased numbers of pulses. Owing to the resultant projected shift in haloclines towards the estuary mouth, these systems may become dominated by freshwater, i.e. hypo-saline, with saline water entering the system only during the low flow season, i.e. winter months along the east coast and low flow years. While beyond the scope of this research, the projected hypo-salinity may be counteracted by a rise in sea level.

In comparison, only slight increases in the magnitude of flows and the number of pulses into estuaries located in the ***southern regions,*** i.e. with all year/late winter rainfall, are projected to occur. In the case of the Breede catchment the higher mean flows and higher numbers of pulses are projected to undergo a temporal shift from winter to summer between the present and intermediate future periods (cf. Results Sub-section 6.1.1). However, the Klein and Krom river systems, which are in the winter and all year rainfall regions, respectively, do not show up these distinct temporal shifts, despite projected increases in flow magnitudes in some months of the year. In general, increases in inflows in these two catchments are projected to occur during the summer period. In contrast, into the distant future the flows are projected to decrease again in these two systems (cf. Results Sub-section 6.1.1). Hence, systems in the south and south eastern coastal regions do not have flows as high as those in the eastern regions, and the projected changes do not indicate the magnitude of increases that are projected to occur in the eastern regions.

As a consequence of current and projected inflows, these estuaries range from moderately stratified, in the case of the Klein, to sectionally homogenous, in the case of the Breede and Krom, both of which are narrow and influenced by tidal fluctuations (cf. Literature Review Sub-section 3.1.1). Into the intermediate and distant future periods, the classification of the Klein estuary could change to becoming highly stratified. The same may occur in both the Krom and Breede estuaries, but this is unlikely, as the projected increases in flows into the intermediate future would have to be significant, which they are not (cf. Results Sub-section

6.1.1). Although, changes in estuarine circulation could occur during the intermediate future, these changes may be reversed, as flows into the distant future are projected to decrease again.

In the ***western regions*** an increase in flows into the intermediate future is projected for the majority of systems studied. However, projections into the distant future once more indicate decreases in flows (cf. Results Sub-section 6.1.1). This is especially apparent in the Berg system. Projections of flows from the Olifants catchment illustrate temporal shifts in the occurrence of mean high flows from winter to summer into the intermediate and distant future (cf. Results Sub-section 6.1.1). Projections of flows entering the Buffels and Groen estuaries into the intermediate future indicate an increase (cf. Results Sub-section 6.1.1). However, as the magnitude of flows entering these estuaries is minimal, these systems are more often than not isolated from marine influences by berms across the mouth which are seldom breached (cf. Results Sub-section 6.1.1, Google Earth Images in Figures 4.5 and 4.6). When the Groen and Buffels estuaries do breach, during very infrequently occurring high flow events, they could be classified as moderately stratified systems (cf. Literature Review Chapter 3.1.1; Results Sub-section 6.1.1). A breaching of these estuaries would result in the entry of saline water which would, in turn, result in the formation of a halocline. Into the intermediate and distant future the classification of circulation in the Buffels and Groen estuaries could change as a consequence of altered future streamflows, but this is unlikely as the projected future increases in flows entering these estuarine ecosystems is negligible. Even if a 100 % increase in the magnitude of flows entering these two estuaries were to occur, as is projected into the intermediate future, it would not make a substantial difference to the overall circulation within the Groen and Buffels systems (cf. Results Sub-section 6.1.1).

Projections into the distant future indicate very slight increases in flows entering the Groen and Buffels estuaries throughout the year, which implies a decrease in flows between the intermediate and distant future periods. In comparison, flow magnitudes for both the Olifants and Berg catchments are projected to increase into the intermediate future during the summer and late summer/autumn periods, respectively (cf. Results Sub-section 6.1.1). However, projections into the distant future indicate a decrease in flows entering the Olifants and Berg estuaries during the winter period. Additionally, projections into the distant future indicate that flow magnitudes into the Olifants system could increase during summer while in contrast, flow magnitudes entering the Berg system decrease throughout the year. This could affect the estuarine circulation in both the Olifants and Berg systems (cf. Results Sub-section 61.1).

From its physical characteristics, the Olifants system would appear to be a highly stratified estuary (cf. Literature Review Sub-section 3.1.1). In contrast, the Berg system, from field experience, is narrow and appears to be dominated by tidal inputs rather than freshwater inflows. Hence, according to the literature reviewed in Chapter 3.1.1 the Berg system is a vertically homogenous system. Projected decreases in flow magnitudes entering the Berg estuary into the more distant future could result in a decrease in the size of this system. However, the classification of the circulation occurring in this system may remain the same into the future because the shape of estuary and its mouth are unlikely to change and because it could still be subjected to tidal influences.

7.2 Discussion on Impacts of Land Uses on Hydrological Responses

Additional to the effects of climate change on streamflows entering estuaries is the conversion of upstream baseline land cover to actual land use, i.e. for agricultural purposes or urban settlement. From the simulations completed in which actual land use was considered in the Klein catchment, the impacts of upstream irrigation were also evaluated (cf. Results Sub-section 6.2). The inclusion of irrigation routines illustrates a marked decrease in inflows, especially during dry years when upstream irrigation abstractions are high. During the dry summer season of the driest year in 10, simulated flows into the Klein estuary cease completely as a consequence of upstream abstractions for irrigation purposes (cf. Results Sub-section 6.2). Projections into the intermediate future indicate an increase in flows entering the Klein estuary for all simulations, as a result of projected increases in rainfall and hence streamflows. However, projections into the distant future show a reversal of flow increases, which is further amplified by the inclusion of upstream irrigation abstractions in the simulations (cf. Results Sub-section 6.2).

An overall observation from this simulation was that the impacts of actual land use and upstream irrigation on flows entering the Klein estuary were not as significant as had been expected (cf. Results Sub-section 6.2). This is probably due to the relatively small area of irrigated agriculture and urban settlement in the Klein catchment (cf. Methodology Chapter 5). Despite the relatively small impact of the conversion of natural vegetation to agricultural land use on flows, there could be direct impacts on the Klein estuary ecosystem.

The first of these impacts is a projected increase in the number of pulses. However, the pulses occurring when actual land use and irrigation routines are included are volumetrically smaller than those occurring under baseline land cover conditions (cf. Results Sub-section 6.1.2). This could imply that flushing events in the estuarine ecosystem may not occur as frequently as a consequence of upstream agricultural influences, and this could result in a build up of toxins in the Klein estuary. This could affect the overall health of this ecosystem.

7.3 Discussion on Ecological Responses to Changes in Freshwater Inflows

Projected changes in flows as a consequence of climate change and anthropogenic interference could alter the circulation of estuaries which, in turn, will impact directly on the survival and distribution of biotic species within estuarine ecosystems (cf. Literature Review Sub-section 3.1.4). Although estuaries are already constantly changing and, in some instances, are ephemeral systems, there are seasonal and tidal patterns that are currently occurring, which may be altered as a result of climate change. Therefore, in some instances species may find that systems that were once able to meet their life cycle requirements are no longer capable of doing so (cf. Literature Review Chapter 3). In certain faunal species this is not problematic, as they do not require only estuarine ecosystems in order to complete their life cycles. However, in obligate species, i.e. those that must spend a certain period of time in estuaries in order to complete their life cycle, changes in inflows may present a major obstacle to the continuing survival of that particular species (cf. Literature Review Chapter 3). Of the many changes in inflows that could occur temperature is of significant concern.

Temperature plays an important role in the functioning of aquatic ecosystems. A considerable number of faunal and floral species found in these systems are sensitive to changes in temperature (cf. Literature Review Chapter 3). As indicated in Sub-section 3.4.1 temperature could increase into the future, with greater increases occurring in the interior of the country. Owing to the future increases in air temperature an increase in water temperature of flows entering the estuarine ecosystem could occur. As a consequence of this significant habitat fragmentation could occur. This, in turn, could result in decreased habitat availability, depending on the tolerance of each species to variation in temperature. Hence, it may be stated that the possible effects of temperature is species dependent, as some species may be adversely affect by increases in temperature, while there maybe a negligible effect on other species.

As a consequence of future increases in water temperature, it is probable that evaporation will increase. The increased water temperature in combination with increased evaporation could increase the possibility of the estuarine ecosystem turning hyper-saline, especially during low flows periods when it is possible for evaporation to exceed inflows. This could compromise the integrity of the estuarine ecosystem. In addition to changes in salinity concentration, as a consequence of projected changes in temperature and streamflow, are changes in other abiotic factors, such as sedimentation, nutrient availability and breaching.

7.4 Discussion on Impacts of Changing Sediment Yields into Estuaries

In the Thukela, Mdloti and Mlalazi estuaries, projections indicate an increase in sediment inputs, especially in the Thukela system (cf. Results Sub-section 6.1.3). This may be due to the increases in stormflow events projected to occur over this region (cf. Literature Review Chapter 3). Additionally, this increase in flow magnitudes could increase the erosive power and carrying capacity of these rivers, which could further increase the sediment load entering these estuarine ecosystems. The projected increases in the quantity of sediments entering estuaries on the east coast could have a number of impacts on these ecosystems, some of which are negative while others are positive.

Projected increases in sediment yields into some systems along the east coast could affect primary production in these estuaries (cf. Literature Review Sub-sections 3.1.2 and 3.1.4; Results Sub-section 6.1.3). Increases in turbidity levels would decrease the light penetration into the water, hence resulting in a reduction in the occurrence of photosynthesis amongst those primary producers in suspension. This could result in a reduction in the number of primary producers in these systems, thereby affecting the nutrients available to the higher trophic levels (cf. Literature Review Sub-section 3.1.4). Higher trophic levels would be affected by a reduction in the number of primary producers as primary consumers rely on these organisms for nutrition. Although a decrease in primary production may occur, there could be an increase in the nutrient availability, as sediments transported from higher up in the catchment are generally nutrient rich (cf. Literature Review Sub-section 3.1.2). However, if the turbidity of the estuary decreases, there could be a marked temporary increase in the productivity of these systems.

In contrast, if the sediment load is projected to decrease, as may occur in the Berg estuary, then the turbidity is likely to decrease (cf. Literature Review Sub-sections 3.1.2 and 3.1.4; Results Sub-section 6.1.3). Hence, light penetration would increase and a temporary exponential increase in the primary productivity could occur in these estuaries. However, as sediment loads entering the Berg estuary are projected to decrease, so will nutrient availability (cf. Literature Review Sub-section 3.1.2 and 3.1.4). Additionally, this could result in a decrease in the number of breaching occurrences. This, in turn, could result in a deficit in the nutrients and chemicals required for primary production (cf. Literature Review Sub-section 3.1.2 and 3.1.4). High increases in the productivity of a system, as a result of decreased turbidity, often could leave a system more degraded than before, as all "surplus" nutrients and chemicals are consumed. In addition, estuaries are often isolated from oceanic influences by the formation of a berm, which results when freshwater inflows decrease, thereby resulting in further nutrient deficiencies.

7.5 Discussion on Berm Formation

The decreased scouring action of estuarine outflows, which prevent the deposition of marine sediments in the mouth of the estuary, promotes the formation of a berm across the estuarine mouth (cf. Literature Review Sub-section 3.1.2). Hence, restricting the interaction, and with that the transfer of nutrients, between the marine and freshwater systems could result in the decreased overall productivity of the estuary (cf. Literature Review Sub-sections 3.1.2 and 3.1.3). In the case study of the Klein estuary, the conversion of natural vegetation to agricultural land use, especially upstream irrigation, has been shown in simulations to promote berm formation (cf. Results Sub-section 6.2).

One of the main reasons for the projected increase in the frequency of berm formation is the decrease, resulting from upstream irrigation abstractions, in inflows entering the Klein estuary which, in turn, would result in decreased outflows from the estuarine mouth. Decreases in outflows from the estuary mouth could be greater than decreases in inflows entering the estuary. This would be due to losses from the estuary itself, which would promote berm formation (cf. Literature Review Chapter 3; Methodology Sub-section 5.8).

In the case of the Klein estuary, irrigation is the major cause of decreased outflows (cf. Results Sub-section 6.2) which, if coupled with marine deposition, could result in an increase in the frequency of berm formation across the estuary mouth (cf. Literature Review Chapter 3). During low rainfall and thus low flow years, when irrigation abstractions are high, it is likely that berms of significant size could form as a result of little or no scouring action during these periods. The implication of this would be that breaching events may not occur for a period of time longer than the normal interval. The resulting isolation of the Klein estuary from marine influences could result in the system turning hypo-saline (cf. Literature Review Chapter 3; Results Sub-section 6.2). However, as berms generally form as a consequence of decreased outflows, which result from decreased inflows and evaporative losses, it is far more likely that this estuary could turn hyper-saline during low flow years. In addition to the effects of freshwater inflows on salinity concentrations of estuary water, are the effects that this may have on the chemistry within the estuarine eco-system (cf. Literature Review Chapter 3). This is described below.

7.6 Discussion on Estuarine Chemistry

The water in estuaries is not simply diluted sea water, but consists of numerous chemicals and trace metals that aid in sustaining life, with only a small number of these being toxic (cf. Literature Review Chapter 3). All chemicals in estuaries are obtained from either the oceanic or the river systems. Hence, in order to facilitate the proper functioning of estuaries, a connection with both the freshwater and marine systems must be maintained (cf. Literature Review Chapter 3). An increase in inflows entering an estuary, as is projected to occur along the eastern and southern coastal regions under future climatic conditions, could result in an excess in ions, such as calcium and sulphate, which are supplied via the river system (cf. Literature Review Chapter 3). This would affect certain organisms such as molluscs and bacteria, which aid in the decomposition processes occurring in estuaries. In contrast, a reduction in certain chemicals entering via the marine system may occur as a result of increases in freshwater inflows, which would force a reduction in tidal influences and could affect some organisms that require certain levels of salinity for their survival (cf. Literature Review Chapter 3). However, the impact of a reduction in marine inputs may not be as significant as a reduction in freshwater inflows, as rivers carry the majority of nutrients and trace metals required for survival of estuarine ecosystems.

Conversely, a decrease in flows, as is projected to occur under future climates in the western coastal regions in systems such as the Berg and Olifants catchments, especially during future winter rainfall periods (cf. Results Sub-section 6.1.1), could result in a decrease in all chemicals and trace metals entering these estuaries. The overall decrease in chemicals could occur as a consequence of the formation of a berm across the mouth of the estuary, which would prevent the entry of marine based chemicals, such as magnesium (cf. Literature Review Chapter 3). Additionally, the formation of a berm across an estuary mouth may cause an accumulation of toxic trace metals, such as arsenic, lead and mercury which, in combination with hyper-saline conditions, could destroy most estuarine ecosystems if tolerance thresholds are exceeded.

Owing to the complete control that the abiotic factors exercise on organisms in estuaries, any changes in streamflows, as a consequence of climate change and/or anthropogenic interferences upstream of the estuary, could have a considerable effect on organisms in estuarine ecosystems. Increased inflows into estuaries would decrease salinity concentrations which could affect the number and distribution of organisms, as many primary producers are vulnerable to fluctuations in salinity, i.e. these organisms are incapable of the necessary osmoregulation, and so cannot control their internal equilibrium (cf. Literature Review Chapter 3). Hence these organisms are unable to tolerate wider salinity ranges, which may occur into future periods as a result of higher fluctuations in streamflows and marine inputs entering estuaries (cf. Literature Review Chapter 3; Results Sub-section 6.1.1). Therefore, if a marked increase in flows entering an estuary occurs, as is projected to occur in the Thukela estuary, then the number and diversity of organisms could decrease as a result of variations in the sediment yields, freshwater and marine inputs (cf. Literature Review Chapter 3; Results Sub-section 6.1.1).

Conversely, in systems along the west coast the projections indicate a decrease in streamflows into the distant future, e.g. in the Berg, Groen and Buffels catchments (cf. Results Sub-section 6.1.1). A decrease in flows entering these estuaries could have a more detrimental effect than an increase in flows, as primary production would increase when turbidity levels decrease, which is due to decreased sediment yields. This results in an increase in photosynthesis and acceleration in the metabolic processes, thereby resulting in a higher rate of consumption of the available nutrients. Once all available nutrients have been consumed, then primary production would decrease very sharply and this would eventually affect all trophic levels within the system. Additionally, prior to the formation of a berm, the estuary would be subjected to greater tidal intrusions as a result of decreased freshwater inflows, which could then increase the salinity concentration considerably and may cause the dehydration of primary producers and their consumers (cf. Literature Review Chapter 3; Results Sub-section 6.1.1).

Hence, in the event of droughts, berms could form as a consequence of decreased scouring action through decreased freshwater inflows. In some instances freshwater inflows may cease, as is projected to occur in the Klein estuary when irrigation routines are included (cf. Results Sub-section 6.2). This would lead to the system becoming hyper-saline as a result of little or no marine interaction due to the berm across the mouth, and evaporation losses. In such systems very few organisms can survive as a result of salinity concentrations exceeding tolerance thresholds (cf. Literature Review Chapter 3). Similarly in such systems, mortality rates may be extremely high and the resulting decomposition of organisms could cause a reduction in dissolved oxygen, potentially turning the entire estuary anaerobic (cf. Literature Review Chapter 3).

7.7 Discussion on Estuarine Ecology and Economic Contributions of Estuarine Systems

As the ecology of estuaries is affected, so are the economic contributions of these systems. In South Africa these contributions are considerable due to economic activities such as tourism and fishing, which are directly linked to the ecological integrity of estuarine ecosystems. Climate change impacts on streamflows entering estuaries vary throughout South Africa (cf. Results Sub-section 6.1.1). Hence, if the ecology of these systems were to be impacted upon by projected changes in inflows, then it would be highly likely that the economic contributions of these systems could be affected.

In some areas, as along the east and south coasts, impacts may be positive if streamflow increases are not too excessive. In contrast, projected increases in temperatures under future climate scenarios could result in increased evaporation losses from these systems. This, in combination with projected decreases in future streamflows, could have a negative effect on estuarine ecosystems, especially if simultaneously upstream abstractions are occurring from their catchments, as in the case of the Klein catchment (cf. Literature Review Chapter 3; Results Sub-section 6.2.1).

However, if the effects of climate change on freshwater inflows into estuaries are more extreme, as is projected for the Thukela and Berg systems, then impacts on the ecological integrity of these systems could be considerable. Changes may take the form of either excessive increases in flows into estuaries or marked decreases in future inflows entering estuarine ecosystems. Therefore, as a consequence of climate and land use changes, a major contributor to the ecological diversity and economic productivity of South Africa could be threatened. In areas such as KwaZulu-Natal and the southern coast the threat lies more with anthropogenic influences which, as illustrated by the case study of the Klein catchment, can have a marked influence on the flow regime into an estuarine system. In other regions, as along the arid west coast, the impacts on streamflows entering estuaries is more likely to be due to climate change rather than anthropogenic interferences if irrigation is not practised upstream. Either way, as a consequence of the location of estuarine ecosystems at the lower end of the catchment, these systems will always be impacted upon by any upstream alteration, whether natural or anthropogenic (cf. Literature Review Chapter 3).

7.8 Overall Conclusions

From the results of the analyses undertaken (cf. Chapter 6) and the literature reviewed (cf. Chapters 2 and 3), it may be concluded that the effects of climate change on estuarine ecosystems is location specific. However, the confidence in the projections of future climates varies considerably across South Africa (Schulze, 2011b). According to the literature reviewed in Sub-section 3.4.3, an increase in precipitation is projected to occur into the future over the eastern regions, while a decrease in precipitation is projected to occur over the western regions (cf. Results Chapter 6). Furthermore, non-uniform temperature increases are projected to occur over the entire country, with higher increases occurring over the interior of South Africa. In addition to the projected changes in climate, there are anthropogenic influences regarding the conversion of natural vegetation to agricultural land uses, which could affect downstream streamflows, especially if irrigation is practised upstream. When the joint changes in both climate and land cover conversion have been accounted for, the impacts of streamflow could, in some regions, be considerable, as summarised below.

From the comparisons of results from simulations in which natural vegetation is assumed, the following broad *direct* impacts of climate change on inflows into estuaries may be made:

- In the eastern regions the magnitude of streamflows entering estuaries is projected to increase into the intermediate and distant future. This increase, in some instances, may be considerable, e.g. in the Thukela system.
- In the southern regions high mean flows are projected to undergo a temporal shift into the summer period instead of occurring mainly in winter. Additionally, the magnitude of

flows entering some of these estuaries is projected to increase considerably in some catchments.

- In the western regions the magnitude of streamflows entering the Groen and Buffels estuaries is projected to increase marginally during the intermediate future. However, into the distant future flows are projected to decrease considerably. In addition, high mean flows are projected to undergo a temporal shift so as occur more into summer rather than in mid-winter.

In conjunction with the literature reviewed in Chapter 3, conclusions may be drawn regarding the possible effects of projected changes in inflows on estuarine ecosystems. Therefore, projected climate changes over South Africa may have the following ***indirect*** impacts on estuarine ecosystems:

- In the eastern regions, as a consequence of projected increases in freshwater inflows, estuaries could become hypo-saline and extremely turbid, thereby decreasing the overall productivity of these ecosystems. This is stated because the most productive systems are those containing both saline water and freshwater, as in a “normal” estuary, and implies considerable decreases in the number of organisms in these systems as a consequence of hypo-salinity.
- In the southern regions future projections show a more temporal rather than quantitative shift in flows entering estuaries, which could present a considerable problem for obligate species that rely on the opening of an estuary mouth at a specific time period in order to complete their life cycle stages.
- In the western regions the changes in inflows are small in most systems. However, the projected decreases in flow magnitudes in systems such as the Berg could have a negative effect on these estuaries, as nutrient inputs could decrease which, in turn, could reduce the overall productivity of these systems. Additionally, these systems could turn hyper-saline as a consequence of increased evaporation, in addition to decreased freshwater inflows and more frequent berm formation, which would prevent tidal intrusions. This would be extremely detrimental to many organisms found in estuaries, in regard to osmoregulation, nutrient and habitat availability.

Hence, if they are considerable, then the effects of climate change on estuarine ecosystems could be highly detrimental to the integrity of these systems. In addition to the effects of climate change, there are those of land cover conversion which could affect streamflows entering estuaries. In this dissertation the Klein estuary was selected to demonstrate the possible effects of land cover conversion on streamflows.

Simulations were conducted utilising actual land use within the Klein catchment, both excluding and including effects of irrigation. The results of these simulations illustrate the effects of land cover conversion, along with those of climate change, on inflows into the Klein estuary and are summarised below:

- When results from simulations utilising actual land use (but excluding irrigation) are compared with those using natural vegetation during the present period, there is a slight increase in the magnitude of streamflows. However, when irrigation is included in these simulations there is a slight decrease in the magnitude of streamflows entering this system, especially during dry years when upstream irrigation abstractions may be high.
- Into the intermediate future the magnitude of streamflows is projected to increase, while into the distant future there is a considerable decrease projected in the magnitude of steamflows entering the Klein estuary.
- Sediment yields increase when results of simulations using agricultural land uses are compared with those assuming natural vegetation.
- The number of high flow pulses into the Klein estuary increases markedly when results of simulations using agricultural land uses are compared with those assuming natural vegetation. It should be re-iterated, however, that pulses reflect relative changes in flows from one day to the next, and not actual volumetric changes. The most marked projected increase in the number of pulses occurs when results of simulations using agricultural land use and including irrigation routines are compared with those from natural vegetation
- Results show a decrease in the number of breaching events when irrigation routines are included in simulations.
- A decrease in breaching frequency would affect nutrient availability, chemical constituents and mixing in this estuarine system.

In summary, the combination of possible effects of climate change with those of land cover conversion could have a more detrimental effect on this ecosystem than either climate or land cover changes by themselves. This, in turn, could have a detrimental effect on people who rely directly on this ecosystem for their livelihoods, such as tour operators and fishermen.

Linking back to the introduction, a brief summary of the problem statement is that although recent hydrological studies have included ecological responses to hydrological shifts, there is still a need to increase the knowledge base with regard to climate change and estuarine ecosystems. This is due to a relatively limited number of comprehensive investigations of the effects of climate change on estuarine ecosystems, especially in a South African context.

From the problem statement in the introductory chapter, the objectives of this study were:

- to simulate the possible effects of climate change on freshwater inflows into 10 selected estuaries along the South African coastline,
- to illustrate the possible effects of land cover conversions in addition to those climate change on streamflows entering estuaries, and
- to show the broad possible effects of the above on the functioning of the estuarine ecosystems during the present and into the intermediate and distant future periods.

Therefore, it may be stated that this project has achieved its objectives, and has contributed to the knowledge of the possible effects of projected future climate and land cover changes on estuarine ecosystems in South Africa. However, there is scope for considerable additional research in this field, which is considered to be still in the developmental stages. Recommendations for future research are discussed in Chapter 8.

8 RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

Estuaries are important ecosystems in South Africa as they form the basis for a number of economic activities. In the research undertaken in this dissertation, the projected effects of climate change on streamflows entering estuaries was illustrated for scenarios into the intermediate and distant future (Results Chapter 6). In addition, the possible effects of the conversion of natural vegetation to agricultural uses on streamflows into estuaries was illustrated in Sub-section 6.2. From this study the following recommendations are made for future research in this field:

- The knowledge of actual land use in each catchment investigated could be improved considerably through site visits and updated land use maps.
- Since the start of this project the number of GCMs available for detailed research has increased, and this may reduce uncertainties in conclusions regarding projections of streamflows during future periods.
- The knowledge regarding the structure and functioning of estuarine ecosystems should be increased in order to project the possible effects of climate change more accurately.
- Further research, utilising the 67 metrics constituting the IHA system, should be undertaken in order to achieve results that will enable a detailed analysis of the possible effects of hydrological changes on the functioning estuarine ecosystems.
- In future, continuous projections of climate changes throughout South Africa, rather than the use of time slices, should increase the confidence of streamflow simulations, as there would be no gaps between periods.
- An increased number of estuaries in South Africa should be subjected to climate change studies, including effects of upstream land uses.
- With the *ACRU* modelling system routines for the accumulation of sediment yields should be developed, as should the effect of dams on sediment movement.
- Further examination of individual estuaries should be undertaken in order to determine the level of dependence of a particular system on sediment yields.
- The possible effects of sea-level rise on estuaries, as a consequence of climate change, should be taken into account in future research.

- A more detailed study on the possible effects of thermal pollution into estuaries, with regards to future climate change, should be undertaken.
- In future research the selection of estuarine ecosystems should be undertaken using the Principle Components Analysis approach which could have grouped estuaries based on climate scenarios and the associated flow metrics likely to influence each estuary the most during each climate scenario, based on eigenvectors.

With the above-mentioned improvements, the possible effects of future climate change on estuaries could be more thoroughly assessed. With this knowledge, conservation strategies regarding estuarine ecosystems (including their upstream catchments) could be developed and implemented. These could conserve the estuarine ecosystems per se, and could protect potential economic contributions. Therefore, future research into this field could be of paramount importance as estuaries affect many facets of the coastal ecology and economy of South Africa.

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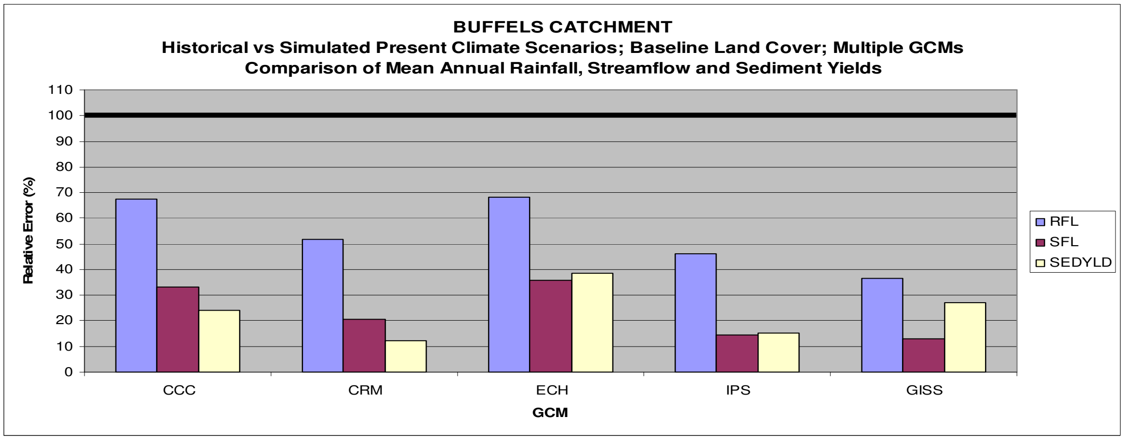
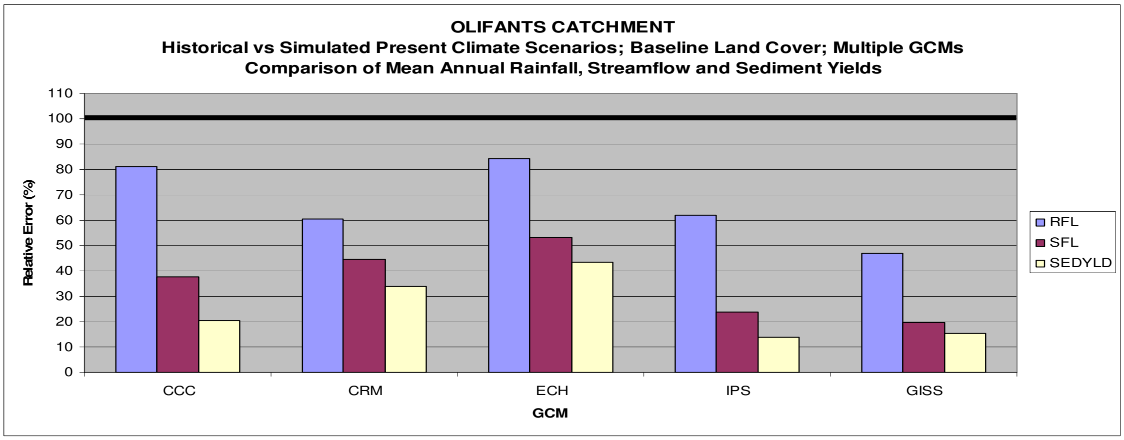
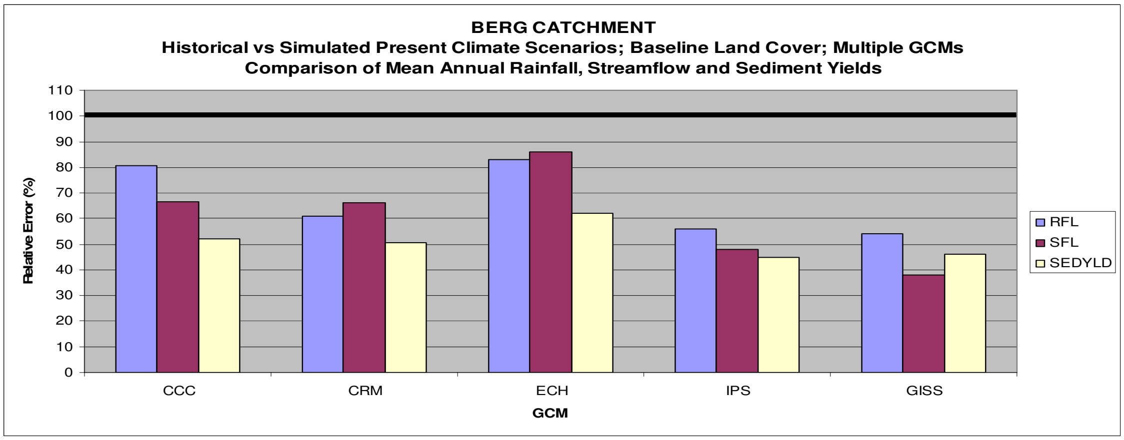
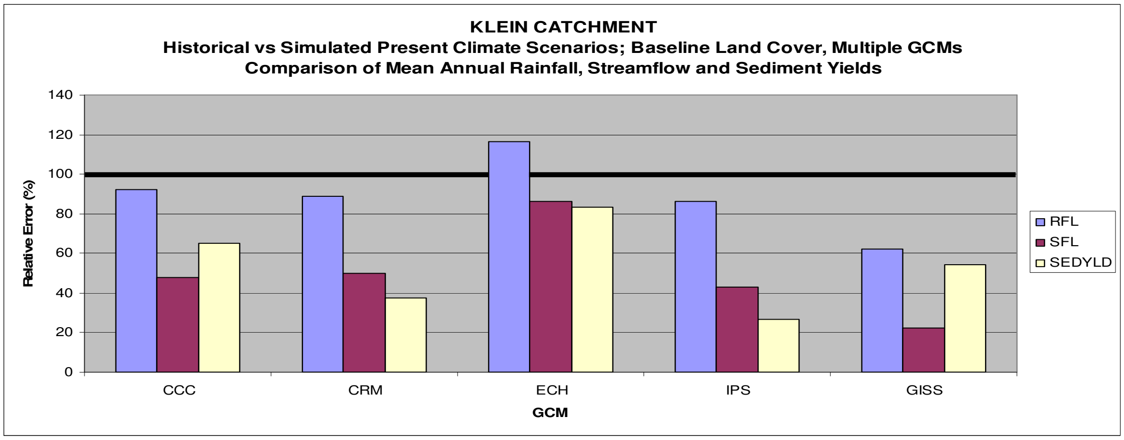
www.google.com, *The Enhanced Greenhouse Effect*, Mozilla Firefox.

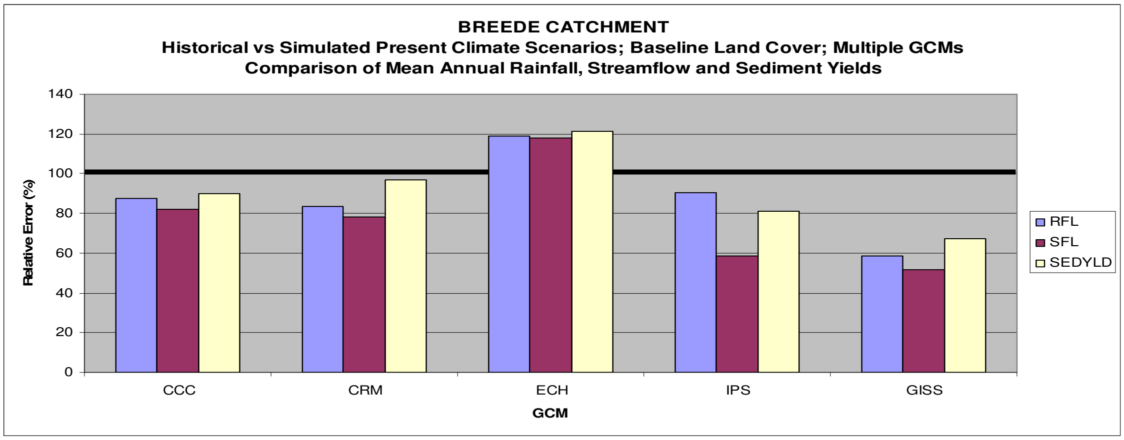
10 APPENDIX A: RELATIVE ERRORS IN GCM OUTPUT COMPARED WITH HISTORICAL DATA FOR THE SAME PERIOD (1971 – 1990)

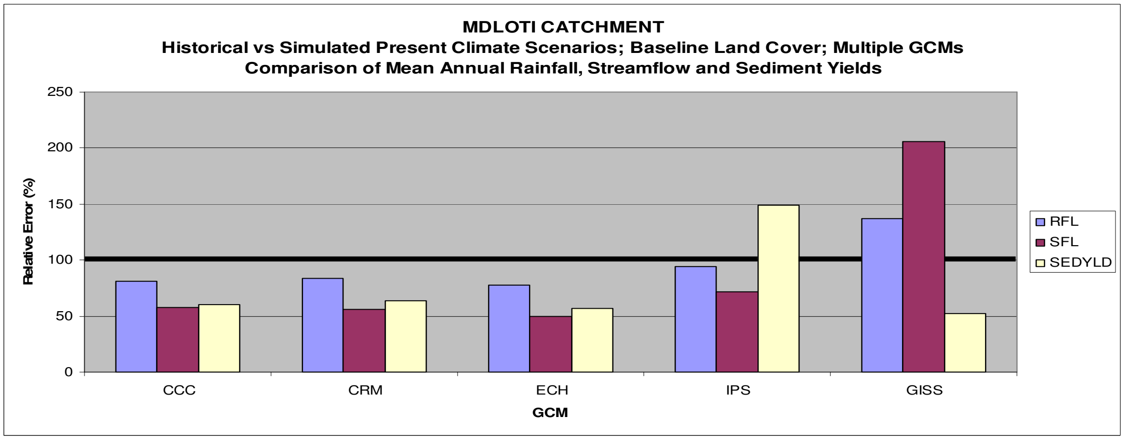







KLEIN CATCHMENT
Historical vs Simulated Present Climate Scenarios; Baseline Land Cover, Multiple GCMs
Comparison of Mean Annual Rainfall, Streamflow and Sediment Yields


BREEDE CATCHMENT
Historical vs Simulated Present Climate Scenarios; Baseline Land Cover; Multiple GCMs
Comparison of Mean Annual Rainfall, Streamflow and Sediment Yields


MDLOTI CATCHMENT
Historical vs Simulated Present Climate Scenarios; Baseline Land Cover; Multiple GCMs
Comparison of Mean Annual Rainfall, Streamflow and Sediment Yields

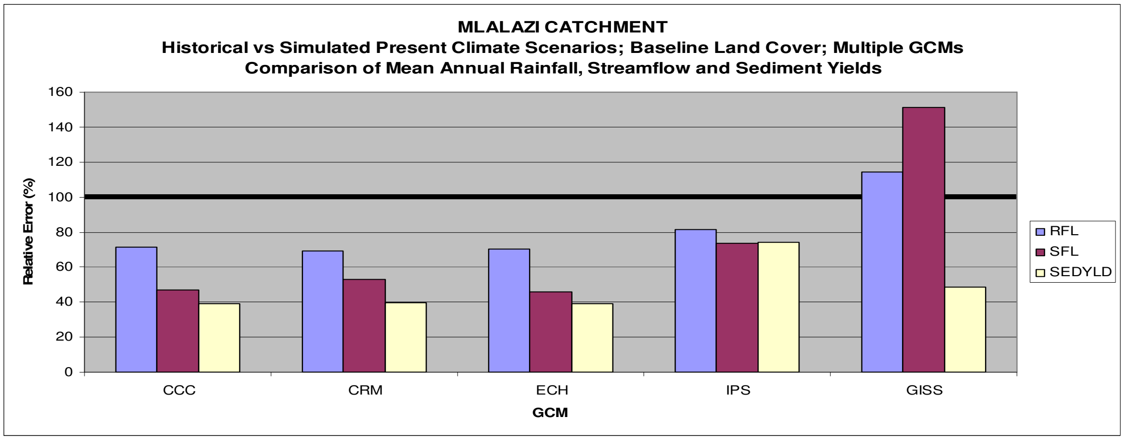


Figure 10.1 to 10.7 Relative errors in GCM derived rainfall, streamflow and sediment yield compared with values derived from historical data for the same period (1971 – 1990), and assumed to be at 100 %, for selected estuaries