CHANGE IN LAND COVER AND WATER ABSTRACTION: MODELLING RUNOFF EFFECTS IN THE BOT RIVER CATCHMENT

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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

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ABSTRACT

River basins have long been attracting human settlement and development, promising water and fertile lands (Newson 1992). The Bot River Catchment on the southern coast of South Africa is no exception. However, much of the development in this catchment has not been controlled and its land and water resources are being abused. This is affecting the water quality and quantity of the river system and estuary at an alarming rate.

In this thesis, the ‘reference’ land cover in the Bot River Catchment is recreated. This term is used to describe “the hydrological state of the catchment as it was when completely covered in natural vegetation, thus before it was impacted by humans” (Jacobs & Bruwer 2002:12). A rainfall-runoff model is employed to investigate the effects of various land covers on the catchment’s runoff quantity, by comparing the simulation results of the catchment’s reference and current state.

The results of the model point to a large reduction in runoff since the reference state of the catchment. As the rainfall-runoff model applied did not allow for modelling of the annual agriculture that dominates the catchment, the runoff reduction was attributed to the smaller areas of perennial agriculture, forestry and alien vegetation infestation. The simulation results confirmed the threat of current land use practices on the environmental integrity of the Bot River Catchment. A transition to agricultural practices that are more suited to the climate is suggested and the eradication of alien vegetation should be seen as a priority. Most importantly, a holistic approach should be taken towards the management of the Bot River Catchment.

The altered hydrodynamic regime of the Bot River Estuary is symptomatic of misuse of the entire catchment. As ongoing demographic and land use pressures create a new generation of water management problems (Department of Water Affairs & Forestry 1993), a deeper understanding of the relationships between the different components in the Bot River Catchment becomes increasingly urgent.

Keywords: catchment, land cover, rainfall-runoff model, runoff, Bot River

OPSOMMING

Riviervalleie is weens die belofte van water en vrugbare grond deur die eeue geteiken vir menslike kolonisering en ontwikkeling (Newson 1992). Die Botrivier Opvanggebied aan die suidelike kus van Suid-Afrika is geen uitsondering nie. Die ontwikkeling van hierdie bekken was egter ongekontroleerd en die water- en grondhulpbronne is meestal misbruik. Soveel so, dat die waterkwaliteit en -kwantiteit van die rivierstelsel en estuarium ernstig geaffekteer word.

In die tesis word die oorspronklike, ongerepte, 'verwysings'-grondbedekking van die Botrivierbekken herskep. Die term 'verwysing' dui op die hidrologiese bekken-toestand onder volledige dekking van natuurlike plantegroei, dus voor blootstelling aan menslike impak (Jacobs & Bruwer 2002). 'n Reënval-afloop model word gebruik om die effek van verskillende grondbedekkings op die omvang van bekkenafloop te bepaal deur die verwysings- en huidige toestande te vergelyk.

Die resultate van die model dui op 'n drastiese vermindering in die gemiddelde jaarlikse afloop sedert die verwysingstand van die bekken. Die reënval-afloop model, soos hier toegepas, het nie modellering van die eenjarige landbougewasse wat die bekken oorheers toegelaat nie, sodat afvloei-vermindering toegeskryf is aan die kleiner areas onder meerjarige gewasse, bosbou en uitheemse indringerplantegroei. Simulasie-resultate bevestig die gevaar van huidige grondgebruikpraktyk vir die Botrivier Opvanggebied se omgewingsintegriteit. Verskuiwing na beter geakklimatiseerde landbougewasse, die uitroei van indringers en 'n holistiese benadering vir bestuur van die Botrivierbekken word aanbeveel.

Die veranderde hidrodinamika van die Botrivier Estuarium is simptomaties van wangebruike oor die hele opvangsgebied. Namate demografiese en grondgebruikdruk nuwe generasies waterbestuursprobleme skep (DWAF 1993), word groter begrip van die verhouding tussen die komponente van die Botrivier Opvangsgebied gebiedend noodsaaklik.

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ACRONYMS

ARSC	Afdaks River subcatchment	**HRSC**	Hopies River subcatchment
BRC	Bot River Catchment	**HSU**	Hydrologically Similar Unit
BRE	Bot River Estuary	**ISAT**	Impervious Surface Analysis Tool
BRSC	Bot River subcatchment	**MAE**	Mean annual evaporation
CAPE	Cape Action Plan for the Environment	**MAP**	Mean annual precipitation
CSIR	Council for Scientific and Industrial Research	**MAR**	Mean annual runoff
DEM	Digital elevation model	**SCS CN**	Soil Conservation Service Curve Number method
DWAF	Department of Water Affairs and Forestry	**SRSC**	Swart River subcatchment
ER	Effective rainfall	**TMG**	Table Mountain Group
GIS	Geographic Information System/s	**WSC**	West subcatchment

CHAPTER 1:INTRODUCTION

A water shortage may well be the next global catastrophe. We face great challenges in the management of South Africa's water resources to prevent such a disaster locally. Water is a limited natural resource and with the country's rapidly growing population and thriving economy, water requirements will soon exceed natural availability. "An integral part of any water management programme" (Weyman 1975:1) is to gather information on current water availability as it allows us to make accurate predictions of availability in the future. A major consideration is the fact that water resources are only one component in the balanced functioning of a natural habitat and as such, they must be managed in combination with all other natural resources (Dent 2001).

The natural resources in the Bot River Catchment (BRC) are being misused but the extent of the damage is unknown. A warning sign is the fact that the Bot River Estuary (BRE) no longer breaches its coastal berm naturally. This is disrupting the hydrodynamics in the BRE and the habitat of various marine life forms (Van Niekerk, Van der Merwe & Huizinga 2005). This thesis investigates the effects of anthropogenic influences on runoff quantity in the catchment, to guide decision makers on a more sustainable use of its land and water resources.

1.1 THE CATCHMENT FRAMEWORK

In 1899, WM Davis recognised the catchment as a spatial phenomenon (Burt & Walling 1984) and it has subsequently been used as the natural unit for water research. Conducting research within a catchment framework is a holistic approach that accounts for the cyclical nature of a river system with "inputs of precipitation and solar radiation, and outputs of discharge, evaporation and reradiation" (Burt & Walling 1984:11). Unlike the other water balance components, runoff cannot be estimated by sampling any area in space, but is concentrated in a channel that drains a much larger area and is therefore measured within that channel. By measuring the other components on the same spatial scale as the runoff, using the catchment framework, the land-water relationship begins to make sense (Weyman 1975).

1.2 THE NATURE OF THE PROBLEM IN THE BOT RIVER CATCHMENT

The ecological integrity and functioning of the BRC are being compromised by anthropogenic influences. Valuable environmentally-sensitive areas are being adversely affected, notably the

BRE, which no longer breaches its coastal berm, as it did naturally and sporadically over the last century. This is attributed to artificial breaching at Kleinmond Estuary and runoff reduction (Van Niekerk, Van der Merwe & Huizinga 2005).

Runoff has decreased due to land cover changes over time, such as afforestation, agricultural intensification, urbanisation and alien vegetation infestation (Present 2001). The volume of runoff in the tributaries determines the water velocity, which in turn affects the capacity of the rivers to export sediment downstream. Sedimentation further reduces the velocity of the river flow, contributing to the state in which the BRE is no longer able to break through its coastal berm (Roberts 2003, pers com).

Increased water demands are an additional matter of concern: the region has a growing population, with associated development pressures, and already faces severe water shortages in the near future. As land uses intensify and indigenous land cover diminishes, the negative impacts of this unsustainable utilisation on the BRC become a growing concern. Land and water use dynamics in the catchment are poorly understood at present. While the hydrodynamics of the BRE have received recent research attention (Van Niekerk, Van der Merwe & Huizinga 2005), the triggering influences from the BRC are under-researched. This research hopes to fill the gap.

1.3 RESEARCH AIM AND OBJECTIVES

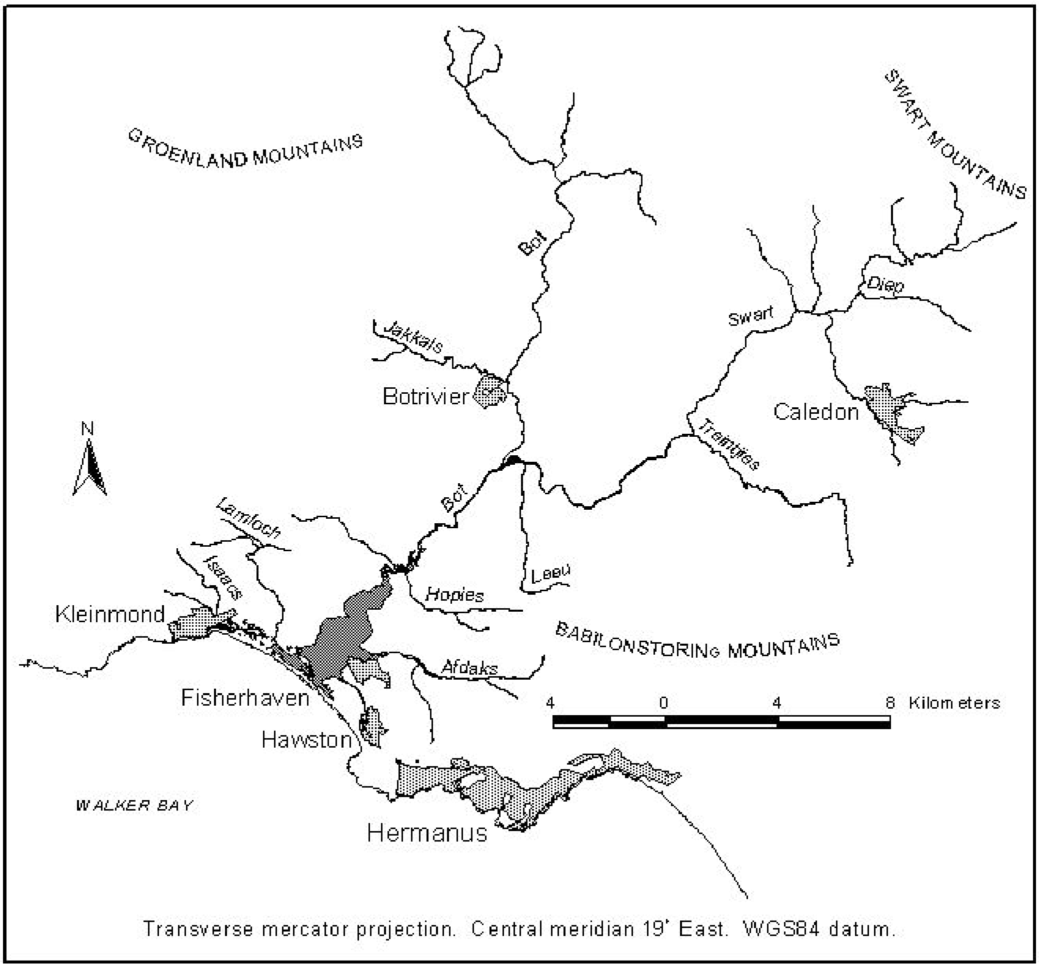
The research aims to use Geographic Information Systems (GIS) for modelling runoff in the BRC, by comparing runoff yields from its reconstructed reference state with the present, and to quantify the effects of land cover change and water abstraction on runoff. A reference state refers to the period in time when anthropogenic influences have not yet altered the natural environment of the catchment, nor its hydrological functioning. This aim is to be reached through realising the following operational research objectives:

1. Construct a hydrological model of the BRC from a digital elevation model (DEM) in GIS.
2. Reconstruct land cover maps of the catchment in its reference (pre-development) and current states.
3. Establish a database in ArcView GIS containing the relevant spatial modelling information for the BRC.

4. Calculate comparative runoff volumes in the catchment by modelling the reference and present state parameters.
5. Correlate the hydrological, water abstraction and land cover data to explain the impacts of change on runoff volumes.
6. Relate findings to catchment and estuarine management.

1.4 THE STUDY AREA AND RIVER SYSTEM

The BRC is located on the southwestern coast of South Africa. It is 907km² in area (Stipinovich 2002) and encompasses the towns of Caledon, Botrivier, Fisherhaven, Kleinmond and Hawston. The fertile valley has many uses: agricultural, residential, recreational and ecological, which are reflected in a variety of land covers. The source of the Bot River is located in the Groenland Mountains and it flows in a southerly direction until it joins with its major tributary, the Swart River, which originates in the Swart Mountains. The Bot River flows into the BRE or vlei, as seen in Figure 1.1.



Source: Van Niekerk 2000: 7

Figure 1.1: The Bot River system

Two other major tributaries of the vlei, the Afdaks and Hopies Rivers, originate in the Babilonstoring Mountains to the east (Department of Water Affairs and Forestry (DWAF) 2003). Two smaller tributaries of the vlei are the Jakkals River and the Isaacs River. The Bot River has cut a fairly deep river valley into the steep relief. The lower course of the river flows across inland and coastal plains that are either level or gently undulating. The plains form the largest farming area in the South coast district (DWAF 2003). The lower catchment area has a steep gradient from the coastal mountain ranges down to the coastal plain forming the banks of the estuary.

1.5 CREATION OF A HYDROLOGICAL MODEL OF THE BOT RIVER CATCHMENT

Previous research by the author divided the BRC into subcatchments based on the local channel network and natural topological boundaries, thereby partly satisfying Objective 1. ArcView's Hydrological Modelling Extension was applied to a DEM of the area to delineate a large number of very small subcatchments (Stipinovich 2002). To reduce the number of subcatchments, ArcView's DEMAT extension was used to derive an aspect grid from the DEM. Using the aspect and the visible flow direction of the rivers downslope, all subcatchments were unioned, moving up from the estuary until a watershed was reached. Within the larger BRC, a more detailed discretisation of five subcatchments was retained, configured around the location of major natural drainage channels. Their physical and geometric properties were calculated, basin area being the significant property in this research, as provided in Table 1.1. At less than

Table 1.1: Subcatchment characteristics

SUBCATCHMENT	**BASIN AREA (km^2)**	**QUATERNARY SUBCATCHMENT**	**MAP (mm)**	**MAE (mm)**	**RAINFALL ZONE ***
1. Bot River	262.7	G40E	722	1400	G4B
2. Swart River	421.9	G40F	515	1400	G4A
3. Afdaks River	38.5	G40G	724	1350	G4B
4. Hopies River	62.7				
5. West Bank	107.9				
Estuary	13.6	-	-	-	-
BRC	**907.3**	**-**	**-**	**-**	**-**

* Rainfall zone as given by Midgley, Pitman & Middleton (1994a)

1000km², the BRC is a rather small basin, with the Swart forming almost half. The mean annual precipitation (MAP) and mean annual evaporation (MAE) figures were provided by Midgley, Pitman & Middleton (1994a). It is evident that the basin experiences a large moisture deficit (MAP - MAE), with the Swart decidedly drier. The five subcatchments were named the Bot River (BRSC), Swart River (SRSC), Afdaks River (ARSC), Hopies River (HRSC) and West (WSC) subcatchments and are shown in Figure 1.2 to illustrate the dominance in size of the two main interior sub-basins.

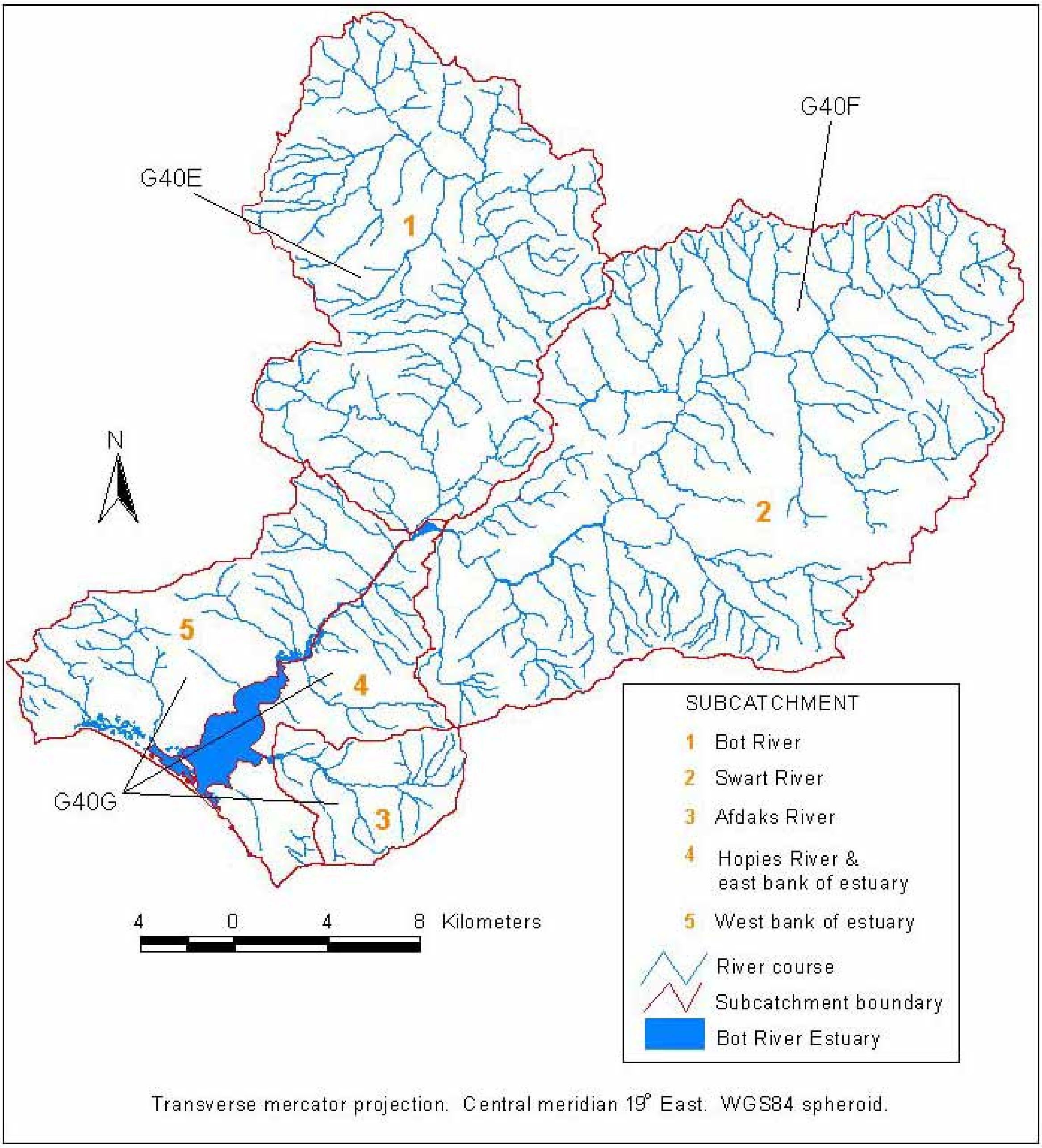


Figure 1.2: Delineation of the Bot River Catchment into five subcatchments

DWAF uses quaternary catchments as their hydrological unit for operational purposes in southern Africa (Meier & Schulze 1995). In Midgley, Pitman & Middleton's (1994a) publication, which was relied upon heavily in this research, the BRC is subdivided into three quaternary subcatchments using the official demarcations of DWAF: G40E, G40F and G40G. These subcatchment boundary delineations coincided with those used in this thesis as indicated in Table 1.1 and in Figure 1.3. The figure shows the extent to which the detailed empirical delineation of subcatchments in GIS (Stipinovich 2002) differs from the official demarcation of DWAF. In this report, the original delineation of five subcatchments was used wherever possible, conserving detail and accuracy, which would be lost in the coarser demarcation of DWAF. Two important aspects of the hydrology in the BRC for this research are its climate and a product of the diverse local hydrological and topographical factors, the BRE.

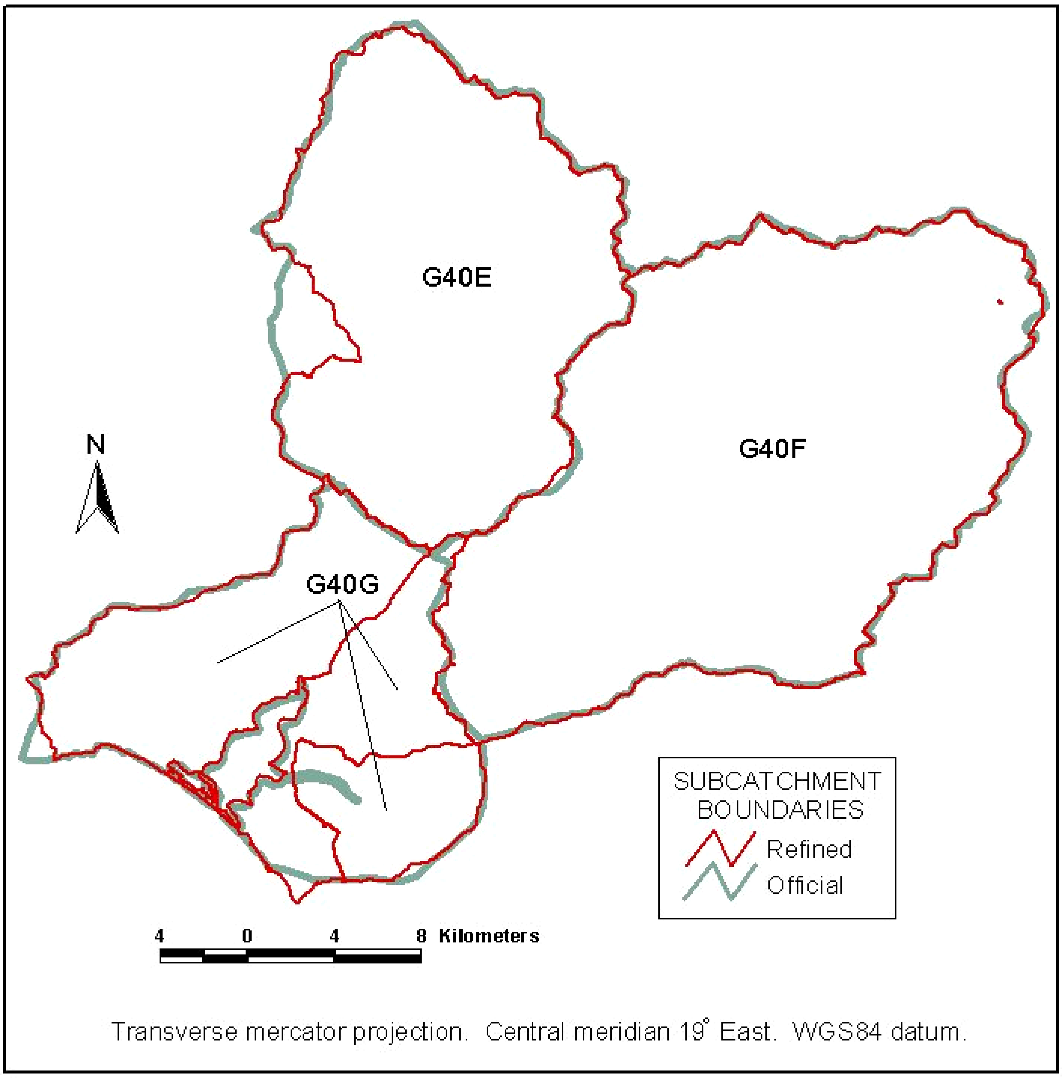


Figure 1.3: Comparison between the refined subcatchment boundaries used in this research and the official boundaries of DWAF

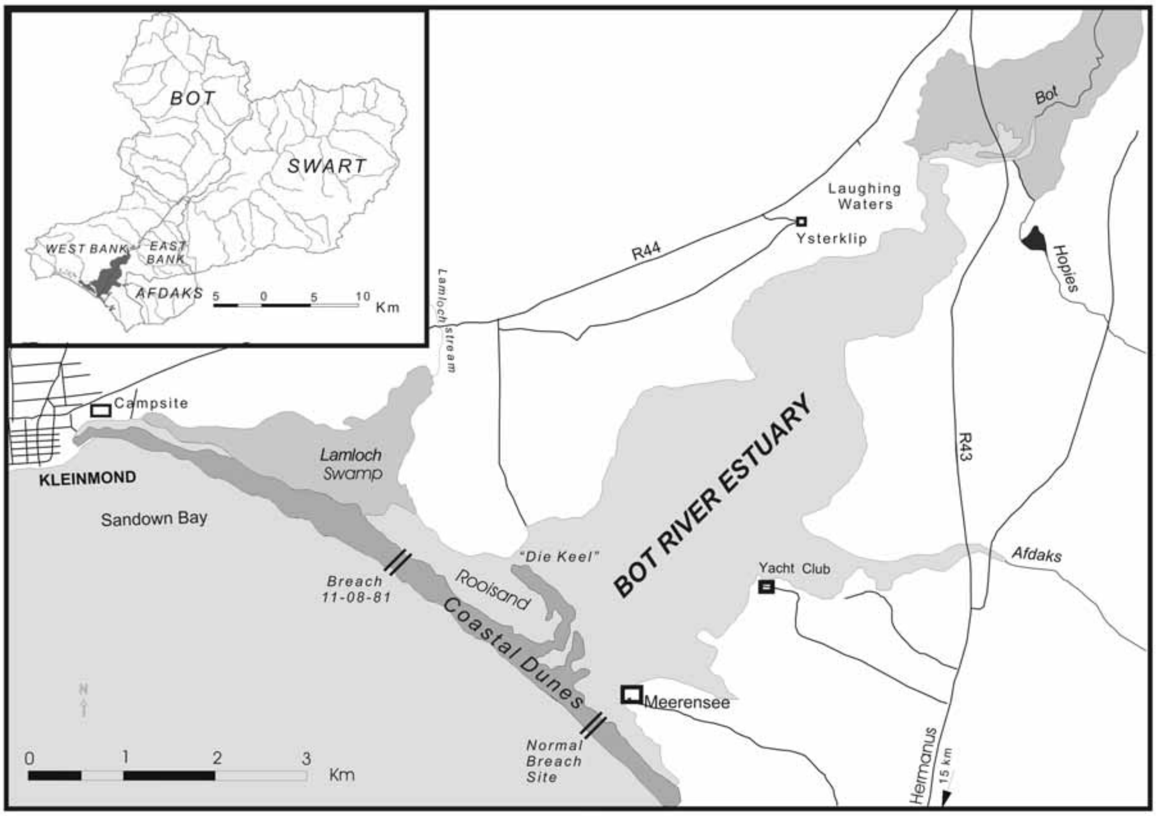
1.5.1 The climate in the Bot River Catchment

The BRC is situated in a semi-humid environment (Pitman 1973). It experiences a typical Mediterranean climate with cool, wet winters and dry, hot summers. Due to oceanic influences, temperature is mild. The average maximum and minimum temperatures in the area are approximately 30°C and 12°C respectively. The wind direction is predominantly northeasterly during the spring and south/southeasterly during the summer. Westerly winds form part of a cold frontal system that carries rain to the area in winter, with the maximum monthly rainfall in July or August. Rainfall is typically sporadic and of low intensity (DWAF 2003). Occasional droughts do occur in the region (DWAF 2004).

According to Midgley, Pitman & Middleton (1994a), the SRSC is located in the rainfall zone G4A, with the other subcatchments located in rainfall zone G4B (See Table 1.1). The subcatchments' MAP range between 500 and 730mm as Table 1.1 indicates, although DWAF (2004) generalises MAP for the catchment in total to 600-800mm. A large moisture imbalance is evident from the MAE rates at about 1400mm. The SRSC receives the lowest rainfall of the five, having the least orographic and coastal climatic influences (DWAF 2004).

1.5.2 The Bot River Estuary

The BRE is the largest estuary in the Western Cape. It is approximately 7.5km long and 3km at its widest point with an approximate total area of 13.6km^2 (depending on level at the time of measurement - DWAF (2003) records the areas as only 10.5km^2). It consists of the large lagoon and the smaller Kleinmond Estuary linked by a wetland, as seen in Figure 1.4. It used to be a tidal estuary, breaching its berm naturally at more regular intervals during high rainfall months, but this occurs seldom now. According to estimations (Van Niekerk, Van der Merwe & Huizinga 2005), the estuary would require nearly all of the natural catchment runoff to breach annually. Because of reduced runoff, the closed estuary mouth must normally now be breached artificially to prevent the estuary from turning into a freshwater lake (DWAF 2003). Artificial breaching and runoff reduction have disturbed the natural functioning of the estuary, preventing it from retaining its saline characteristics (Van Niekerk, Van der Merwe and Huizinga 2005).



Source: Van Niekerk, Van der Merwe & Huizinga 2005

Figure 1.4: The Bot River Estuary

The estuary is a sensitive environmental area and is ranked highly nationally on the basis of its conservation status, importance for fish and biodiversity. Part of the estuary lies within the transition zone of the Kogelberg Biosphere Reserve, which has significant ecological value, protecting 150 species of plants that do not grow anywhere else in the world. For these reasons, there is great concern for the natural state of the BRE and a need for research into its preservation. A lengthy data collection was initiated in preparation for this research, conducted in response to the problem of runoff reduction.

1.6 SOURCES OF DATA

As Table 1.2 indicates, data sourced for this research were obtained from a range of sources. This included primary data in tabular, digital image and analogue map formats. A number of secondary sources were obtained, also in tabular or GIS overlay formats. In the case of imagery, subsequent manipulation entailed the clipping of catchment extent from the larger databases to ensure a fully geo-referenced and matching range of input imagery for analytical and modelling

Table 1.2: Sources of data for the Bot River Catchment

DATA PRODUCT	SOURCE	TYPE/ FORMAT
DEM	Van Niekerk (2000, pers com), GEOM [1]	ArcView grid (20m resolution)
Watershed boundaries	Stipinovich (2002), GEOM	Shapefile from ArcView Hydrological Modelling
Land cover	Stipinovich (2002), GEOM	ArcView shapefiles from November 1999 satellite images
Land cover statistics	Stipinovich (2002), GEOM; (Midgley, Pitman & Middleton 1994a)	ArcView shapefiles and tabular data
Impervious surfaces	Stipinovich (2002), GEOM	Shapefile from ArcView Impervious Surface Analysis Tool Extension
Botanical areas	CapeNature	ArcView shapefile (20m resolution)
General BRC information	DWAF; Council for Scientific and Industrial Research (CSIR)	Documentation
Relationship between geology and botany	National Botanical Institute	Documentation and ArcView shapefile
Rainfall map	“3319 Worcester” Average Annual Rainfall map, GEOM	1:250 000 Analogue paper map
Rainfall-runoff model parameters and hydrological data	(Midgley, Pitman & Middleton 1994a); Ninham Shand Consulting Engineers	Tabular data
Hydrological and meteorological data	DWAF	Tabular data
Geohydrology	Parsons, Parsons & Associates, Specialist Groundwater Consultants	Tabular data
Water abstraction data	V3 Consulting Engineers, Worcester	Tabular data
Pitman-based SHELL rainfall-runoff model	Ninham Shand Consulting Engineers	Computer program
Statplot program & training in SHELL model use	Kamish of Ninham Shand Consulting Engineers	Computer program and tabular data

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[1] GEOM = Department of Geography and Environmental Studies, University of Stellenbosch, Stellenbosch, South Africa.

purposes. Tabular data were specifically required to calibrate models realistically. Empirical results were generated in GIS from imagery obtained as indicated. The sources for information as the table testifies were reliable official institutions and reputable consultancy firms active in research in the private sector.

1.7 RESEARCH DESIGN AND REPORT STRUCTURE

The research sequence, displayed in Figure 1.5, entailed the establishment of a GIS database for the BRC by deriving slope and hydrological boundaries from the DEM and incorporating other relevant variables. Land cover for the current state had been obtained through analysis of satellite imagery. Land cover for the reference state was modelled for the known relationship between underlying geology and natural vegetation communities. The result was combined with a generated rainfall-runoff model to establish the change in runoff due to altered catchment land use and water abstraction.

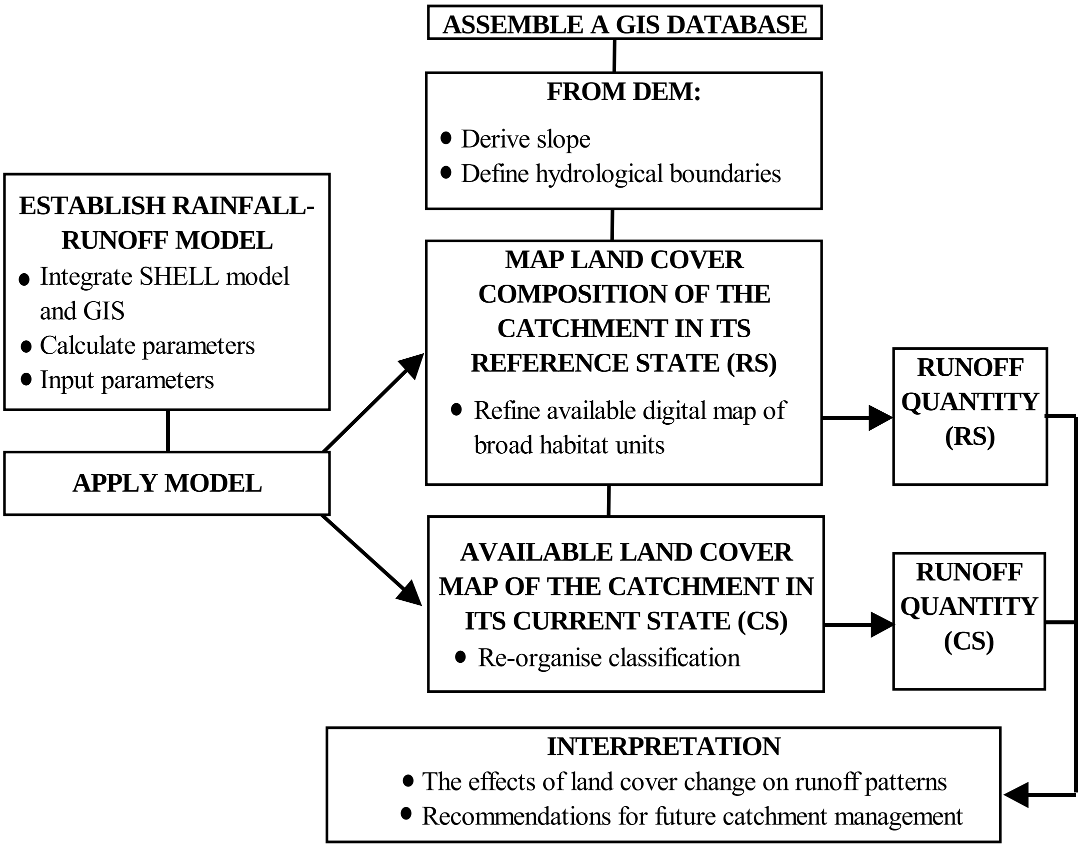


Figure 1.5: Research design

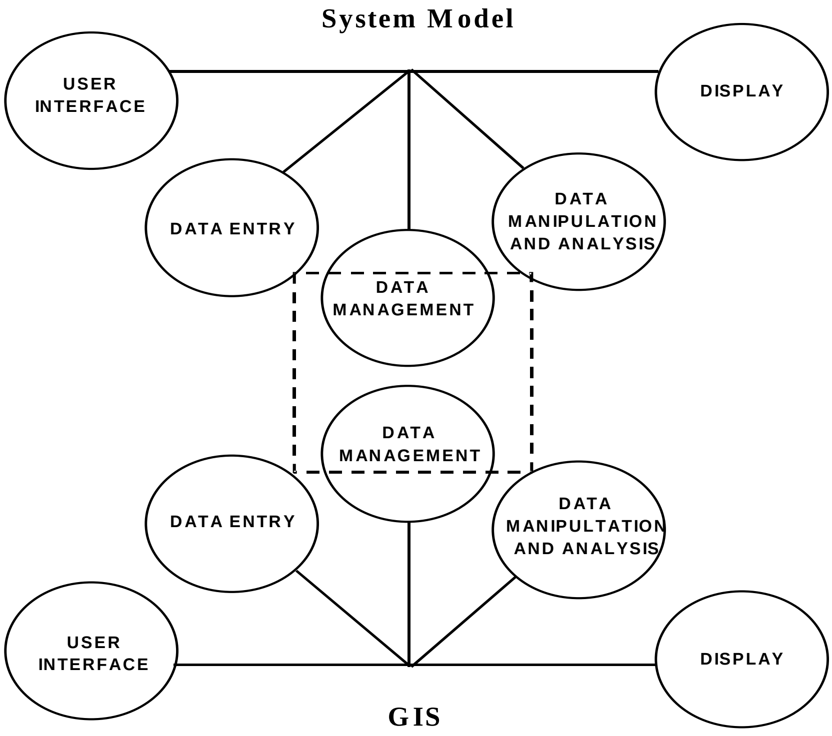
The report is structured as follows: In Chapter 2, published literature on hydrological modelling is reviewed to ensure scientifically sound application in the thesis and a rainfall-runoff model selected. Chapter 3 discusses the spatial analysis of the land cover composition in the BRC as an indication of how the catchment has been altered. In Chapter 4, the preparation and application of the rainfall-runoff model are explained. In Chapter 5, the thesis is brought to a logical conclusion in a comprehensive summary and synthesis of results.

CHAPTER 2: RAINFALL-RUNOFF MODELS: A REVIEW

This review was directed primarily towards gaining a broad understanding of rainfall-runoff models and their connection with GIS in preparation for the research on the BRC. The emphasis of the review fell on modelling methodology, as this was the most challenging aspect of the proposed research. The added challenge of modelling in South African conditions was noted. The review culminated in the "educated" choice of a rainfall-runoff model for this research.

2.1 GEOGRAPHICAL INFORMATION SYSTEM USE IN MODELLING

A GIS can determine topographic and hydrologic attributes at a scale not practicable by traditional methods (Wolff-Piggott 1995). This allows models "a spatial context that was lacking in the past" (Spence, Dalton & Kite 1995:62). There are three possible levels of integration between models and GIS (Van Deursen 1995). A low level involves the use of separate GIS and models, with exchange files. The majority of the model applications reviewed were only loosely coupled to the GIS (Stuart & Stocks 1993; Chairat & Delleur 1993) and the interfacing between them was rarely fully automated (Tarboton & Schulze 1992). A medium level has a common database structure supporting both GIS operations and model runs, as shown in Figure 2.1.



Source: Wolff-Piggott 1995: ii

Figure 2.1: Schematic diagram of a medium linkage between GIS and models

A high level of integration is considered by Van Deursen (1995:16) to be "the natural evolution for both GIS and simulation models". A closer coupling between a rainfall-runoff model and a GIS is possible using a distributed model. Distributed models divide a study area into a fine grid of cells, which lends itself very readily to the GIS raster data structure (Stuart & Stocks 1993). As a result, development of this approach has received "increasing impetus" in both the research and technical field (La Barbera, Lanza & Siccardi 1993:176).

Usage of the distributed approach in this thesis is prevented by its current complexity (La Barbera, Lanza & Siccardi 1993) and the fact that it often produces poorer simulations than simple models (Gan, Dlamini & Biftu 1997). In modelling, "map production and the assessment of cause [and] effect relationships is considered an important aspect of coupling GIS" and rainfall-runoff models (Kienzle 1993:309). However, the GIS user must have skill in hydrological modelling to prevent the output of polished graphics that lack accuracy and significance (Harden 1993).

2.2 RAINFALL-RUNOFF MODELS

A rainfall-runoff model is a set of complex transfer functions (Hughes 2000) that provides the capability to predict streamflow from routinely measured climate data (Wooldridge, Kalma & Kuczera 2001). The functions are calibrated by the model user with specific values to mimic the local water balance, with inputs of precipitation and outputs of evaporation and transpiration, and inputs/outputs of storage. Disadvantages of models are that they require extensive resources in terms of expertise, time and information in order to generate reliable results (Hughes 2000).

A model is matched to the problem to be solved. Its conceptual base should capture the major hydrological processes of the catchment (Gan, Dlamini & Biftu 1997) and its time steps should adequately represent the rates of change of the process under study. Different hydrological models are therefore used to simulate different runoff generation processes in different regions (Schmitz & De Villiers 1997; Van Deursen 1995; Haan, Barfield & Hayes 1994; Boughton & Droop 2003). Three approaches can be taken: use of an existing model, modification of an existing model or development of a new model, which is only justifiable for large and important projects (Haan, Barfield & Hayes 1994). Some of hydrological modelling's key issues were discussed frequently in the literature and are summarised below: model complexity, parameter and data inputs, and model uncertainty.

2.2.1 Model complexity

As an increase in model complexity does not necessarily mean an increase in accuracy, it is difficult to choose the optimum level of complexity needed for the desired results (Van Deursen 1995). Complexity is determined by the number of subsystems, the amount of state variables, the mathematical equations of the processes (Van Deursen 1995) and the types of data available (Gan, Dlamini & Biftu 1997). Van Deursen (1995), who dealt with complexity in detail, supported the use of conceptually robust simple models. These can use readily available GIS data and are quick and easy to run, but he also noted their potential oversimplification and loss of spatial and temporal resolution.

2.2.2 Model parameters and data inputs

Calibration is the process of discovering the optimal values for the model parameters. It is an estimate as the value is not quantifiable in the field. Each parameter represents one of the component processes in the model and is input as a coefficient. Only a minimal description of these processes is needed to generate the characteristic responses for each landscape or climate unit (Wooldridge, Kalma & Kuczera 2001). A parameter may be highly sensitive and a small change in its value can have a significant effect on the model output (James 1994). Gan, Dlamini & Biftu (1997) criticised the growing tendency to use more complex models than is required, which leads to overparameterisation and in fact, inferior results.

Parameters can be calibrated in the following ways: in forward modelling, field or map measurements are used to set parameter values, and in inverse modelling, parameter values are altered until error differences between model predictions and observed outputs are minimised (Van Dijck 2000). To have no error difference is virtually impossible and rather than reducing the error in one property at the cost of the others, a more “meaningful approach [is] to accept reasonably small errors in all…properties” (Pitman 1973:5.8).

2.2.3 Model uncertainty

The results of a model should always be considered in a relative rather than absolute sense (Van Dijck 2000). This is due to uncertainty regarding how well actual processes are represented in the model and how well the parameters used characterise the catchment (Haan, Barfield & Hayes

1994). Model uncertainty is the "degree to which the output of a simulation represents the observed outcome of the physical system" (James 1994:135). There is never true satisfaction for the model user as even if the fit is acceptable, the calibration may be based on an imperfect input of time series of rainfall and evapotranspiration data (Hughes 1995).

2.3 MODELLING THE SOUTH AFRICAN CONDITIONS

Understanding of the hydrological processes in South Africa's predominantly arid or semi-arid climate is poor compared to understanding of those in humid environments (Herald 1989). The increased complexity and wider range of hydrological processes in dry catchments are harder to model and more sensitive to model structure (Gan, Dlamini & Biftu 1997). The majority of rainfall-runoff models have been developed for application in temperate or wet conditions. A version of the Pitman model, PITM, was developed for South African conditions and has been previously calibrated and assessed as successful for this purpose. Gumbo et al. (2002) found the Soil Conservation Service (SCS) Curve Number (CN) method provided the adequate balance between ease of use and accuracy. Adapted to South African conditions as the SCS-SA method, this model estimates runoff efficiently in a GIS environment. Boughton & Droop (2003) confirmed that it is probably the most used rainfall-runoff model in the world, due to its simplicity.

2.4 SUMMARY OF THE REVIEW

Over the past 25 years, models have become essential in the assessment of the environment's reaction to human interference (Van Deursen 1995) and in devising management strategies to minimise the impacts (Chanasyk, Mapfumo & Willms 2003). Due to the developing nature of the hydrological modelling field, many authors included helpful recommendations and warnings on misuse of models and discussion of major concepts. Surprisingly few elaborated on the reasons for selecting a particular model and many assumed that the reader would have a sophisticated level of understanding. Nobody covered exactly how the models are formatted or how they are input into the computer. As a result of the review, the choice of rainfall-runoff model to be applied to the BRC could be narrowed down to two: the SCS-SA CN model (Gumbo et al. 2002) and the PITM model (Herald 1989). Both appealed due to their configuration for the South African climate and their apparent simplicity.

2.5 THE SELECTED MODEL

It was surprisingly difficult to obtain a model that could be used on modern computers. Most publications mentioned their model's name but not its source (Mohan & Shrestha s.d.; Chanasyk, Mapfumo & Willms 2003; Boughton & Droop 2003; Gan, Dlamini & Biftu 1997). These days, runoff models seem to be developed 'in house' in organisations according to their unique requirements. Finally, such an 'in house' model, the Pitman-based SHELL model, was obtained with the assistance of Ninham Shand Consulting Engineers (Beuster 2003, pers com).

The SHELL model is a "container" model within which runs the Pitman model component that accounts for all natural factors (principally precipitation and evaporation) and the separate attached submodules that account for the intercept effects of various modern land cover types: RESSIM (water impoundment), IRRDEM (irrigated agricultural crops), FORESTRY and ALIENVEG. The greatest appeal of the SHELL model was its simplicity and the fact that its chief parameters were precalculated for individual South African catchments and readily available in Midgley, Pitman & Middleton (1994a). Additional parameters to be used in calibrating the model were calculated in the GIS program, ArcView 3.2.

2.5.1 The model calibration process

Calibration is based to a certain extent on subjective reasoning (Pitman, Potgieter, Middleton & Midgley 1981), which requires hydrological and modelling expertise. Fortunately, parameters can usually be mapped and generalised to provide estimates for specific regions (Pitman, Potgieter, Middleton & Midgley 1981), based on climate, vegetation and geology. Midgley, Pitman & Middleton (1994a) provide regionalised parameters for each of the quaternary catchments in the country, which can be used in the Pitman base module of the SHELL model. These parameters are summarised in Table 2.1. The way the Pitman model parameters are used to model the hydrological cycle in a catchment is illustrated in Figure 2.2 and discussed in the text.

Precipitation (P) moves through certain processes before entering a river system as runoff. Some of the precipitation goes into the interception storage of the vegetation (PI). Once PI is filled, further precipitation will infiltrate the soil and be stored as soil moisture (S). Both PI and S are subject to evapotranspiration. The parameter R controls the rate at which catchment evaporation diminishes as S, soil moisture storage capacity, is decreased and no longer meets its full potential, ST, the maximum soil moisture capacity (Pitman 1973). When ST has been reached, any excess moisture forms surface runoff. The parameters ZMIN and ZMAX are the nominal minimum and maximum infiltration capacities for the portion of the catchment surface that is pervious, impervious areas being represented by the parameter AI (Pitman 1976). AI represents only the proportion of impervious catchment area that is adjacent or connected to stream channels.

Table 2.1: Pitman Model parameters

PARAMETER	**UNITS**	**DESCRIPTION**
P	mm/month	Monthly Precipitation
PE	mm/month	Monthly Total Evaporation / Potential Evaporation
POW	-	Power of Soil Moisture-Runoff equations
SL	mm	Soil Moisture Storage below which no runoff occurs (~Wilting Point)
ST	mm	Maximum Soil Moisture capacity (~Porosity / Saturation)
S	mm	Soil Moisture Storage capacity
FT	mm/month	Runoff from soil when Soil Moisture is at full capacity
GW	mm/month	Maximum Groundwater Runoff
AI	%	Impervious portion of the catchment
ZMIN	mm/month	Minimum catchment absorption rate
ZMAX	mm/month	Maximum catchment absorption rate
PI	mm	Vegetation interception Storage
TL	months	Lag of surface runoff
GL	months	Lag of runoff from subsurface soil moisture
R	-	Evaporation-Soil Moisture storage relationship

Of the water infiltrating the soil, the *quantity* percolating down to the groundwater supply is determined by the evaporation rate and soil moisture (S). Evaporation is controlled by the potential evaporation (PE), S and R. High temperatures, low humidity and high wind speed increase the rate of PE. When ST is reached, further precipitation will form surface runoff, represented by the parameter FT. The *rate* of percolation of water infiltrating the soil to groundwater is controlled by the parameters S, ST, SL, FT and POW. SL is the soil moisture storage capacity, below which percolation and runoff cease (Pitman 1976). POW is the power of the assumed soil moisture-percolation curve. The water percolating downwards recharges the groundwater zone, found some depth beneath the land surface (Weyman 1975).

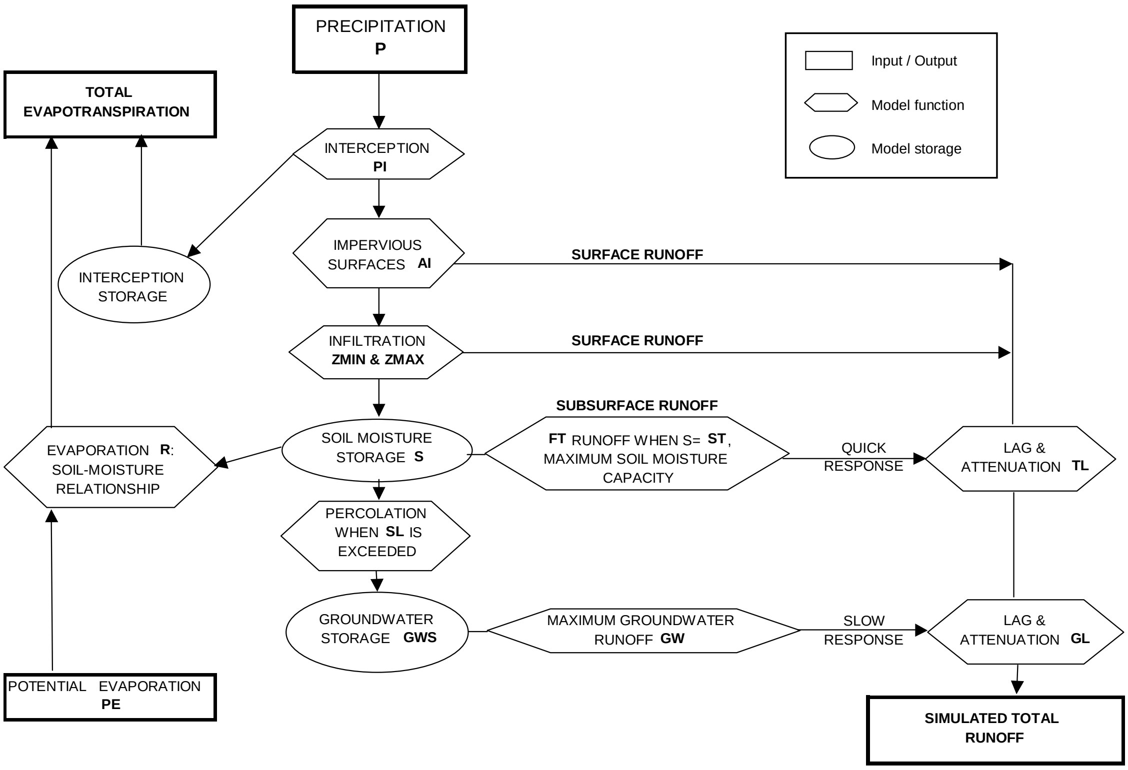


Figure 2.2: Pitman modelling process

The processes representing lateral movement of water through the catchment are suitably lagged to simulate the fact that runoff is subject to time delay and attenuation (Pitman 1973). As the single parameter used to simulate the lag in this research, TL (time lag) results in a good simulation of average flow distribution but not the best simulation for individual months (Pitman 1976). It is quite adequate for this research as only a final annual streamflow total is required. The parameter GL models the slow response lag of subsurface runoff from groundwater storage. GW, the maximum groundwater runoff, and GL together determine the outflow from groundwater to the river system. The model calculates the various components until the input data are exhausted and the simulation then terminates (Pitman 1976).

2.5.2 GIS and model integration

GIS data models can currently only represent continuous phenomena with discrete data models, such as vector or raster. In this thesis, the data model was vector, with the subcatchments stored as contiguous vector polygons in ArcView. Hydrological and spatial data stored for each polygon in the ArcView database was input into the submodule files manually by the model user. The SHELL model was operated as an executable computer program, separate from the GIS, and was activated from a network folder that contained the relevant parameter files. The model was run so that for each polygon, an individual output file was generated. The complete GIS-model coupling consisted of:

- A GIS database containing data on the features in the BRC to be modelled.
- Formulation of these features' spatial and hydrological variables as model parameter inputs.
- Organisation and planning of the operation of the model.
- Displaying the results of the SHELL model's input and output in the form of maps and graphs.

The spatial data representing the BRC in its reference and current states was now prepared and converted into a tabular format in ArcView in anticipation of the modelling calibration process. Before the selected runoff model could be activated, the land cover of the BRC had to be mapped and analysed for the current as well as the pre-development stages. This task was reported in Chapter 3.

CHAPTER 3: LAND COVER IN THE BOT RIVER CATCHMENT: PRESENT AND PAST

Runoff simulated from a catchment in its recreated pre-development state serves as a reference against which to compare present day runoff. The difference in runoff quantity allows one to evaluate the impact of modern land cover conditions on the catchment (Kienzle & Schulze 1995). To recreate the catchment vegetation as it was before anthropological influences set in, the research plan was to correlate established relationships between vegetation and geology with a map of the geology in the BRC. Present and past land cover quantification (Objective 2) and organisation of the spatial data (Objective 3) therefore form the main sections of this chapter.

3.1 CURRENT LAND COVER COMPOSITION

Land cover in the BRC has altered considerably and to understand how this has affected runoff quantity, the current scenario was mapped and the known effects on runoff of the various land cover types were investigated. A GIS database in ArcView was established to contain and organise the extensive spatial information gathered. The land cover map and statistics are the result of previous research (Stipinovich 2002). As the map is of utmost importance to this research, the mapping methodology used in its creation is discussed here briefly. Digital satellite images of the area were interpreted, supported by field control. Land cover types were digitised as polygon themes. Linear elements, such as roads, were included as they have a significant impact on runoff. All themes were merged and clipped to the watershed boundary for spatial evaluation.

The current land cover composition in the BRC is shown in Figure 3.1 and illustrates the predominance of annual grain (mainly wheat) production in the basin. Towards the steep valley sides natural fynbos still dominates, while greater variety of negative human-induced land use types (urban, alien vegetation infestation) abound closer to the estuary and the coastline. The land cover area for each type was calculated for each subcatchment separately as shown in Table 3.1. These figures were used extensively in calibrating the rainfall-runoff model. They show clearly that the dominant land cover modification since pre-development times has been annual agricultural intensification. This takes up almost half the BRC land area. The other agricultural practices of forestry, cultivated fynbos and perennial agriculture are comparatively minor in areal extent. Urbanisation, though rapidly expanding, is still relatively minimal in areal terms. The combined area covered by road surfaces is noteworthy for its effect on runoff productivity

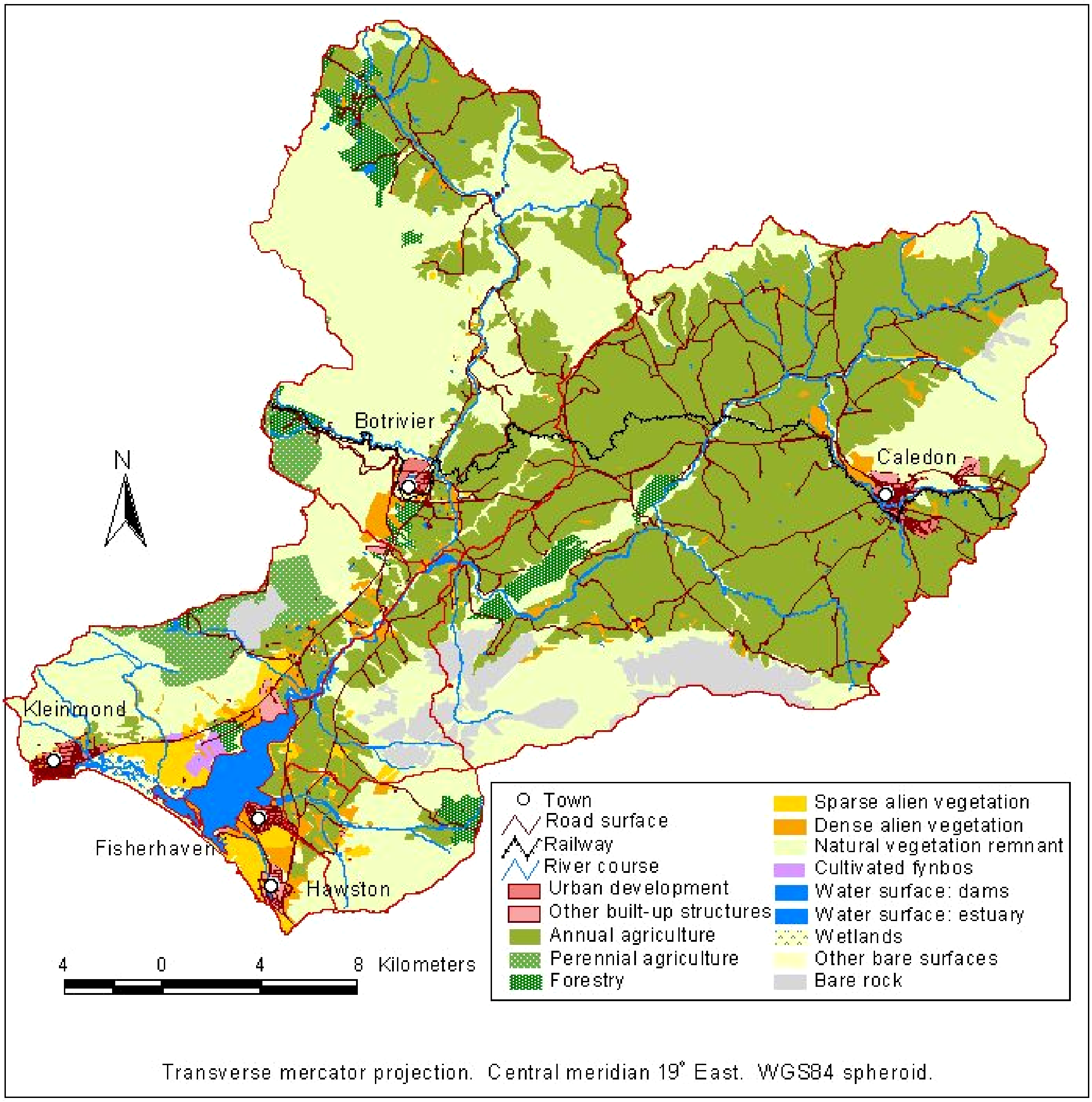


Figure 3.1: Current land cover in the Bot River Catchment

as it virtually covers the same area of impervious surface as the towns. Alien vegetation infestations exist chiefly on land near urban areas, in the riparian zone and are most dense around the estuary. Only some 40% (if one includes the 'bare rock' land cover type, which has subsequently been noted as being sparsely vegetated in fynbos) of the BRC remains in its natural state.

Field orientation helped to refine the digitised land cover to optimum accuracy. Rows of alien trees had not been distinguished despite their prevalence in the field. Bare sand, opencast mines, quarries, and degraded areas appeared the same on the satellite images due to their similar spectral reflectance characteristics and were grouped together as 'Other bare surfaces'. Areas

Table 3.1: Areas of land cover per subcatchment in the current Bot River Catchment

LAND COVER TYPE	**AREA PER SUBCATCHMENT (km^2)**							**% OF TOTAL CATCHMENT**
	BOT RIVER	**SWART RIVER**	**AFDAKS RIVER**	**HOPIES RIVER**	**WEST BANK**	**BOTVLEI**	**TOTAL**	
Urban built-up (town)	1.7	2.6	0.2	3.0	2.7	-	10.2	1.1
Other built-up	0.3	1.3	0.1	1.7	2.2	-	5.6	0.6
Road surface (all classes)	2.0	3.7	0.2	0.7	1.1	-	7.7	0.8
Annual agriculture	86.0	274.4	5.9	20.6	12.1	-	399.0	44.0
Perennial agriculture	4.5	-	-	-	17.4	-	21.9	2.4
Forestry plantation	12.9	7.2	2.8	-	1.7	-	24.6	2.7
Cultivated fynbos	-	-	-	-	2.1	-	2.1	0.2
Natural fynbos and renosterveld	146.9	93.1	24.7	17.2	43.4	-	325.3	35.9
Sparse alien vegetation	0.5	0.8	1.0	6.6	7.8	-	16.7	1.8
Dense alien vegetation	4.9	6.5	2.8	4.8	5.8	-	24.8	2.7
Waterbodies	1.4	1.1	0.3	0.3	0.8	-	3.9	0.4
Water surface: estuary	-	-	-	-	-	13.6	13.6	1.5
River course	0.7	1.5	0.2	0.6	0.5	-	3.5	0.4
Wetland	-	-	-	-	3.1	-	3.1	0.3
Bare rock (mountainous)	-	28.1	-	6.3	3.9	-	38.3	4.2
Other bare surfaces	0.9	1.6	0.3	0.9	3.3	-	7.0	0.8
Total BRC area (km^2)	262.7	421.9	38.5	62.7	107.9	13.6	907.3	100.0
% of total catchment	29.0	46.5	4.2	6.9	11.9	1.5	100.0	-

digitised as bare rock were in fact mountainous regions, vegetated with fynbos. Overall, generalisations of the more complex and fragmented reality were unavoidable due to scale limitations. With the digital mapping of the current BRC available, the reference state was established so that the potential effects of land cover changes over time could be examined.

3.2 RECONSTRUCTION OF THE REFERENCE STATE LAND COVER

The Cape Floral Kingdom, also known as the Capensic biome, is one of the smallest of the six floral kingdoms in the world and yet is a major reason why South Africa is called one of the 12 biological "mega-diversity" countries of the world (Younge 2000:1). The BRC still has relatively large areas of Capensic vegetation, particularly on steeper slopes, which prohibited urban or agricultural development in the past. By studying these remnants of the catchment in its reference state, and by working with known relationships between vegetation and geological substrates, a map of the reference state of the entire catchment was produced.

3.2.1 Reconstruction methodology overview

The actual conditions in the reference state of the BRC are unknown, as they have not been recorded in the past. Various assumptions must thus be made in order to recreate this state of pre-development times, the first of which being that pre-development times constitute conditions in the 19th Century before the advent of major mechanised agricultural activity. In light of this relatively brief time span, the climate, topography, soil and geology in the BRC are assumed to have remained constant variables. The vegetation cover is therefore the only element which requires reconstruction to eliminate the effect and impact of human developments. Geology was taken to be the dominant factor influencing vegetation type and location, with the Mediterranean climatic influences assumed to be the same as in modern times.

3.2.2 Catchment geology and its effect on runoff and vegetation

It was first necessary to introduce the geological substrates present in the BRC. In addition to strongly influencing the vegetation cover, the nature of the ground surface, soil and underlying parent material influence the quantity and quality of the runoff a catchment produces (Weyman 1975). Understanding the geology therefore supports a deeper understanding of catchment water movement. Groundwater flows at low velocities through the substrate underlying a catchment, which can act as a large storage medium. Water only enters the underlying substrate if the overlying rock is permeable (Weyman 1975).

The dominant geological substrates in the BRC are Table Mountain Group (TMG) sandstone and Bokkeveld shale. The coarse-grained, resistant TMG sandstone forms the rugged, upthrown northwestern and southeastern areas and is highly permeable. It forms the second most important aquifer in the country (Rosewarne 2000). The weathered, fine-grained Bokkeveld shale produces a comparatively subdued topography (Parsons 2002), yielding an overlying clay soil with a very low permeability (Weyman 1975). Where the Bokkeveld shale and the TMG sandstone meet in the westerly areas, the geological substrate is not consolidated, creating a fault line. Water is released through springs located along the fault. Near the estuary and along the coast, unconsolidated Quaternary deposits abound.

Geological influence on vegetation type is considered to be an indirect control, "[a] composite, with geomorphology and aspect" affecting vegetation distribution (Chevallier et al. 2003:16). According to Acocks (1988), two veld types theoretically covered the BRC in its natural state: 'Temperate and transitional forest and scrub types V' and 'sclerophyllous bush types VII'. The former is renosterveld, or 'false fynbos', and is associated with shale. The latter is fynbos and is associated with sandstone substrates. Acocks (1988:97) described the renosterveld at the time of his research as being "mostly ploughed up for growing wheat" and in poor condition. The fynbos had not been destroyed to the same extent due to its mountainous location. The areas of the natural vegetation groups calculated from Acocks (1988) in GIS are provided in Table 3.2.

Table 3.2: Areas of fynbos and renosterveld in each subcatchment

SUBCATCHMENT	**AREA OF SCLEROPHYLLOUS "FYNBOS" (km²)**	**%**	**TEMPERATE AND TRANSITIONAL FOREST AND SCRUB TYPE "COASTAL RENOSTERVELD" (km²)**	**%**	**TOTAL (km²)**
Bot River	123.5	47.0	139.2	53.0	262.7
Swart River	156.1	37.0	265.8	63.0	421.9
Afdaks River	38.5	100.0	-	-	38.5
Hopies River	61.9	98.7	0.8	1.3	62.7
West bank	107.5	99.6	0.4	0.4	107.9
BRC land area	487.5	54.5	406.2	45.5	893.7
Estuary					13.6
BRC TOTAL					907.3

As indicated in the table, fynbos and renosterveld were fairly evenly distributed in the BRC in pre-development times. The ARSC, HRSC and WSC were almost entirely covered by fynbos, whereas the cover over the upper subcatchments, the BRSC and the SRSC, was nearly 60% renosterveld. It was hoped that a refinement of these broad sandstone-fynbos and shale-renosterveld relationships could be made to enable closer comparison between the mapped current and reference states of the BRC.

3.2.3 Reference state land cover in the Bot River Catchment

Mapping of a more refined reference state land cover was achieved through the use of data on broad habitat units of the Western Cape created by CapeNature and recommended by Von Hase

(2003, pers com). CapeNature defined the habitat units as having a unique combination of homogenous climate, geology, and topography. Wherever these factors combined to provide a suitable habitat for a certain type of indigenous vegetation, it was assumed to have occurred there during the reference state. As the CapeNature broad habitat unit shapefile provided a continuous cover of data for the study area, it was adapted for use with only minor alterations. This involved addition of detail on surface phenomena that could be assumed to have existed in pre-development times: the estuary, river system, wetland, dunes and beaches, all digitised earlier (Stipinovich 2002). Without any evidence to prove otherwise, the spatial extent and exact location of these features in pre-development times were assumed consistent with present times and were therefore adopted for comparative purposes. The 10 broad habitat units, which occur in the study area, are those illustrated in Figure 3.2.

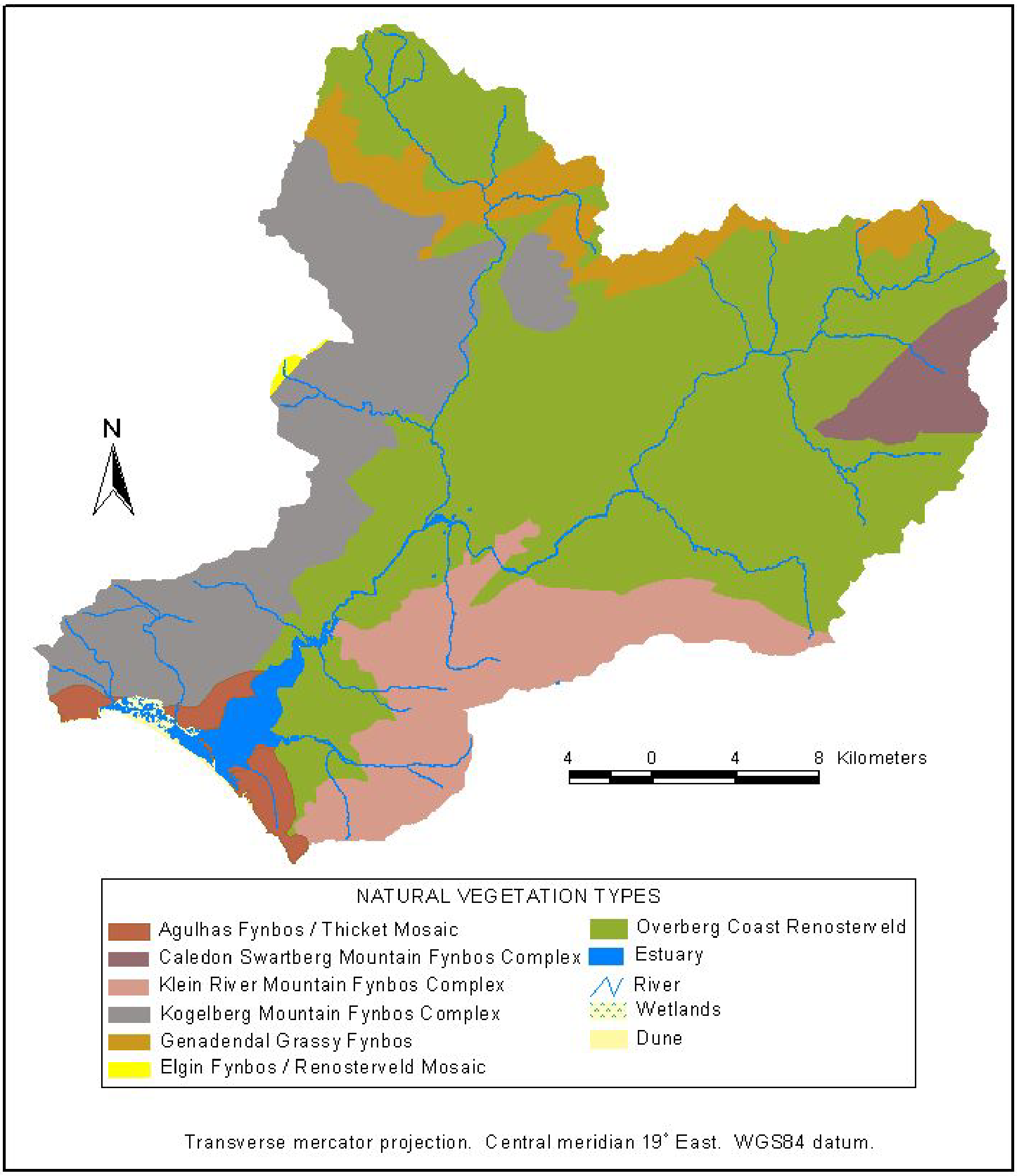


Figure 3.2: Recreated land cover in a reference Bot River Catchment

The areas of the habitat units are provided in Table 3.3. In the map of the reference land cover, it is clear that the feature classified as 'bare rock' in the current land cover map was ignored as, from subsequent observations in the field, sparse fynbos vegetates these areas. The 'waterbodies' of current times are primarily farm dams used for irrigation. Therefore, only waterbodies within the wetlands and those forming part of the estuary were included in the reference land cover map. All manmade developments were obviously excluded.

Table 3.3: Areas of land cover per subcatchment in the reference Bot River Catchment

LAND COVER TYPE	**AREA PER SUBCATCHMENT (km^2)**							**% OF TOTAL CATCHMENT**
	BOT RIVER	**SWART RIVER**	**AFDAKS RIVER**	**HOPIES RIVER**	**WEST BANK**	**BOT RIVER ESTUARY**	**TOTAL**	
Agulhas Fynbos / Thicket Mosaic	-	-	-	9.5	8.7	-	18.2	2.0
Caledon Swartberg Mountain Fynbos Complex	-	31.7	-	-	-	-	31.7	3.5
Klein River Mountain Fynbos Complex	-	69.8	29.1	22.8	-	-	121.7	13.4
Kogelberg Mountain Fynbos Complex	108.6	-	-	-	75.5	-	184.1	20.3
Genadendal Grassy Fynbos	39.8	18.8	-	-	-	-	58.6	6.5
Elgin Fynbos / Renosterveld Mosaic	1.1	-	-	-	-	-	1.1	0.1
Overberg Coast Renosterveld	112.6	300.0	9.2	29.5	18.9	-	470.2	51.8
Water surface: estuary	-	-	-	-	-	13.6	13.6	1.5
River course	0.6	1.6	0.2	0.6	0.5	-	3.5	0.4
Wetland	-	-	-	-	3.1	-	3.1	0.3
Dune	-	-	-	0.3	1.2	-	1.5	0.2
Total BRC area (km^2)	262.7	421.9	38.5	62.7	107.9	13.6	907.3	100.0
% of total catchment	29.0	46.5	4.2	6.9	11.9	1.5	100.0	-

Correlating the CapeNature mapping with the geology, Kogelberg Mountain Fynbos takes up a fifth of the area, dominating the western edge of the catchment. Klein River Mountain Fynbos Complex covers the southeastern mountainous areas. Both of these fynbos species are found on a substrate of TMG sandstone. The Agulhas Fynbos/ Thicket Mosaic is found on the alluvial plains of Quaternary aeolian and drift sand flanking the BRE. Overberg Coast Renosterveld is the principal vegetation type, taking up over half the catchment area in the central eastern sector on a substrate of Bokkeveld shale. The combined area of the various fynbos species thus take up the other half of the catchment. On magnification, the CapeNature shapefile subcatchment delineation differed slightly from that generated for this study. However, these discrepancies could be smoothed to provide a comparative database that was used to establish exactly what land cover change had taken place since the reference state.

3.3 THE MAGNITUDE AND EFFECT OF LAND COVER CHANGE AND WATER ABSTRACTION

The land cover within a catchment influences the various processes converting precipitation to runoff. Large changes in area of natural vegetation to high water consumptive usage will cause dramatic changes in the water yield (Kienzle & Schulze 1995). Natural vegetation currently constitutes only 40% of the cover in the BRC (Stipinovich 2002) indicating a significant alteration in land cover composition over time. Although the effects of current land cover on runoff as a static element of the catchment cannot be quantified meaningfully (Tarboton & Schulze 1992), temporal land cover changes can be, when analysed in association with the relevant long-term hydrological data. Therefore, the nature of change and replacement is quantified first, before the effects of various land cover categories on runoff are discussed.

3.3.1 The magnitude of land cover change

To establish the nature of change, the present and reference overlays were crosstabulated in GIS to find the area that has altered from one land cover type to another. These values and the total percentage area loss of each particular fynbos and renosterveld species are given in Table 3.4. Where the current land cover type was classified as "natural vegetation", it was assumed that the reference land cover type still existed there.

Of greatest significance is that nearly 60% of the original cover has been altered. The main loss in the BRC has been of Overberg Coast Renosterveld, which was previously found on the gently undulating fertile plains. These plains have proved ideal for annual agriculture, urban development and forestry, while alien infestation has gained a foothold. A similarly great loss has been of Agulhas Fynbos/ Thicket Mosaic, which existed on the now relatively highly developed (urban) coastal belt and estuary banks, where alien vegetation has also become established. The Kogelberg complex, now protected for biodiversity purposes, has experienced the largest loss to perennial agriculture, while annual crop production and alien infestation have both made significant inroads. The other mountain fynbos zones have been the least affected due to their location on steep slopes, which has prohibited the typical land cover changes to urban and agricultural practices.

Table 3.4: Land cover change from reference to current state

REFERENCE LAND COVER	**CURRENT LAND COVER (km^2)**									**Reference land cover loss (%)**
	Urban *	Annual agriculture	Perennial agriculture	Forestry	Alien vegetation	Natural** vegetation	Estuary	Other ***	**TOTAL AREA (Reference)**	
Agulhas Fynbos / Thicket Mosaic	7.3	0.0	0.0	0.8	6.9	3.2	0.0	0.0	18.2	82.4
Caledon Swartberg Mountain Fynbos Complex	1.0	0.7	0.0	0.0	0.5	29.5	0.0	0.0	31.7	6.9
Klein River Mountain Fynbos Complex	1.0	9.5	0.0	5.7	2.2	103.0	0.0	0.3	121.7	15.4
Kogelberg Mountain Fynbos Complex	4.6	9.4	20.8	3.5	7.4	137.4	0.0	1.0	184.1	25.4
Genadendal Grassy Fynbos	0.6	15.4	0.0	2.9	1.3	37.9	0.0	0.5	58.6	35.3
Elgin Fynbos / Renosterveld Mosaic	0.0	0.0	0.4	0.2	0.0	0.5	0.0	0.0	1.1	54.5
Overberg Coast Renosterveld	16.0	364.0	0.7	11.5	21.7	54.2	0.0	2.1	470.2	88.5
Estuary	0.0	0.0	0.0	0.0	0.0	0.0	13.6	0.0	13.6	0.0
Other	0.0	0.0	0.0	0.0	1.5	0.0	0.0	6.6	8.1	18.5
TOTAL AREA (Current)	30.5	399.0	21.9	24.6	41.5	365.7	13.6	10.5	907.3	57.0

* Urban = ‘urban built-up’, ‘other built-up’, ‘road surfaces’ and ‘other bare surfaces’

** Natural vegetation = ‘natural fynbos and renosterveld’, ‘bare rock’ and ‘cultivated fynbos’

*** Other = ‘wetlands’, ‘waterbodies’, ‘dunes’ and ‘river course’ (Refer to Tables 3.1 and 3.3)

With over 80% loss of Agulhas Fynbos/ Thicket Mosaic and almost 90% loss of Overberg Coast Renosterveld, the magnitude of the land cover change is clearly alarming.

3.3.2 Effects of alien vegetation on runoff

The alien species found in the BRC include Port Jackson willow, Black wattle, Rock hakea, Acacia, eucalyptus, Rooikrans and pine (Miles 2003, pers com). A V3 report estimated that alien vegetation infestation reduces the MAR of the BRC by approximately 22% (Council for Scientific and Industrial Research (CSIR) 2004). Its worst effect is in summer, when it is estimated that up to 40% of the streamflow is evapotranspired by alien vegetation between 6a.m. and 6p.m. (Roberts 2003, pers com). Areas with a long history of alien vegetation invasion also experience chronic fire problems, soil erosion and a reduction in biodiversity (Chapman & Versfeld 1995). The ‘Work for Water’ project is controlling the spread of alien vegetation infestations in the basin.

3.3.3 Effects of afforestation on runoff

The main exotic forestry species in the BRC is Mediterranean pine, an important source of construction timber. Exotic forests affect the hydrological regime of a catchment by increasing rates of evapotranspiration and infiltration of precipitation, which results in greater subsurface flow (Wooldridge, Kalma & Kuczera 2001). The overall effect is a reduction in total runoff. Afforestation in the BRC is gradually being eradicated over the next twenty years (Roberts 2003, pers com).

3.3.4 Effects of urbanisation and groundwater abstractions on runoff

Urbanisation in the final analysis refers to the permanent change in land use from the original indigenous vegetation to the commercial and industrial land uses of the urban setting. It is the most forceful land use change affecting the flow regime in a catchment (Haan, Barfield & Hayes 1994; Stephenson 1993). Urban surfaces form an impervious area that prevents infiltration of precipitation into the soil and runoff dramatically increases (James 1994). Gutters and drains further increase the efficiency of the runoff network and groundwater recharge is radically decreased (Weyman 1975).

Researchers agree that a river system will be severely impacted if urban land cover increases beyond 10% of the basin area. However, it is in the abstraction of water for domestic and industrial use that the largest impact is generated. The BRC is located within a prime tourism region. There is a rapid population increase, which triples temporarily over the holiday season, and a large housing backlog (Von Düring 2002, pers com). However, most towns in the area rely on groundwater for their domestic water supply (Rosewarne 2000). The TMG aquifer is expected to be able to support the future increase in water demands.

It is well established that groundwater and surface water are interconnected components of the river system (Bailey 2003). Exploitation of groundwater reserves will most certainly affect runoff patterns and should be included in runoff modelling if possible. This was the original intention in this research. Data on the location and yield of boreholes in the BRC was collected from Rosewarne (2000), the CSIR (2004) and DWAF (2003). However, the groundwater-surface water relationship is not sufficiently understood, even by modelling experts (Parsons, Hughes & Bursey 2003). A groundwater specialist (Parsons 2003, pers com), consulted for assistance in this regard, advised against its inclusion because in the case of the BRC, groundwater abstractions are relatively small and would complicate modelling unduly without adding significantly to the results.

3.3.5 Effects of agricultural intensification and irrigation abstractions on runoff

Agriculture is the backbone of the economy in the region (CSIR 2004; Table 3.1) and annual cropland covers almost half the total BRC area (Stipinovich 2002). There are also small areas of perennial agriculture and cultivated fynbos. A change in land cover from natural vegetation to agricultural crops often results in a drop in interception rates, a rapid delivery of storm flow to streams and a reduction in infiltration capacity of the soils due to compaction.

The direct effect of agriculture on runoff takes place through irrigation abstraction. Water abstractions from the river system for irrigation are widespread and vary from diffuse water demands to selected concentrations of irrigated commercial crops (CSIR 2004). The extent of irrigation can be approximated by determining the capacity of major irrigation dams. University of Stellenbosch's WR90 network site provided a coverage which showed the locations of the nation's registered dams. Registered dams are the large, established dams that are officially recorded and monitored. The 14 registered dams that fell within the study area were selected, as shown in Figure 3.3.

Besides the larger registered dams, smaller irrigation dams are scattered profusely throughout the agricultural landscape in the BRC (Stipinovich 2002). Tarboton & Schulze (1992) discovered that several small dams will impact water resources even more than a single large reservoir that yields the same water supply. Over one hundred minor waterbodies were digitised in the land cover mapping. Waterbodies lying in the wetlands area and on the banks of the estuary were considered to be of natural origin. This concluded the digital mapping of the reference and current states of the BRC and formed the basis for the runoff modelling process. In Chapter 4, after compilation of the hydrological data for the BRC, the rainfall-runoff model is applied.

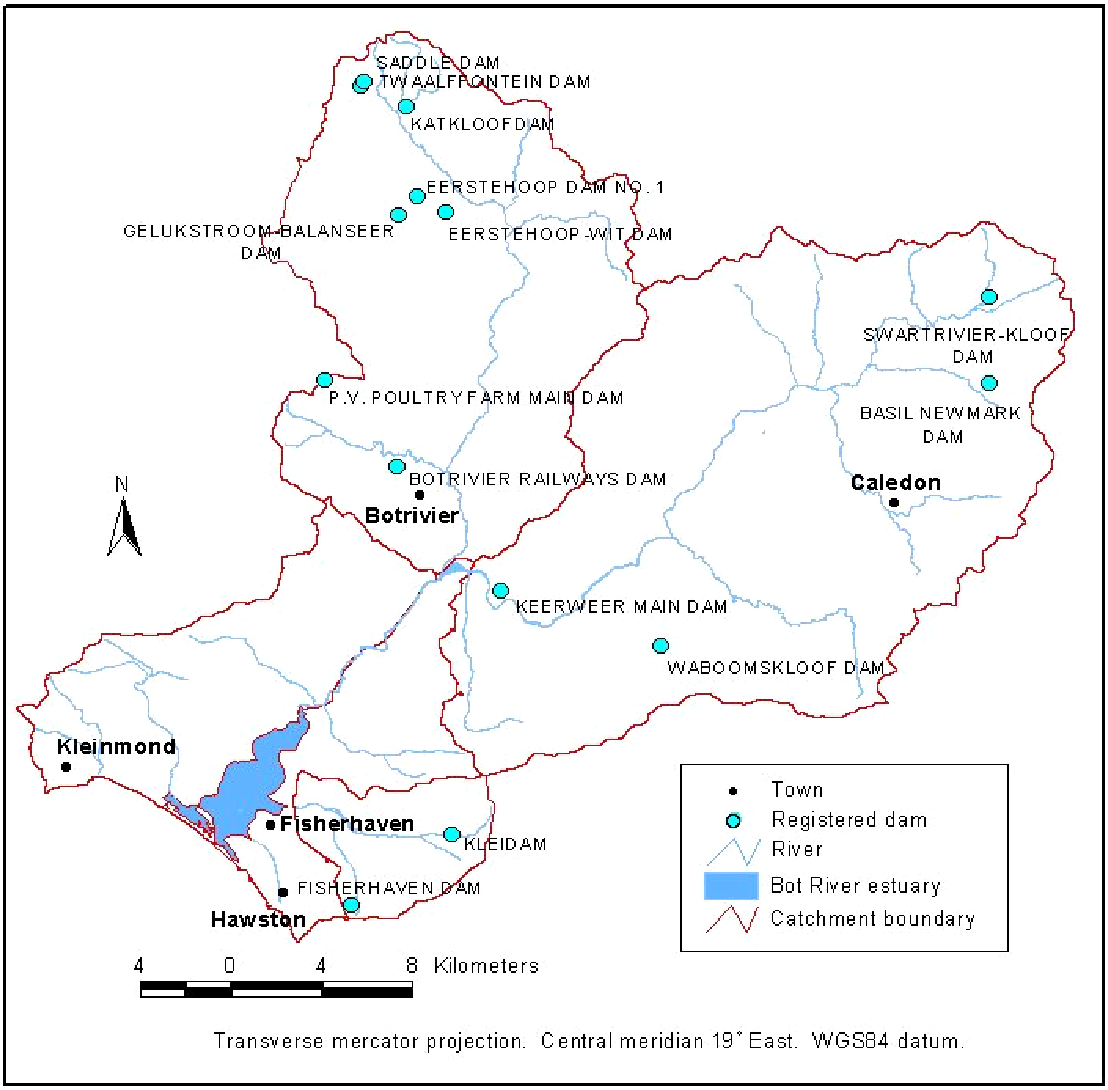


Figure 3.3: Location of registered dams in the Bot River Catchment

CHAPTER 4: SIMULATING RUNOFF IN THE BOT RIVER CATCHMENT

As the preparation for simulating the runoff in the BRC progressed, it became clear that the subcatchment delineations made thus far were insufficient for that purpose. Since MAP and MAE vary spatially across demarcated subcatchments, this chapter starts by re-demarcation and capturing of the relevant spatial values for practically applicable units. Then the SHELL model and its submodules are calibrated and run for the reference and current states of the BRC, in fulfilment of Objective 4.

4.1 DELIMITING REFINED SPATIAL UNITS FOR MODELLING

To assess the impacts of land cover change on hydrology, many researchers have lauded the practice of discretising the catchment under study into smaller ‘response units’ (Meier & Schulze 1995; Stuart & Stocks 1993; Spence, Dalton & Kite 1995). Response units subdivide a watershed along threshold changes in spatial characteristics. When a unit boundary is defined so that the important hydrological characteristics within each can be assumed to be of a relatively constant value, it is known as a Hydrologically Similar Unit (HSU). HSUs take the shape of polygons, partitioning the study area into irregularly shaped contiguous regions (Kemp 1993). They are hydrologically linked so that streamflow is routed from one unit to the next until an overall runoff total is calculated. At the same time, the hydrological response of each unit to localized land cover change can be identified (Meier & Schulze 1995).

The practice of discretisation began in response to the findings of several authors that a river basin is highly sensitive to the spatial variability of landscape characteristics and rainfall inputs (La Barbera, Lanza & Siccardi 1993). It is known as the semi-distributed approach. Topography, i.e. watershed boundaries, can be used to delineate a unit but that typically does not adequately represent the hydrological information content within (Grayson et al. 1993). The subcatchment boundaries were therefore further subdivided into HSUs on the basis of known spatial variation of MAE and MAP characteristics in the BRC.

4.1.1 Evaporation over the Bot River Catchment

The MAE in the catchment varies from a northern zone between 1400mm and 1500mm and a southern zone between 1300mm and 1400mm (Midgley, Pitman & Middleton 1994b), the boundary cutting across the BRSC and the SRSC, as shown in Figure 4.1.

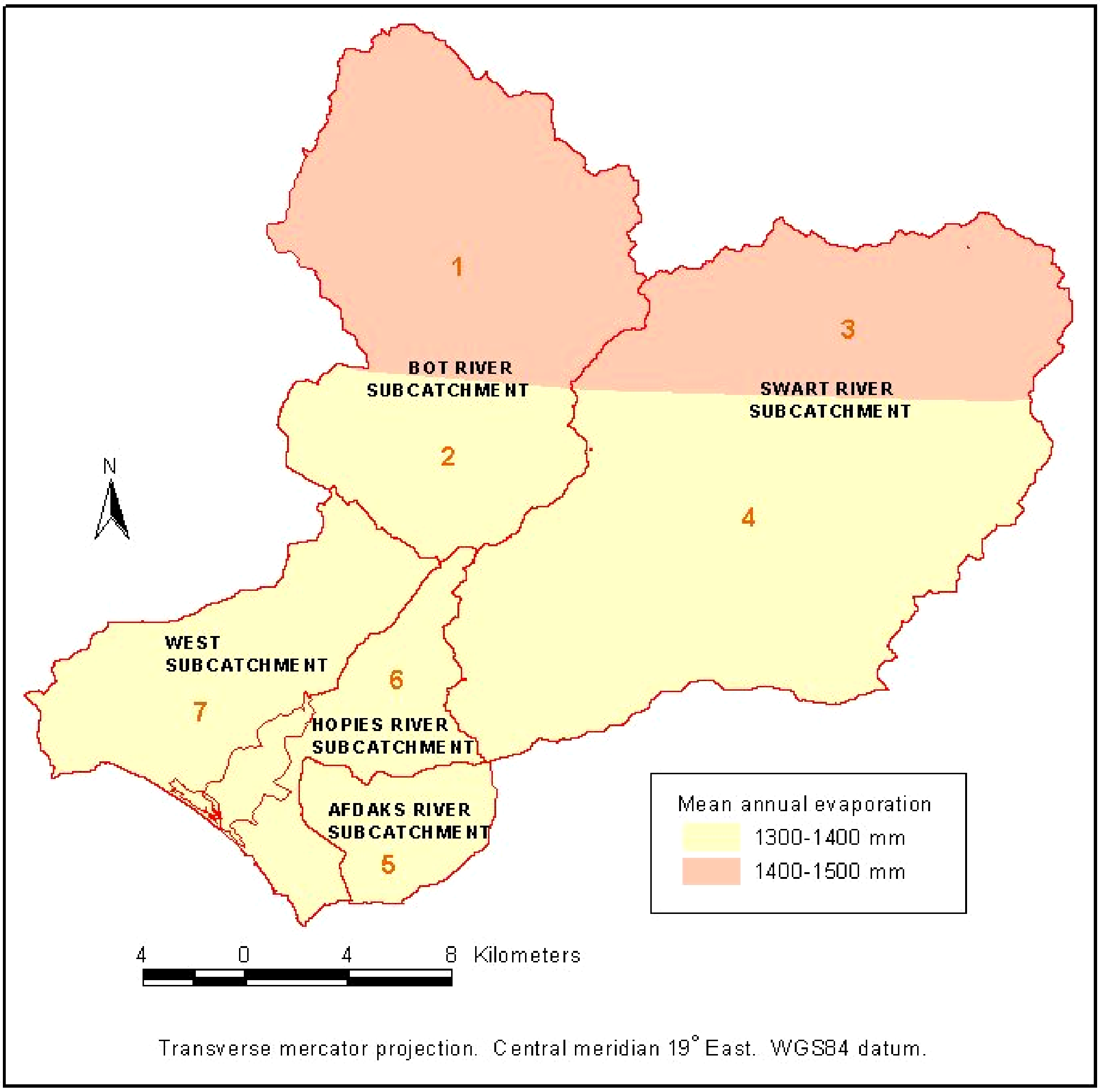


Figure 4.1: Mean annual evaporation in the Bot River Catchment

The University of Stellenbosch WR90 network site provided a coverage of the MAE zones. The BRSC and the SRSC polygons across which the evaporation threshold line fell were split, thus subdividing the five subcatchments into seven HSUs with homogeneous MAE characteristics. It allowed for input of the highest detail of MAE values possible in the modelling process.

Midgley, Pitman & Middleton (1994a) provided percentage of the MAE monthly values for evaporation zone 23C, in which the catchment lies. Table 4.1 indicates the monthly mean S-pan evaporation values for the different HSUs, which were calculated by multiplying the percentage

Table 4.1: Mean monthly S-pan evaporation (mm)

MONTH	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
HSU 1 and 3	127.0	177.3	208.5	213.6	180.2	157.5	98.0	56.6	43.5	48.1	56.6	83.1
HSU 2, 4, 5, 6 and 7	118.3	165.1	194.1	198.9	167.8	146.6	91.3	52.7	40.5	44.8	52.7	77.4

values by either 1350mm or 1450mm, depending on whether the HSU lay to the south of the boundary of the evaporation zone or to the north respectively.

4.1.2 Rainfall over the Bot River Catchment

Midgley, Pitman & Middleton (1994a) provided three monthly rainfall percentage of the MAP values specific to DWAF's delineation of subcatchments: G40E, G40F and G40G. This formed three HSUs in the BRC with cohesive MAP characteristics, which were subdivided as in Figure 4.2 into the seven HSUs (based on the spatial variation of the MAE), three sharing the same MAP value.

Multiplying the MAP values for G40E, G40F and G40G by the percentage MAP values of rainfall zones G4A and G4B (See Table 1.1) provided further hydrological information in the form of monthly average rainfall for the period 1920 to 1989. These monthly values were converted into a format acceptable to input into the SHELL model and saved as two "rainfiles": one for rainfall zone G4A and one for rainfall zone G4B. With the final hydrological response units prepared, the hydrological modelling process commenced.

4.2 CALIBRATION OF THE RAINFALL-RUNOFF MODEL

Calibration of the model to simulate virgin runoff involves using only the essential elements of a rainfall-runoff model: monthly precipitation and potential monthly evapotranspiration (Pitman 1976). Simulation of current runoff requires additional information input, such as quantitative data on water abstractions and land use (Hughes 1995). These steps are presented chronologically, followed by simulation of the runoff yields in both the reference and current states.

4.2.1 Model for the reference state runoff

Before the model was calibrated to simulate the reference catchment state, the sequence of model execution was defined. This emulated the stream order principle, so that downstream HSUs included the predetermined runoff contributions of the HSUs upstream (Tarboton & Schulze 1992). Figure 4.2 shows the model network, with a Pitman module used to simulate the runoff from each HSU. The module outputs were added as illustrated until a total MAR for the reference state of the BRC was calculated.

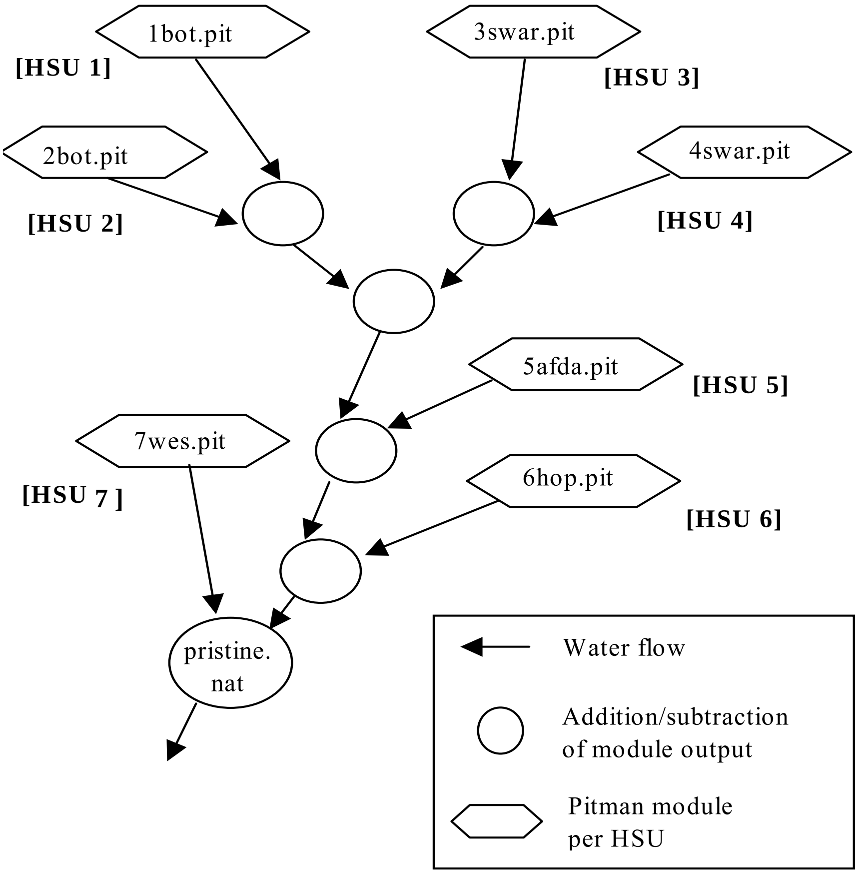


Figure 4.2: SHELL model network for reference state catchment runoff simulation

Numerous tests by Pitman (1977) revealed that the most important influence on accurate results in the simulation of long-term runoff is the volume of rainfall input, rather than the model structure. Use of the entire available rainfall-streamflow record for calibration as in this research assists in ensuring the most accurate, “hydrologically diverse” conditioning of the model parameters (Wooldridge, Kalma & Kuczera 2001:25).

Table 4.2 provides the core parameter values given by Midgley, Pitman & Middleton (1994a) to be used in the Pitman module. Beuster (2003, pers com) confirmed that the use of Midgley,

Table 4.2: Pitman Model parameter values for G40E, G40F and G40G

	POW	**SL**	**ST**	**FT**	**GW/FT**	**ZMIN**	**ZMAX**	**PI**	**TL**	**GL**	**R**
VALUE	2.0	0.0	250	4.0	0.00	20	350	1.50	0.25	0.0	0.00

Pitman & Middleton's (1994a) established parameter values for calibration of the model was adequate and meant that comparison with observed streamflow data was unnecessary. To investigate whether the model was being employed correctly, the reference state of the catchment was modelled first as this largely used the established parameters. Midgley, Pitman & Middleton (1994a) provided parameter sets for the two types of natural veld found in the BRC based on Acocks (1988). Given in Table 4.3, it is clear that the differences between the two groups are negligible. It is agreed that false sclerophyllous bush types are "mostly indistinguishable from the true fynbos" (Acocks 1988:122) and the difference of their effect on runoff is similarly unmarked (Von Hase 2003, pers com). Therefore, this research did not distinguish between the two types and the model's inbuilt Pitman parameters for natural vegetation were instead applied. With the reference state parameters input into the model, the runoff yields were successfully simulated using the SHELL model. Modelling of the current state of the catchment was a more complex process.

Table 4.3: Natural crop factors

MONTH	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Sclerophyllous Bush (fynbos)	0.60	0.60	0.60	0.60	0.55	0.55	0.55	0.45	0.40	0.20	0.35	0.50
False Sclerophyllous Bush (false fynbos)	0.55	0.55	0.55	0.55	0.55	0.50	0.50	0.40	0.35	0.20	0.35	0.50

Source: Midgley, Pitman & Middleton 1994a: 3.5

4.2.2 Model for the current state runoff

The model for the current runoff needs to be viewed from the overall framework before each of the submodules accounting for specific influential runoff aspects are calibrated separately.

4.2.2.1 The model framework

Additional parameter values and submodules were added to the core Pitman modules modelling each HSU to represent the current state of the BRC. These were the SHELL submodules called ALIENVEG, FORESTRY and RESSIM. These submodules are used to simulate the effect of alien vegetation infestation, afforestation, and water impoundment and abstraction respectively. Table 4.4 updates the areas of land cover types in the HSUs 1 and 2 (BRSC) and the HSUs 3 and

Table 4.4: Land cover areas for the hydrologically similar units 1, 2, 3 and 4

LAND COVER TYPE	**AREA PER HSU (km²) ***			
	BOT RIVER HSU 1	**BOT RIVER HSU 2**	**SWART RIVER HSU 3**	**SWART RIVER HSU 4**
Urban built up (town)	-	1.7	-	2.6
Other built up	0.1	0.2	-	1.3
Road surface (all classes)	0.9	1.2	1.1	2.6
Annual agriculture (cereals/grazing)	57.3	28.7	97.3	177.1
Perennial agriculture (orchard, vineyard)	0.1	4.4	-	-
Forestry plantation	9.0	3.9	-	7.2
Cultivated fynbos	-	-	-	-
Natural fynbos and renosterveld	109.6	37.2	29.8	63.4
Sparse alien vegetation	0.4	0.2	0.3	0.5
Dense alien vegetation	1.3	3.6	2.1	4.4
Waterbodies	1.0	0.4	0.4	0.8
Water surface: estuary	-	-	-	-
River course	0.4	0.2	0.6	0.8
Wetland	-	-	-	-
Bare rock (mountainous)	-	-	1.4	26.7
Other bare surface (beach, excavations)	0.6	0.3	-	1.5
Total area of HSU (km²)	180.7	82.0	133.0	288.9

* The values of HSUs 5, 6 and 7 are the values for ARSC, HRSC and WRSC as in Table 3.1.

4 (SRSC), as the values were necessary as parameter inputs in the submodules. The values of HSUs 5, 6 and 7 (ARSC, HRSC and WSC respectively) remain the same as in Table 3.1. Outlining the model network further was essential in organising the sequence in which the modules were to be solved as the process became more complicated. Figure 4.3 illustrates how the SHELL model network was built up gradually from the basic Pitman module structure shown in Figure 4.2.

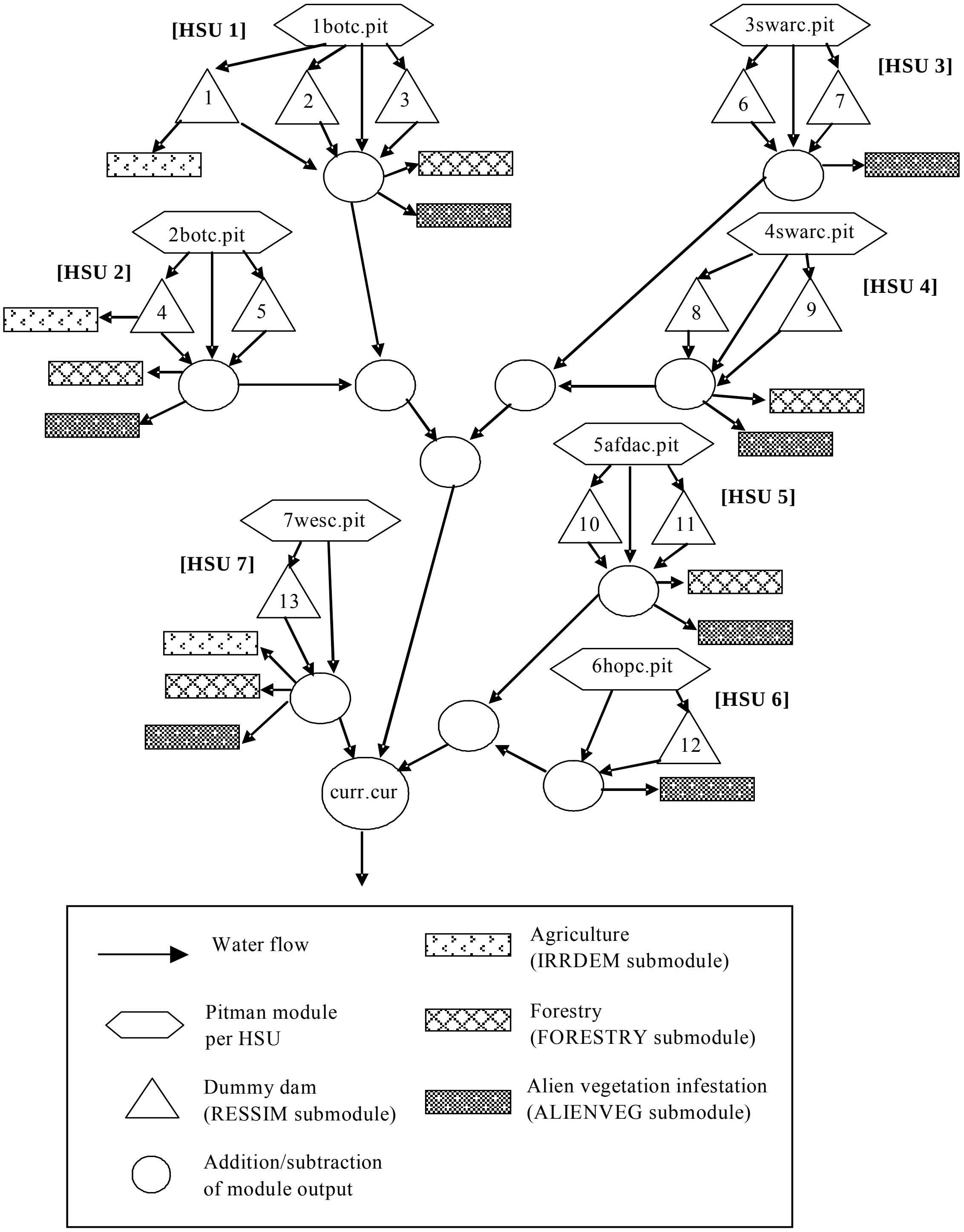


Figure 4.3: SHELL model network for current state catchment runoff simulation

Irrigation and dam abstractions were added directly to the Pitman modules in the network using the IRRDEM and RESSIM submodules respectively. The ALIENVEG and FORESTRY submodules were modelled separately from the network and treated as separate response units, as advised by Kamish (2004, pers com). Only their output files were brought into the network and subtracted from the appropriate HSU output. Each group of IRRDEM, FORESTRY and ALIENVEG submodules combined with a Pitman module, represented one of the seven HSUs and produced a separate output file. These were summed consecutively by the SHELL model program to produce a total output for the BRC.

The naming system of 1botc.pit and so on, was devised by the author and proved very efficient. The HSU, the subcatchment in which it lies, the type of submodule and the fact that it is the current state of the catchment being modelled, denoted by the ‘c’ at the end, were immediately evident. Other naming conventions found in the literature were not readily comprehensible.

4.2.2.2 Modelling dam impoundment volume and water abstraction with the RESSIM submodule

The RESSIM submodule allowed for 65 possible coefficients to represent various hydrodynamic effects. The parameters that were calibrated are described here. The values of the coefficients a and b (See Appendix B for the formulae) were suggested as being 0.4 and 0.5 respectively by Kamish (2004, pers com). Calculated for his research on catchments neighbouring the Bot River’s, they could be assumed to apply to the BRC due to similar topographical relief. Due to the commencement of the modelling in October, the end of the winter rainfall season, the initial storage state of the dams was given a value of 100%. The assumption was that the dams were all full to capacity at that time. The dead storage for registered dams was given a value of 0.1. The dead storage value for dummy dams was given as zero as they are typically pumped dry if need be.

Although it has been noted that farm dams should definitely be modelled, “information relating to the transfer and storage of water…is either scarce or locally excessive and complex in the Western Cape” (Midgley, Pitman & Middleton 1994a: 1.14). According to Kamish (2004, pers com), individual modelling of each dam goes well beyond the requirements of this research. To simplify the process, dummy dams were used to represent the water impoundments found in each HSU. Table 4.5 shows the groupings of the registered dams (with known volumes) to be

Table 4.5: Dummy dams representing registered dams

DUMMY DAM	REGISTERED DAM	COMBINED CAPACITIES (FSC 10^6m^3)
1	Saddle dam, Twaalffontein dam, Katkloof dam	1.2
2	Eerstehoop dam No. 1, Eerstehoop-Wit dam, Gelukstroom-Balanseer dam	0.7
4	PV Poultry Farm Main dam, Botrivier Railways dam	0.7
6	Swartrivier-Kloof dam, Basil Newmark dam	0.7
8	Keerweer Main dam, Waboomskloof dam	0.6
10	Kleidam, Fisherhaven dam	0.5

represented in each HSU. The dummy dam number refers to the dummy dam's position in the modelling sequence given in Figure 4.3.

To the contrary, the capacities for individual minor water impoundments were not available from Midgley, Pitman & Middleton (1994a). The solution was to apply Pythagoras' Theorem to calculate the approximate capacity of each dummy dam in cubic metres, as demonstrated in Figure 4.4. To derive the surface area of all unregistered dams, the current land cover map was analysed in ArcView so that this data could be roughly extracted, following the methodology used by Jacobs & Bruwer (2002). By deriving contours from the DEM grid and overlaying these over the current land cover map, the average slope under the minor impoundments was found to be five degrees. The angle of the dam wall to the water surface was assumed to be 90°. Applying the standard formula, tan(θ) = length of opposite side / length of adjacent side, tan(5°) was taken to calculate the height of the dam wall in metres.

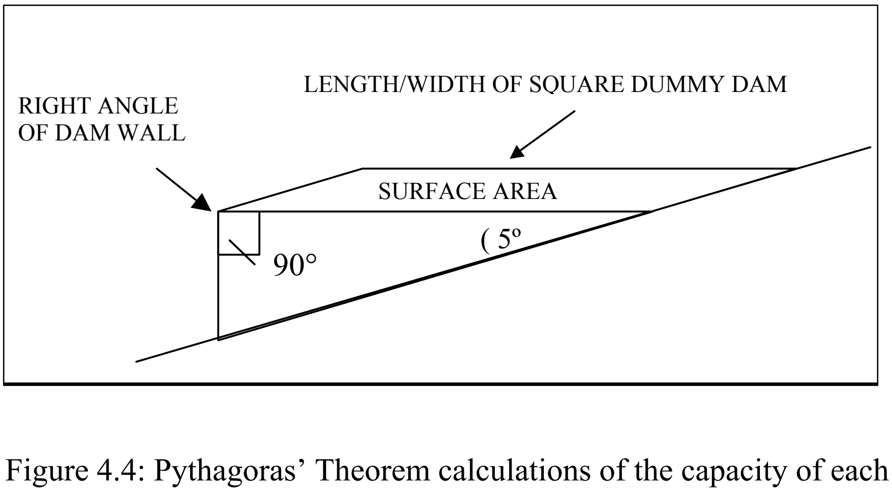


Figure 4.4: Pythagoras' Theorem calculations of the capacity of each dummy dam

Altogether, the minor waterbodies covered 4.8km² of the BRC area. This was more than a third of the size of the BRE, illustrating how small waterbodies can be incorrectly construed as insignificant.

Estimation of the minor water impoundment capacities in this way was approximate but served to incorporate them into the modelling. The values calculated for each of the HSUs lumped minor water impoundments are presented in Table 4.6 and show the preponderance of dams in HSU 1 and HSU 4.

Table 4.6: Dummy dams representing minor water impoundments

HSU	DUMMY DAM	SURFACE AREA OF DUMMY DAM (km²)	LENGTH OF DUMMY DAM (m)	CAPACITY OF DUMMY DAM (10^6m^3)
1	3	0.8	911.0	3.3
2	5	0.4	616.4	1.0
3	7	0.4	600.0	0.9
4	9	0.7	854.4	2.7
5	11	0.2	447.2	0.4
6	12	0.1	346.4	0.2
7	13	0.5	700.0	1.5

The RESSIM module required an input file of the monthly dam abstractions for the modelling of each dummy dam. Emulating research in the neighbouring Klein River catchment, a “ball park figure” (Jacobs & Bruwer 2002:31) was used to represent the abstraction for each month and each subcatchment due to storage in and use from dams. According to Van Niekerk (2000, pers com), this was estimated at 10% of the MAR in the BRC. Midgley, Pitman & Middleton (1994a) provided MAR values for the subcatchments G40E, G40F and G40G as $37.5x10^6$ m^3, $21.7x10^6$ m^3 and $29.9x10^6$ m^3 respectively. These values were divided by the number of dummy dams being modelled so that each subcatchment abstracted 10% of its MAR per month. Instead of dividing these figures by 12 to get 12 monthly abstraction values, the division was by eight as local irrigation only occurs between September and April in the dry summer months (Roberts 2003, pers com). Winter months were given a value of zero. As these dams are primarily for agricultural irrigation purposes, their possible abstraction for domestic purposes was ignored.

To calculate the required monthly values for reservoir evaporation parameters, which varied depending upon which HSU the dummy dam was located in, the mean monthly S-pan evaporation values (see Table 4.1) were multiplied by the pan factors for open water evaporation available from Midgley, Pitman & Middleton (1994a). The pan factors are given in Table 4.7 and the calculated monthly reservoir evaporation in Table 4.8.

Table 4.7: Pan factors for open water evaporation

MONTH	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Lake evaporation	0.81	0.82	0.83	0.84	0.88	0.88	0.88	0.87	0.85	0.83	0.81	0.81

Source: Midgley, Pitman & Middleton 1994a: 3.3.1

Table 4.8: Monthly reservoir evaporation (mm)

MONTH	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
HSUs 1 and 3	103	145	174	180	165	139	86	50	37	40	46	67
HSUs 2, 4, 5, 6 and 7	96	135	161	167	148	129	80	46	35	37	43	62

The MULTIP step was used to portion out the proportion of runoff that was estimated to pass through each dummy dam being modelled. To estimate the proportion of runoff, dam catchment boundaries were accurately amalgamated from detailed delineation of catchments generated from the DEM, for each of the groupings of registered dams, as shown in Figure 4.5. It shows that most of the high rainfall mountain catchments impounding most runoff, are accounted for.

The approximate proportion of runoff flowing through each dummy dam was given by the ratio of each dummy dam catchment area representing registered dams to the total area of the HSU, as suggested by Kamish (2004, pers com). A quarter of the remaining surface area in each HSU was apportioned to the dummy dam representing the minor water impoundments. The fact that the Basil Newmark dam boundary overlapped into HSU 4 could be ignored. The technique used to include dams in the modelling process was approximate, as the true proportion of runoff abstracted by each dummy dam was unknown.

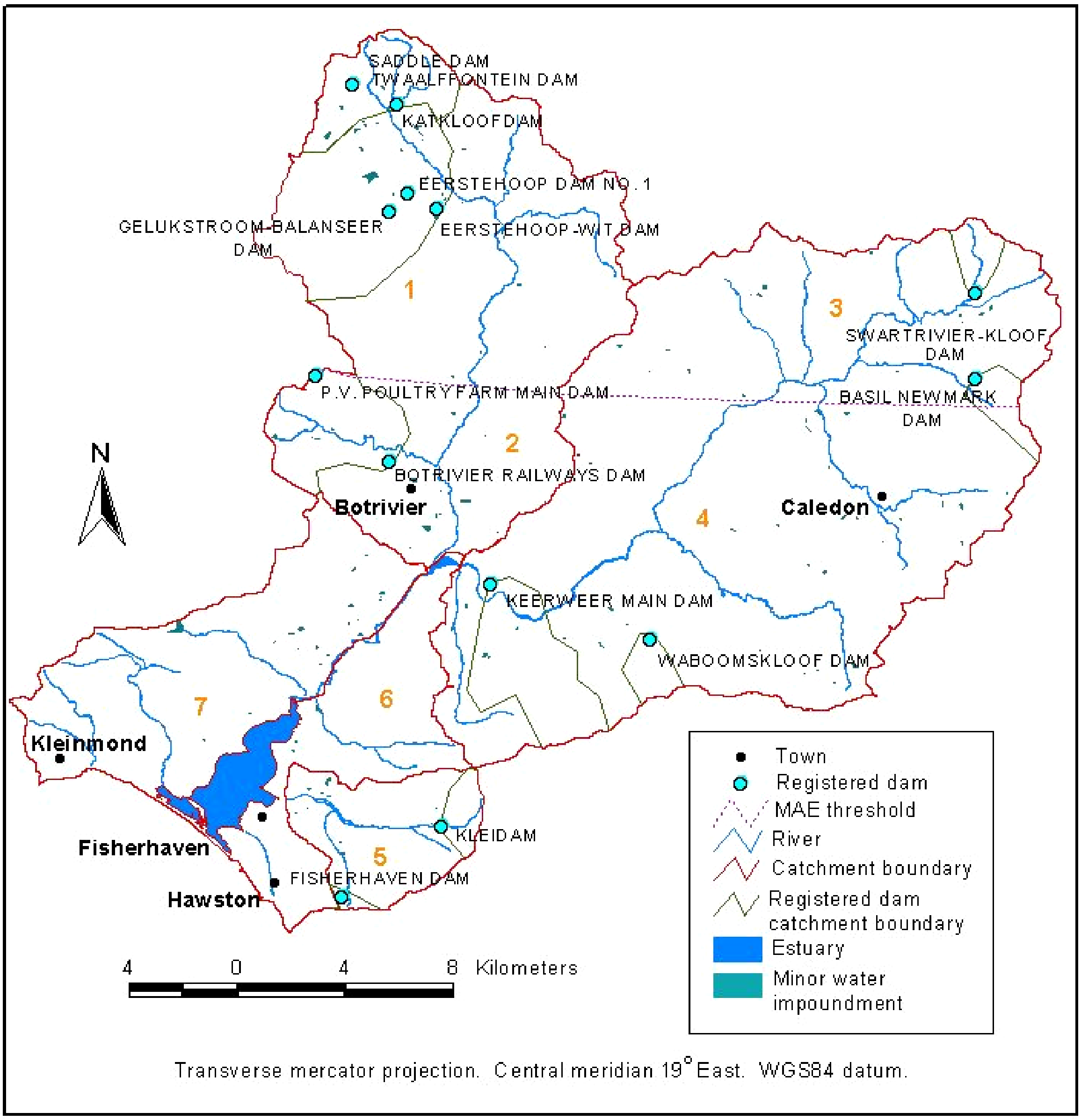


Figure 4.5: Estimation of dam catchment boundaries based on river system

Ensuring that 100% of the available runoff passed through the network, and assigning a proportionate quantity to each dummy dam was considered sufficient. The results of the factor calculations are shown in Table 4.9. The remainder of the runoff produced by each Pitman module was assumed to flow uninterrupted in the river system.

Table 4.9: Proportions of runoff directed through each dam grouping

HSU	DUMMY DAM	DAM CATCHMENT BOUNDARY (km^2)	RUNOFF DIRECTED THROUGH (%)	MULTIP FACTOR
1	1	19.9	11	0.11
	2	49.5	28	0.28
	3		15	0.15
	Not passing through dam		46	0.46
2	4	23.0	28	0.28
	5		18	0.18
	Not passing through dam		54	0.54
3	6	11.0	8	0.08
	7		23	0.23
	Not passing through dam		69	0.69
4	8	31.3	11	0.11
	9		22	0.22
	Not passing through dam		67	0.67
5	10	6.0	16	0.16
	11		21	0.21
	Not passing through dam		63	0.63
6	12		25	0.25
	Not passing through dam		75	0.75
7	13		25	0.25
	Not passing through dam		75	0.75

Further standard RESSIM parameters were left at the default value as directed by Kamish (2004, pers com). Input of a value in place of the default values would typically capture added land cover change and water abstraction detail.

4.2.2.3 Modelling irrigation with the IRRDEM submodule

In the original digitising of the current land cover, individual crop types could not be distinguished from the available imagery. Crop factors for irrigated crops are provided in Midgley, Pitman & Middleton (1994a) but for more specific crop types than the author's 'annual' or 'perennial' classification. Van der Merwe (2004, pers com) advised the use of the dominant crop cover factor in each case, wheat and deciduous fruit trees respectively. The factors are given in Table 4.10, should they be implemented.

Table 4.10: Agricultural crop factors

MONTH	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Deciduous trees	0.24	0.27	0.36	0.45	0.57	0.48	0.20	0.20	0.20	0.20	0.20	0.20
Wheat	0.17	-	-	-	-	-	-	0.16	0.34	0.79	1.00	0.87

Source: Midgley, Pitman & Middleton 1994a: 3.4

However, despite the available factors for wheat, the IRRDEM submodule does not allow for modelling of such dryland crops, unless irrigated. Beuster (2003, pers com) suggested that although the water use of wheat will differ from that of natural vegetation (See Tables 4.2 and 4.10), this difference would be negligible in comparison to the other catchment water uses. Annual agriculture, the dominant land cover, could therefore be ignored.

The IRRDEM submodule required monthly values of the effective rainfall (ER) and A-pan evaporation values for each HSU modelled. ER can be described as “that which is received during the growing period of a crop and is available to meet consumptive water requirements” (Dastane 1978). The irrigated crops that occupy the largest proportion of land, in this case, deciduous trees, are used as a reference to express the ER. ER values were computed using the U.S. Bureau of Reclamation Method as it is recommended for arid and semi-arid regions. It uses the mean seasonal precipitation of the five driest consecutive years, which were 1968 to 1972 in the BRC. In this method, “percentage values are given to increments of monthly rainfall ranging from greater than 90% for the first 25mm…or fraction thereof, to 0% for precipitation increments above some 150mm” (Dastane 1978) as shown in Table 4.11.

Table 4.11: US Bureau of Reclamation Method of estimating the effective rainfall

PRECIPITATION INCREMENT (mm)	% EFFECTIVE	EFFECTIVE PRECIPITATION ACCUMULATED (mm)
0.0 - 25.4	90 - 100	22.9 - 25.4
25.4 - 50.8	85 - 95	44.4 - 49.5
50.8 - 76.2	75 - 90	63.5 - 72.4
76.2 - 101.6	50 - 80	76.2 - 92.7
101.6 - 127.0	30 - 60	83.8 - 107.9
127.0 - 152.4	10 - 40	86.4 - 118.1
Over 152.4	0 - 10	86.4 - 120.6

Adapted from: Dastane 1978

The decision to use the upper or lower value in the percent and ER range was based on whether the precipitation increment was towards the lower or higher value itself. This method was attractive as it was the least complicated of many available methodologies for ER estimation. The ER values chosen fall within the correct range given by the U.S. Bureau of Reclamation method. The conversion calculations are shown in the appendix in Tables A.1, A.2, and A.3. The results are given in Table 4.12.

Table 4.12: Effective rainfall in the subcatchments

	BRSC (HSU 1 and 2)		**SRSC (HSU 3 and 4)**		**ARSC, HRSC and WSC (HSU 5, 6 and 7)**	
MONTH	**ER (mm)**	**%**	**ER (mm)**	**%**	**ER (mm)**	**%**
Oct	63.5	75	44.4	85	63.5	75
Nov	22.9	90	22.9	90	22.9	90
Dec	22.9	90	22.9	90	22.9	90
Jan	44.4	85	22.9	90	44.4	85
Feb	44.4	85	44.4	85	44.4	85
Mar	22.9	90	22.9	90	22.9	90
Apr	44.4	85	44.4	85	44.4	85
May	63.5	75	44.4	85	63.5	75
Jun	72.4	90	63.5	75	72.4	90
Jul	92.7	80	63.5	75	92.7	80
Aug	76.2	50	72.4	90	76.2	50
Sep	63.5	75	44.4	85	63.5	75

The conversion of the available S-pan evaporation data to A-pan evaporation data used the following equation (Midgley, Pitman & Middleton 1994a:3.2):

$$(\text{A-pan}) = 26.3622 + 1.0786 \times (\text{S-pan})$$

The results, given in Tables 4.13, emphasise the significant moisture imbalance in the catchment and the seasonal nature of the imbalance.

Table 4.13: S-pan to A-pan conversions for the hydrologically similar units 1 to 7

MONTH	HSU 1, HSU 3		HSUs 2, 4 - 7	
	S-PAN EVAPORATION (mm)	A-PAN EVAPORATION * (mm)	S-PAN EVAPORATION (mm)	A-PAN EVAPORATION * (mm)
Oct	127	163	118	154
Nov	177	217	165	204
Dec	209	252	194	236
Jan	214	257	199	241
Feb	180	221	168	208
Mar	158	197	147	185
Apr	98	132	91	125
May	57	88	53	84
Jun	44	74	41	71
Jul	48	78	45	75
Aug	57	88	53	84
Sep	83	116	77	109

* Conversion factor: x (1.0786 + 26.3622)

Kamish (2004, pers com) provided the necessary global parameters of irrigation efficiencies from his research on neighbouring Breede River catchment as shown in Table 4.14. It shows the extensive loss of water due to the local irrigation process and various practices.

Table 4.14: Irrigation efficiency values

TYPE OF IRRIGATION	EFFICIENCY (%)
Flood	40
Spray	60
Micro	85
Drip	90

Based on observation, it was assumed that most perennial agriculture in the BRC would use spray irrigation. Because irrigation abstraction for perennial crops is relatively small, the selected application mode has insignificant influence on the model results. The RESSIM and IRRDEM submodule results reflected the water demands of the land cover categories and were subtracted consecutively from the Pitman output for each HSU.

The coefficient required in the Pitman module, which is related to irrigation, is the Irrigation Return Flow (PIWTR). This is the filtering of the water used in irrigating farmland back into the catchment runoff. It was given a value of zero to simplify the modelling, because this data was not available, and because the effect was judged to be negligible.

4.2.2.4 Modelling alien vegetation infestation using the ALIENVEG submodule

The ALIENVEG submodule does not cater for distinguishing between sparse and dense areas of vegetation, which were therefore combined and modelled as one representative area. The impact of alien vegetation on runoff quantity is so harsh that it was considered appropriate to include both sparsely and densely vegetated areas as similar in the modelling. The alien vegetation in the BRC is riparian and comprised chiefly of tall shrubs (Stipinovich 2002), varying from young to mature plants (Miles 2003, pers com). These factors were input into the ALIENVEG submodule. In the absence of more specific values, other parameters were left at the general default values, as recommended by Kamish (2004, pers com).

4.2.2.5 Modelling afforestation with the FORESTRY submodule

FF is an afforestation parameter in the Pitman module. The value for FF is assumed to be the ratio soil moisture of forest cover: soil moisture of natural vegetation. FF was given a value of one, tying the MAR reduction closely with van der Zel's curve for a 15 year rotation (Pitman, Potgieter, Middleton & Midgley 1981). The trees were assumed to have an average age of 15 years, following the work of Tarboton & Schulze (1992). As the dominant plantation species in the catchment is pine, this was chosen as the representative tree species. All land cover area values used were obtained directly from the 2002 land cover map (Stipinovich 2002). These differed from Midgley, Pitman & Middleton (1994a) significantly in the case of plantations in the lower subcatchments and are more accurate. Table 4.15 presents the parameter values required for the IRRDEM, ALIENVEG and FORESTRY submodules, which were derived from the maps produced in ArcView.

Table 4.15: SHELL model parameter values for the current catchment conditions

HSU	**PITMAN MODULE**		**SUBMODULE**		
	Area* (km²)	**Impervious area: total HSU area (ratio)**	**IRRDEM Deciduous trees (km²)**	**FORESTRY Area (km²)**	**ALIENVEG Alien vegetation (km²)**
1	170.1	0.005	0.1	9.0	1.7
2	74.3	0.041	4.4	3.9	3.8
3	130.6	0.019	-	-	2.4
4	276.5	0.120	-	7.2	5.0
5	31.7	0.017	-	2.8	3.8
6	51.3	0.229	-	-	11.4
7	92.6	0.106	17.4	1.7	13.6

* Minus the areas of alien vegetation, deciduous crops and forestry, which were modelled separately.

The final run of the SHELL model included all of the submodules, grouped to model each of the HSUs, in the specified sequence. The reference and current catchment state runoff yields were successfully simulated and the results tabulated as a comparison with the findings of DWAF (Van Niekerk 2000) to enable discussion of the findings.

4.3 ESTIMATED RUNOFF IN THE CATCHMENT'S REFERENCE STATE

Using the SHELL model, the virgin MAR for the BRC was calculated as $93.3 \times 10^6 m^3$. Although the cumulative model total registered $100.4 \times 10^6 m^3$ and Pitman & Kakebeeke (1997) suggest this may be the more accurate result, it seemed more appropriate to use the summed total of the individual HSUs to allow comparison with the similar figures reported by DWAF (Van Niekerk 2000) and Midgley, Pitman & Middleton (1994a). A simulated output of $93.3 \times 10^6 m^3$ compared favourably with rival calculations of $116 \times 10^6 m^3$ by Noble & Hemens (in Cilliers & De Jager 1997), $86 \times 10^6 m^3$ by V3 Consulting Engineers and $88.6 \times 10^6 m^3$ by DWAF (Van Niekerk 2000). The rival estimates average $96.8 \times 10^6 m^3$ – less than $4 \times 10^6 m^3$ off from this study's result. The favourable comparison of the SHELL model virgin MAR simulation results with the others can be attributed to the more accurate calibration of the basic Pitman module in this study. The virgin MAR of each subcatchment as simulated by the SHELL model and by DWAF is given in Table 4.16.

Table 4.16: Simulated virgin MAR of subcatchments compared

SUBCATCHMENT	**SHELL**		**DWAF ***	
	VIRGIN MAR (10^6m^3)	**SIZE (km^2)**	**VIRGIN MAR (10^6m^3)**	**SIZE (km^2)**
Bot River	35.3	262.7	37.2	252
Swart River	32.0	421.9	21.7	360
Afdaks River	4.1	38.5	29.7	-
Hopies River	8.9	62.7		
West	13.0	107.9		
Estuary	Not modelled	13.6	Not modelled	-
TOTAL	93.3	907.3	88.6	-

* Subcatchments defined slightly differently by DWAF (Van Niekerk 2000)

The DWAF (Van Niekerk 2000) subcatchment named “Afdaks and Trib” presumably includes the HRSC and WSC, as their simulated runoff total matches the comparable SHELL model’s combined output for these subcatchments. The results for the BRSC by SHELL agreed closely with those estimated by DWAF where the difference is attributable to different area demarcations (DWAF did not include runoff downstream of Roode Heuvel). The real discrepancy between the simulated discharge results is in the values for the SRSC and this is attributed to DWAF’s modelling methodology being a less detailed portrayal of that subcatchment.

4.4 ESTIMATED RUNOFF IN THE CATCHMENT’S CURRENT STATE

Overall, the SHELL model results were credible. As Table 4.17 shows, the SHELL model simulation output for the current state of the BRC was $69.8x10^6m^3$, compared to $67.2x10^6m^3$ by DWAF (Van Niekerk 2000). This strong agreement suggested that the increased level of detail modelled with the SHELL model had not produced significant further information. On the contrary, the MAR total for the BRC provided by Midgley, Pitman & Middleton (1994a) was relatively different at $89.1x10^6$ m^3. This disagreement was unexpected as Midgley, Pitman & Middleton’s (1994a) established parameters were used to calibrate very important components of the Pitman module in the SHELL model. The difference was attributed to the many other less significant parameters, for which the input was based on the accurate spatial values derived in ArcView.

Table 4.17: Simulated current MAR of subcatchments compared

SUBCATCHMENT	SHELL			DWAF *		MIDGLEY, PITMAN & MIDDLETON	
	CURRENT MAR (10^6m^3)		SIZE (km^2)	CURRENT MAR (10^6m^3)	SIZE (km^2)	CURRENT MAR (10^6m^3)	SIZE (km^2)
Bot River	35.6		262.7	24.8	252.0	37.5	277.6
Swart River	15.6		421.9	18.7	360.0	21.7	422.5
Afdaks River	3.1	18.6	38.5	23.7	-	29.9	208.5
Hopies River	6.4		62.7				
West	9.1		107.9				
Estuary	Not modelled		13.6	Not modelled	-	Not modelled	-
TOTAL	69.8		907.3	67.2	-	89.1	-

* Subcatchments defined slightly differently by DWAF (Van Niekerk 2000)

4.5 DISCUSSION OF REFERENCE AND CURRENT RUNOFF RESULTS

Predicting the hydrological effects of land cover change using rainfall-runoff models is still "a difficult if not impossible objective" (Wooldridge, Kalma & Kuczera 2001:31) due to the difficulty in determining the correct parameter values to define catchment conditions. Qualitative reasoning must thus support the interpretation of simulation results. The changes in land cover (both areal and proportional) that have occurred in the BRC since its reference state were correlated with the model outputs in Table 4.18 for possible explanation of runoff impacts. It enabled the isolation of those with most effect on the local ecosystem, in fulfilment of Objective 5. Summing the dummy dam capacities indicates the proliferation of retention dams in each subcatchment. SHELL and DWAF results agree that runoff in the BRC has been reduced by one quarter, but there are significant differences among the results for the various subcatchments. While DWAF estimates a one-third reduction in the BRSC, the SHELL results show no change. The latter, however, estimates a large reduction in the SRSC, five times above that of DWAF. Results for the other catchments are similar.

Turning to land cover change for explanation, the switch to annual crops offer most potential. It covers a third of both the BRSC and the HRSC and three fifths of the SRSC, but unfortunately its effects could not be accounted for in the modelling. Since the DWAF figures for the BRSC are based on actual weir gauge measurement, it has to be assumed that the effects of all five land cover category changes as well as the irrigation dam storage are insufficiently accounted for in

Table 4.18: Comparison of change in runoff and land cover in subcatchments

SUB CATCHMENT	Runoff change: 10^6m^3 (%)		Land cover change (additional submodules): km^2 (%)				Dummy dam volume: 10^6m^3
	SHELL Model	**DWAF**	Annual crops	Perennial crops	Forestry	Alien vegetation	
Bot River	0.3 (0.8)	-12.4 (-33.3)	86.1 (32.8)	4.5 (1.7)	12.9 (4.9)	5.4 (2.1)	6.9
Swart River	-16.4 (-46.5)	-3.0 (-8.1)	274.5 (65.1)	0 (0)	7.2 (1.7)	7.3 (1.7)	5.0
Afdaks River	-1 (-2.8)	-6.0 (-16.1)	5.9 (15.3)	0 (0)	2.8 (7.3)	3.8 (9.9)	0.9
Hopies River	-2.5 (-7.1)		20.7 (33.0)	0 (0)	0 (0)	11.4 (18.2)	0.2
West	-3.9 (-11.0)		12.1 (11.2)	17.4 (16.1)	1.7 (1.6)	13.6 (12.6)	1.5
BRC	-23.5 (-25.2)	-21.4 (-24.2)	399.3 (44.0)	21.9 (2.4)	24.6 (2.7)	41.5 (4.6)	14.4

SHELL. On the contrary, the vast changes having taken place towards annual crop production in the SRSC seem to be well accounted for in SHELL – in fact to such an extent that the combined reductions in the BRSC and SRSC agree largely between DWAF and SHELL results. Similar agreement is evident for the other smaller subcatchments – hence the overall agreement in total runoff reduction.

Urbanisation is still relatively minimal in the BRC and although the percentage impervious surface was modelled, in each subcatchment this value was sufficiently insignificant to be disregarded. Some of the modelling results bear scrutiny: The total estimated annual water use in the BRC by forestry and alien vegetation was 1.8×10^6m^3 and 0.4×10^6m^3 respectively. Perennial agriculture was estimated to use five times more: 12×10^6m^3 per year. As the WSC has the most perennial agriculture in proportion to its total area, its MAR could be expected to have decreased most – a fact borne out by the modelled results. The WSC indeed experienced a considerable decrease in MAR of 30%, second only to the estimated reduction for the SRSC. The WSC has also been heavily infested by alien vegetation, which would contribute to that decrease. The harmful effects of alien vegetation infestation were thus highlighted. The ARSC has the highest proportion of forestry to its total land area and approximately one tenth is infested with alien vegetation. Much of the remaining surface is still natural vegetation, however, which appears to mitigate its impact on water use compared to the HRSC and the WSC.

With four out of five subcatchments seemingly experiencing a decrease in MAR of over 25%, it is clear that the extent and type of land cover change is a cause for alarm. With the burgeoning local population and the catchment's primary land use being agriculture, the risk of future full reliance on the "vast" groundwater source, the TMG aquifer, is substantial. The aquifer appears to have reached some of its limits already: local springs have been known to dry up due to over-pumping of nearby boreholes. If overuse allowed seawater to intrude, the aquifer water quality would be irreversibly degraded (Rosewarne 2000).

Although the SHELL results correlated strongly with the findings of DWAF (Van Niekerk 2000), they were markedly lower than the earlier results calculated by Midgley, Pitman & Middleton's (1994a). Possibly land cover change over the interim decade explains some of this difference. The "interaction and interdependency" (National Department of Agriculture 2002) of the land and water catchment components have been demonstrated in the strong link between change from indigenous land cover and runoff reduction. Above all, the crucial research question was addressed, proving that land cover change in the catchment is instrumental in affecting the breaching pattern of the BRE through its 25% reduction of runoff.

CHAPTER 5:CONCLUSION

Rainfall-runoff models simplify the complex and uncertain hydrological and environmental processes occurring in a catchment to allow for their simulation (Loucks 1993). The simplifications are based on assumptions as well as observations and measurements. As a result, the simulation can only be used as an indication of the "likely range of possible consequences" of the activities taking place there (Loucks 1993:399). However, this allows us to get a glimpse of the future and prepare for it by managing our water resources accordingly. The research results are now summarised and evaluated, before recommendations for management and further research are offered.

5.1 SUMMARY OF RESEARCH RESULTS

The salient research results relate to the main issues addressed in Chapter 1-3, in line with the research objectives. In Chapter 2, the selection of a fairly user-friendly runoff model was justified from a literature overview. The application of a Pitman-based model was decided upon, because it proved to be relatively simple to operate, default values for many parameters were available for South African catchments, local expertise could be consulted and the executable computer files for the various submodules were obtainable

In Chapter 3, an analysis of both current and reference state land cover statistics were performed. The results showed the extensive (60% replacement) change that has occurred in the catchment. Much of the earlier indigenous vegetation cover has been lost – especially of the lower-lying Overberg Coast Renosterveld (88.5%) and Kogelberg Fynbos (25.4%) communities. These were mostly replaced by annual crop production (mostly wheat, covering 44% of the basin), but lately deciduous fruit (21.9km^2) and other irrigated perennial crops have been expanding – especially towards the northwest of the basin. Irrigation dams estimated to retain 14.4x10^{6}m^3 of water proliferated throughout the basin, but especially in the BRSC and SRSC. Forestry plantations are expanding (24.6km^2) and, perhaps more alarming, alien vegetation (41.5km^2 infesting 4.6% of the basin) has become a problem throughout the basin, but especially around the estuary and along the river courses.

In Chapter 4, the selected Pitman-based SHELL model was calibrated by stipulating the various parameter values obtained from a range of reputable sources. The results of the model runs for both the reference and current sates of the catchment produced some expected and some unexpected results. The results estimated a 25% decline in runoff from the reference state. This result concurred with that of DWAF and confirmed that the change in the hydrodynamic regime of the Bot Estuary can to a large extent be attributed to the reduction of runoff from the catchment. Unexpectedly, however, the modelled figures for the BRSC did not concur with the measured results from DWAF. This discrepancy was compensated for in the figures for the other subcatchments and could possibly be attributed to the fact that the substantial annual cropland coverage could not be modelled in the application.

5.2 EVALUATION OF THE RESEARCH RESULTS

This research was undertaken as several individuals who were well acquainted with available data on the BRC (Van der Merwe 2003, pers com; Van Niekerk 2003, pers com; Roberts 2003, pers com) indicated that such a comprehensive modelling of the catchment had not yet been undertaken. The overriding aim was achieved, which was to compare runoff yields between the reference state of the BRC and the present; and to analyse the effects of land cover change and water abstractions on runoff. The objectives were achieved in the following accomplishments:

- Construction of a hydrological model of the BRC (Objective 1)
- Reconstruction of the reference state of the catchment (Objective 2)
- Creation of an ArcView GIS database (Objective 3)
- Application of the SHELL rainfall-runoff model and development of the simulation to include forestry, alien vegetation and irrigation and dam abstractions (Objective 4)
- Evaluation of the correlations between land cover change and runoff volumes (Objective 5)
- Relation of the findings to catchment and estuarine management (Objective 6)

Significant land cover change issues were highlighted by the SHELL output. The decrease in MAR from the BRC into the estuary since pre-development times is clearly impacting on the delicate balance of the catchment ecology. Significantly, the Bot River Estuary is no longer breaching its coastal berm and its gradual transformation into a freshwater lake is threatening catchment biodiversity. From the patterns detected on a subcatchment scale, alien vegetation infestations are a major cause of the runoff reduction and this is concerning as infestations cover approximately the same area of the BRC as the established forestry plantations and perennial agriculture combined and spread rapidly if uncontrolled. Perennial crops are relatively minimal in extent in the BRC but have a significant accumulative effect due to their excessive water demands, as demonstrated in the WSC. Urbanisation is minimal and predominantly confined to the lower coastal belt and is therefore not a significant problem as of yet.

Overall the research was highly successful in reaching the objectives as indicated. The results may have been even more satisfying had all land cover elements been able to be factored in. This may have addressed the somewhat surprising deviation in the runoff figures estimated for the BRSC. While some qualitative reasons for the discrepancy could be offered, these could not fully account for the fact that a catchment that has been targeted for perennial crop production and the irrigation dam construction to service it, forestry plantations and a fair amount of alien vegetation, yielded modelling results showing no reduction since the reference state.

5.3 RECOMMENDATIONS FOR LAND USE MANAGEMENT

Recent national policies encourage forestry and agriculture to enhance timber exports and meet the food demands of the growing population (Kienzle & Schulze 1995). Integrated catchment management has to balance the potential economic benefits of changing to these agricultural land covers with related reductions in streamflow in order to be successful (Kienzle & Schulze 1995). In terms of management of agricultural practices in the catchment, it is recommended that expansion of perennial agriculture be curbed, due to its significant effect on runoff. That is, unless the TMG aquifer is proved to support its further expansion sustainably. Cultivated fynbos is a highly suitable form of agriculture for the catchment and should be encouraged.

The proliferation of alien vegetation throughout the catchment and its rapid rate of infestation, make it potentially an even more serious threat on the catchment ecosystem than the agricultural land uses. It must be recognised that the increased runoff obtained by eradicating alien vegetation in the catchment is only a fraction of the cost compared to the construction of new water supply schemes (Chapman & Versfeld 1995; CSIR 2004). The quantification of actual water use by each species of alien vegetation would assist in more accurate estimations of their effect on water resources in future runoff modelling (Larsen, Görgens & Little 2003).

A holistic view has been adopted by the local municipalities regarding water demand and supply. This is a most productive approach and should be continued (Jacobs et al. 2002). The entire catchment must be considered in water resource management, not only the BRE over which there is the greatest concern. Although the model results are not absolute, the implications of the significant reduction in runoff due to land cover change is alarming and should be considered in all future management strategies for the BRC. An example of such a holistic approach is offered by the proposed management strategy for ensuring the survival of the Bot Estuary as an important and valuable coastal feature through anthropogenic intervention by Van Niekerk, Van der Merwe and Huizinga (2005).

5.4 RECOMMENDATIONS FOR FUTURE RESEARCH

As has been emphasized throughout the thesis, catchment runoff modelling is a complex process that can hope to yield no more than close approximations. Therefore, the main recommendation for future research concerns model application. The purpose of applying the model was hindered by its inability to model annual cereal production. A repeat simulation is recommended, using a model that allows for the simulation of the effects of non-irrigated crops. The BRC is largely devoted to annual agriculture and this land cover–runoff relationship in the catchment needs to be researched further.

A more comprehensive modelling of water abstractions in the BRC could be done as this research failed to make direct links between dam abstractions and runoff effects. Such an investigation would reveal the potential for future abstractions. Interbasin transfers that were not considered large enough to be included by Midgley, Pitman & Middleton (1994a) in their national overview were not modelled. In the future, a more elaborate modelling of the catchment could include these transfers. The Bot River Estuary (the waterbody) itself should also be included to factor in its input into the water balance equation.

The process of modelling in this research was hindered by the lack of publicly available published information on data preparation, analysis procedures, and manuals on how to use the various models. This research required assistance from experts in decoding the SHELL model, in the absence of a manual. It would be extremely beneficial for future modellers to have access to training, “to build capacity in the understanding and use of rainfall-runoff models in southern Africa” (Hughes 1995). Models should be packaged with manuals and examples in a software form, suitable for use within specific regions. Perhaps a most fruitful avenue for the next generation of GIS applications should be component modules that would allow direct runoff modelling operations from within the GIS package. This would obviate the need to transport data between various platforms as has had to be done here. To this end, it is hoped that this thesis can decode some of the complexities of rainfall-runoff modelling, acting as a guide for the amateur and the GIS specialist alike.

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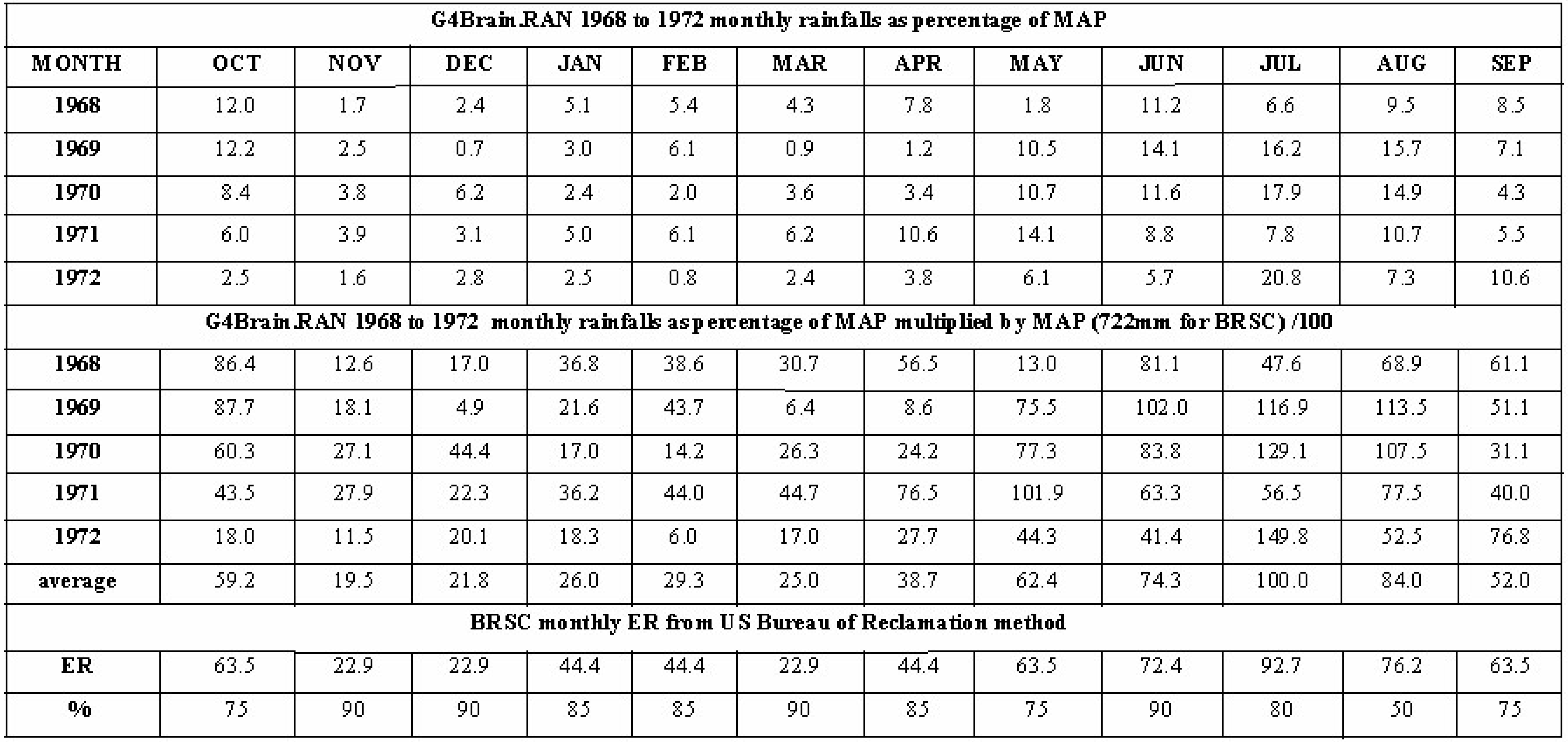
APPENDICES

APPENDIX A:

Table A.1: Calculations of effective rainfall (ER) for Bot River subcatchment (BRSC)



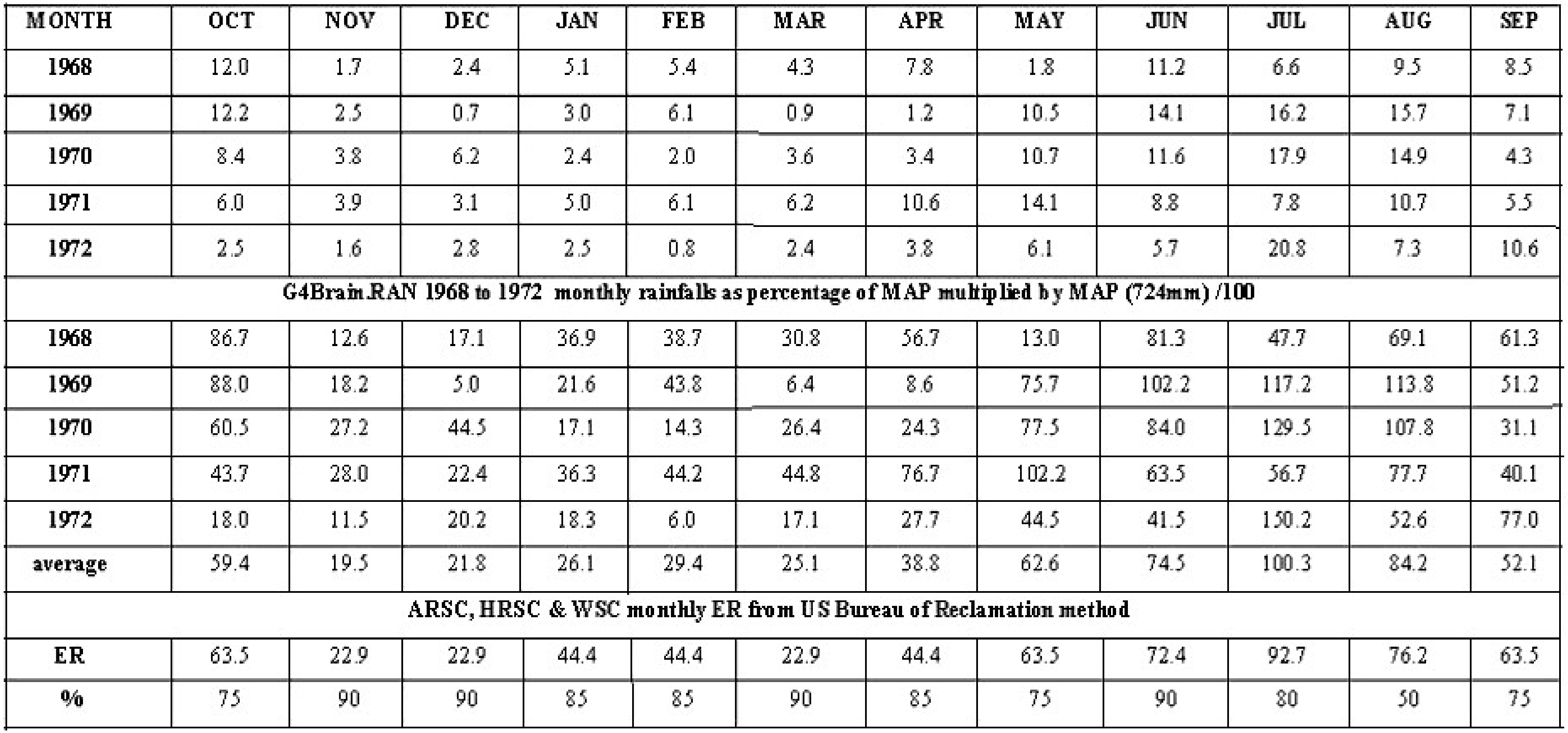
G4Brain.RAN 1968 to 1972 monthly rainfalls as percentage of MAP												
MONTH	**OCT**	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**
1968	12.0	1.7	2.4	5.1	5.4	4.3	7.8	1.8	11.2	6.6	9.5	8.5
1969	12.2	2.5	0.7	3.0	6.1	0.9	1.2	10.5	14.1	16.2	15.7	7.1
1970	8.4	3.8	6.2	2.4	2.0	3.6	3.4	10.7	11.6	17.9	14.9	4.3
1971	6.0	3.9	3.1	5.0	6.1	6.2	10.6	14.1	8.8	7.8	10.7	5.5
1972	2.5	1.6	2.8	2.5	0.8	2.4	3.8	6.1	5.7	20.8	7.3	10.6
G4Brain.RAN 1968 to 1972 monthly rainfalls as percentage of MAP multiplied by MAP (722mm for BRSC) /100												
1968	86.4	12.6	17.0	36.8	38.6	30.7	56.5	13.0	81.1	47.6	68.9	61.1
1969	87.7	18.1	4.9	21.6	43.7	6.4	8.6	75.5	102.0	116.9	113.5	51.1
1970	60.3	27.1	44.4	17.0	14.2	26.3	24.2	77.3	83.8	129.1	107.5	31.1
1971	43.5	27.9	22.3	36.2	44.0	44.7	76.5	101.9	63.3	56.5	77.5	40.0
1972	18.0	11.5	20.1	18.3	6.0	17.0	27.7	44.3	41.4	149.8	52.5	76.8
average	59.2	19.5	21.8	26.0	29.3	25.0	38.7	62.4	74.3	100.0	84.0	52.0
BRSC monthly ER from US Bureau of Reclamation method												
ER	63.5	22.9	22.9	44.4	44.4	22.9	44.4	63.5	72.4	92.7	76.2	63.5
%	75	90	90	85	85	90	85	75	90	80	50	75

Table A.2: Calculations of effective rainfall (ER) for Swart River subcatchment (SRSC)

G4Arain.RAN 1968-1972 monthly rainfalls as percentage of MAP

MONTH	**OCT**	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**
1968	8.5	4.8	1.8	5.2	4.6	3.5	12.3	1.4	11.4	5.9	7.6	4.7
1969	8.5	3.7	0.3	1.7	10.8	0.5	0.4	9.4	14.4	15.9	18.6	6.8
1970	6.6	0.9	3.1	0.5	2.7	4.5	4.0	9.4	11.4	15.8	20.5	5.0
1971	6.2	5.5	6.3	4.0	6.4	4.4	16.1	11.8	10.8	8.5	16.5	8.3
1972	2.8	3.5	2.5	1.0	0.6	1.3	3.6	7.3	4.6	12.0	9.1	9.8
G4Arain.RAN 1968-1972 monthly rainfalls as percentage of MAP multiplied by MAP (515mm for SRSC) /100												
1968	43.8	24.8	9.2	27.0	23.7	17.9	63.1	7.3	58.9	30.3	38.9	24.2
1969	43.7	19.0	1.6	8.9	55.4	2.5	2.2	48.3	74.0	82.0	95.5	34.9
1970	34.0	4.6	16.0	2.8	13.6	23.3	20.8	48.3	58.7	81.3	105.8	25.9
1971	32.1	28.3	32.7	20.4	33.1	22.9	82.8	60.5	55.4	43.9	84.8	42.6
1972	14.2	18.1	12.7	5.3	3.1	6.9	18.4	37.4	23.6	61.7	46.7	50.5
average	33.6	19.0	14.5	12.9	25.8	14.7	37.5	40.3	54.1	59.9	74.3	35.6
SRSC monthly ER from US Bureau of Reclamation method												
ER	44.4	22.9	22.9	22.9	44.4	22.9	44.4	44.4	63.5	63.5	72.4	44.4
%	85	90	90	90	85	90	85	85	75	75	90	85

Table A.3: Calculations of effective rainfall (ER) for the Afdaks River, Hopies River and West subcatchments (ARSC, HRSC and WSC)



MONTH	**OCT**	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**
1968	12.0	1.7	2.4	5.1	5.4	4.3	7.8	1.8	11.2	6.6	9.5	8.5
1969	12.2	2.5	0.7	3.0	6.1	0.9	1.2	10.5	14.1	16.2	15.7	7.1
1970	8.4	3.8	6.2	2.4	2.0	3.6	3.4	10.7	11.6	17.9	14.9	4.3
1971	6.0	3.9	3.1	5.0	6.1	6.2	10.6	14.1	8.8	7.8	10.7	5.5
1972	2.5	1.6	2.8	2.5	0.8	2.4	3.8	6.1	5.7	20.8	7.3	10.6
G4Brain.RAN 1968 to 1972 monthly rainfalls as percentage of MAP multiplied by MAP (724mm) /100												
1968	86.7	12.6	17.1	36.9	38.7	30.8	56.7	13.0	81.3	47.7	69.1	61.3
1969	88.0	18.2	5.0	21.6	43.8	6.4	8.6	75.7	102.2	117.2	113.8	51.2
1970	60.5	27.2	44.5	17.1	14.3	26.4	24.3	77.5	84.0	129.5	107.8	31.1
1971	43.7	28.0	22.4	36.3	44.2	44.8	76.7	102.2	63.5	56.7	77.7	40.1
1972	18.0	11.5	20.2	18.3	6.0	17.1	27.7	44.5	41.5	150.2	52.6	77.0
average	59.4	19.5	21.8	26.1	29.4	25.1	38.8	62.6	74.5	100.3	84.2	52.1
ARSC, HRSC & WSC monthly ER from US Bureau of Reclamation method												
ER	63.5	22.9	22.9	44.4	44.4	22.9	44.4	63.5	72.4	92.7	76.2	63.5
%	75	90	90	85	85	90	85	75	90	80	50	75

APPENDIX B:

Appendix B.1 Formulae for calculation of RESSIM submodule parameters *a* and *b*

$$A = aS^b$$

Let:

A = area of reservoir surface (km^2)

S = storage volume in reservoir (x10^{6}m^3)

"The constants *a* and *b* can be determined by plotting pairs of storage (x10^{6}m^3, x-axis) and area (km^2, y-axis) on log-log paper. The slope of the best-fit straight line through the points yields the value of *b*. The value of *a* is equal to the intercept on the y-axis at a value of x (storage) equal to 1" (Midgley, Pitman & Middleton 1994a: 11.26).