Delineating River Network Quinary Catchments for South Africa and Allocating Associated Daily Hydrological Information

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

Background to the Project

Nested hierarchical catchments or hydrological unit boundaries are being used as planning units in planning, management and implementation decision making in water resources. In South Africa, these catchments, which are endorsed by the Department of Water Affairs (DWA), range from primary, through to secondary and tertiary, with the smallest operational unit being the quaternary catchment. Until very recently, the latter was the finest spatial level of data resolution. Substantial datasets and information are linked to these scaled catchments. Manual catchment delineation which was subjective, error-prone, costly and time-consuming preceded automated catchment extraction or mapping within Geographic Information Systems (GIS). Nested hierarchical catchments are employed in a wide range of applications (e.g. water resource management, conservation planning, environmental impact or flow assessments, climate change and hydrological modelling). However, these studies have often highlighted the need for sub-quaternary scale information, i.e. catchment delineation at a scale smaller than the quaternary level. This stems from the fact that quaternary catchments are fairly large topographical units within which the physiography can be highly heterogeneous. Because runoff to rainfall responses are non-linear, any quaternary catchment interpolation to finer resolutions would yield hydrologically incorrect results.

Presently, sub-delineation of catchments is taking place piecemeal, both locally and internationally. This is problematic because consistent and standardized methods and protocols for are lacking, and conflicting boundary extractions hinder data sharing and comparison of assessment and monitoring information. The usage and implementation of final products are also challenging because of a lack of government (and other) authority agreement or endorsement. This project was initiated to produce a fifth level quinary catchment GIS layer with linked hydrology for which the pre-cursors were altitudinal and river network quinary catchments. These catchments originated from three Water Research Commission (WRC) projects. The altitudinally based quinary catchments representing hydrological and agricultural response zones (5838 upper, middle and lower quinary catchments within the RSA, Lesotho and Swaziland) emanated from the WRC climate change reports 1562/1/10 and 1843/2/11 respectively. The National Freshwater Ecosystem Priority Area project (NFEPA; WRC report 1801/2/11) employed 9417 sub-quaternary catchments as planning units to manage the water resource and the surrounding land. A nationally accepted quinary catchment layer is an important first step in operational decision making and general coordination. In addition, reliable hydrological data at the appropriated scale (in this case the quinary catchments) is essential for hydrological modelling and integrated water resource management.

Project aims

The project aims were addressed in full and are reported on in this document. They are:

- to develop a nationally accepted river network quinary catchment GIS layer and metadata for South Africa, Swaziland and Lesotho,
- to populate these quinary catchments with associated daily hydrological data
- to provide an assessment of its reliability.

Methods

The boundaries of quaternary catchments were refined in an aligned WRC project (K5/1908) that aimed to prepare a hydrologically improved DEM for southern Africa. The river network quinary catchments delineated in this project are defined as nested hydrological catchments around the river reach of the 1:500 000 DWA river network and major dams. The following rules guided the delineation of the river network quinaries:

- Quinaries were nested within the DWA Quaternary Catchments as delineated in the WRC project K5/1908.
- Every quinary contains a 1:500 000 river segment, defined as the stretch of river from the source to a tributary, or from a tributary to another tributary.
- Quinary catchments which did not contribute to the runoff for the estuary mouth were merged into a catchment which drains to the coast.
- Quinary catchments were delineated for entire primary catchments even if they extended beyond the borders of South Africa, and then clipped to the border of South Africa based on the DWA quaternary catchments.
- Quinary catchments were delineated so that catchments can be modelled upstream of major dams.

The quaternary catchments were built as walls into the DEMs used to delineate the quaternary catchments in ArcHYDRO. The DEMs were exported as geotiffs into GRASS 6.4.2 and r.watershed was used to delineate various scale catchments. An exterior basin threshold of 5 000 cells was used to create a river network quinary catchment GIS layer with an average area of 30 km^2. A larger exterior basin threshold was, however, used for topographically flat catchments. The river network quinary catchments were cleaned up in ArcGIS so that a quinary catchment was delineated along the 1:500 000 river reach code, particularly along the coastal primary catchments of South Africa.

This report also discusses the methodology used in creating altitudinal quinaries and the methodology used to assign daily hydrological data to those. The methodology used to transpose the daily hydrological data to the river network quinaries is given for the following hydrological information: daily rainfall values; daily minimum and maximum temperatures; daily values of solar radiation; daily vapour pressure deficit; daily reference potential evapotranspiration; hydrological soils attributes and hydrological baseline land cover attributes.

Results and discussion

One of the major constraints in generating a river network quinary GIS layer is the rule that the catchments need to be generated around the 1:500 000 river reach. The 1:500 000 river network GIS layer is not spatially consistent in terms of detail and scale of mapping. It was originally generated for cartographic purposes and as a result there are complications in using it to generate river network catchments around the river reach. Despite the 1:500 000 rivers being burned into the DEM, the catchments derived always required significant manual GIS cleaning. In some cases, where the pour points obtained from DWA were manually moved, the generated catchments from GRASS aligned very poorly with the borders of the updated quaternary catchments.

Three primary catchments were selected for the purpose of reporting on the river network quinary catchments. Summary statistics are given for these catchments and compared to characteristics of the NFEPA sub-quaternary catchments, which represents a precursor GIS layer of river network quinary catchments for South Africa, generated for the NFEPA project. For the three primary catchments, the number of river network quinaries compares favourably with the number of NFEPA sub-quaternary catchments. The average river network quinary areas delineated for Primary catchment U, J and E are 104 km^2, 100 km^2 and 108 km^2 respectively.

For operational modelling of many elements of Integrated Water Resource Management (IWRM), hydrological simulations need to be undertaken at daily time steps. Diurnality encapsulates, albeit not perfectly, many hydrologically related processes (e.g. evaporation, transpiration and many discrete rainfall and related stormflow events). Furthermore, many operational decisions are made according to daily conditions (e.g. irrigation, tillage, reservoir operations).

There are, however, two other major reasons for promoting daily time step modelling. The first is the availability of data, with South Africa having approximately 1800 stations with over 40 years of rainfall records. Secondly, daily time step models provide a vast array of potential and realistic and, in the context of the National Water Act and IWRM, highly relevant output which monthly models do not. The advent of quality controlled daily integrated radar and satellite derived rainfall values is likely to improve distributed hydrological modelling in South Africa, with major benefits to many facets of IWRM.

Conclusions and recommendations

Significant progress has been made in developing skills to automate the delineation of nested sub-catchment boundaries for South Africa, stemming from: (i) the release of the updated quaternary catchments GIS layer and associated ancillary GIS layer, such as hydrologically corrected DEMs, flow direction paths and catchment pour points; and (ii) the piloting of different software packages (GRASS, ArcGIS) and rules for sub-catchment delineation within this project. In addition, the project team has harnessed much knowledge that has been developed over the years through related WRC projects on how to scientifically develop estimates of daily hydrological, daily climatic, soils and land cover data and summarize these into different sub-catchment boundaries.

The river network quinary catchments build successfully on the knowledge and lessons learnt during the delineation of sub-quaternary catchments for the NFEPA project. The river network quinary catchments delineated in this project are defined as nested hydrological catchments around the river reach of the 1:500 000 DWA river network and major dams. Given the tight time frames of the project, there has not been sufficient time and opportunity to engage with the Department of Water Affairs around the river network quinaries produced. The river network quinaries are seen as an intermediate product which can be taken to the DWA in order to engage with the hydrologists and relevant parties so that a DWA endorsed layer of quinaries can be finalised.

In a scientifically defensible way, the next step is to merge the concepts of nested hierarchal river network quinaries and altitudinal quinaries to create a finer scale catchment which more accurately reflects the hydrological flow path, land use changes and rainfall changes within the a quinary catchment. A key recommendation is that up until the quinary level, the nested hierarchical catchments are watershed delineated, but at the sixth catchment level, altitudinal catchments are useful as they reflect the relatively homogenous hydrological response zones, based on elevation and thus changes in rainfall, soils, land use and with that changes in runoff.

The concepts of the methods for altitudinal and river network quinary catchments need to be used as a point of departure for a follow-on project and be used to produce a merged layer of relatively homogenous response zones (in terms of hydrology, soils and land use). As a standalone layer, the altitudinal quinary catchments and the river network quinary catchments are limited in their application, but if the layers are merged they can form a powerful tool for many applications around water resource planning and management, and assessment of ecosystem services.

The confidence that can be afforded to the hydrological data is highly dependent on the proximity of the rainfall stations to catchments, as well as effective monitoring of trends at the rainfall stations. Strategic decisions need to be taken on which rainfall stations are a priority to maintain in the South African monitoring network of stations, as well as to identify potential gaps in the network where new rainfall stations should be sited.

Endorsement and naming conventions need to be established to facilitate the attachment of additional research data. Additional data sets can be taken into account, especially those currently collected at a quaternary level, for example, alien vegetation, FEPAs, ecosystem service data, baseflow data.

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Dr A Senzanje	University of KwaZulu-Natal (UKZN)
Mr H Weepener	Agricultural Research Council (ARC))
Ms C Rajah	Department of Water Affairs (DWA)
Ms N Fourie	Department of Water Affairs (DWA)
Dr M Silberbauer	Department of Water Affairs (DWA)

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CAPACITY BUILDING

This short-term project was not particularly suited for extensive capacity building. Attempts were made to include post-graduates in various analytical tasks. However, the short-term nature and advanced analyses needed in the project resulted in the project staff completing this work themselves. Nevertheless, ten BSc Hydrology Honours students (at the UKZN) took a course called, "Advanced Hydrological Modelling Skills". They are:
SG Hlalukane
J Hoosen
F Morris
TC Ndlovu
HT Thenga
S Gokool
O Mokonto
MS Selela
AP Watson
TZ Lamula.

These students worked with the project dataset and learnt from the Geographic Information Systems (GIS) analyses. They have been investigating the appropriate methods of assigning hydrological and other variables to the river network catchments (this project). Their investigations showed that the proposed method of transferring existing variables from the altitudinally based hydrological and agricultural response zones to the river network quinary catchments by proximity was not going to be scientifically sound. It was concluded that it would be best to approach the variable allocation *ab initio* and reassign all the variables based on the methodology explained in this publication.

Furthermore, A Maherry, J Nel, I Kotzee, D Le Maitre and C Petersen (CSIR) attended a two-day *ACRU* modelling course on the 20 and 21 October 2010 held at Roodeplaat Training Centre near Pretoria.

Lastly, this project contributed considerably towards higher degrees (MSc and PhD) of two members of the project staff, viz. Ms LB Smith-Adao and Mr MJC Horan.

TECHNOLOGY TRANSFER

- The BSc Hydrology Honours course above.
- The two-day ACRU course above.
- A journal article entitled “Deriving river network quinary catchments for South Africa” is in preparation for submission to Water SA. This article was co-funded with another WRC project, K5/1801.

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LIST OF ACRONYMS

ARC	Agricultural Research Council
ACRU	Agricultural Catchments Research Unit
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CSIR	Council for Scientific and Industrial Research
DEM	Digital Elevation Model
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
E_p	Potential Evapotranspiration
E_r	Reference Potential Evaporation
GDEM	Global Digital Elevation Model
GIS	Geographical Information System
GeoTIFFs	Geographic Tagged Image File Format
GRASS	Geographic Resources Analysis Support System
IWRM	Integrated Water Resource Management
FEPA	Freshwater Ecosystem Priority Areas
NFEPA	National Freshwater Ecosystem Priority Area
NRCS	Natural Resources Conservation Service
QDB	Quaternary Catchments Database
RQS	Resource Quality Services (Department of Water Affairs)
RSA	Republic of South Africa
R_s	Solar Radiation
SRTM	Shuttle Radar Topography Mission
Tra	Temperature Range
USA	United States of America
USGS's	United States Geological Survey's
UKZN	University of KwaZulu-Natal
UP	University of Pretoria
VPD	Vapour Pressure Deficit
WBD	Watershed Boundary Dataset
WITS	University of the Witwatersrand
WRC	Water Research Commission
WRNA	W R Nyabeze and Associates

CHAPTER 1: INTRODUCTION

1.1 Background to project

Worldwide catchment and hydrological unit boundaries are typically used as a spatial context for making decisions concerning the planning, management and implementation of, for example, socio-economic development, environmental or natural water resource goals (e.g. Verdin and Verdin, 1999; Kingsford, 2000; Berelson *et al*., 2004; Shi *et al*., 2004; Schulze, 2011). Qing and Yixiang (2005) defined a catchment, also called a drainage basin or watershed, as the entire land area of water flowing to an outlet point, whereas Berelson *et al*. (2004) described it as a topographically represented area within which surface water drains to a common outlet. Over the years numerous datasets and considerable information (e.g. land cover, geology, soil erosion, streamflow, rainfall, etc.) have been summarized on the basis of catchment boundaries (Midgley *et al*., 1994; Hughes, 2004; Middleton and Bailey, 2008). Prior to automated catchment extraction or mapping made possible through continued advances in spatial datasets and hydrological modelling techniques within Geographic Information Systems (GIS) (Bongartz, 2003; Berelson *et al*., 2004; Strager *et al*., 2009), catchment delineation was an error-prone, costly, time-consuming and often extremely subjective manual exercise (Berelson *et al*., 2004; Qing and Yixiang, 2005). Catchments were delineated from topographical maps using expert knowledge (Midgley *et al*., 1994) and enhanced with aerial photography and remotely sensed imagery interpretation (Berelson *et al*., 2004). These landscape units are available in a nested hierarchy of scales (Martínez-Casasnovas and Stuiver, 1998) which further enhance their application as planning units for assessment and reporting (Shi *et al*., 2004). A hierarchy is a graded organizational structure whereby the upper levels of organization provide the template from which lower levels emerge. The upper levels also exert some constraint on the lower levels. Fundamental to hierarchical systems is the fact that each particular level is a distinct functional entity that is part of a larger whole (O'Neill *et al*., 1986; Dollar *et al*., 2007).

Examples of nested hierarchical catchments or hydrological units are provided by the United States of America (USA) and the Republic of South Africa (RSA). In the early 1970s river basin delineation resulted in the United States Geological Survey's (USGS's) fourth level State Hydrologic Unit Map series (Seaber *et al*., 1987). These units were recently further divided by the USGS and the Natural Resources Conservation Service (NRCS) into six levels. The latter situation resulted from more detailed hydrological studies necessitating smaller subdivisions. The expanded system is known as the national Watershed Boundary Dataset (WBD). Guidelines and standards with prescribed average sizes of the sub-catchments per level (read scale) and suitable coding system accompany this dataset (Berelson *et al*., 2004). In the RSA, together with Swaziland and Lesotho, 22 primary catchments have been sub-divided into secondary, then tertiary and finally 1946 quaternary catchments (Figure 1.1; Midgley *et al*., 1994). Primary catchments were first mapped in 1899 for the Cape of Good Hope which was then followed in 1913 by a national map of catchments (McDonald, 1989). Tertiary and secondary catchment delineation was undertaken in 1965 by the former Department of Water Affairs and Forestry (DWAF) which is now the Department of Water Affairs (DWA), using contour lines and spot heights from 1:50 000 hardcopy topographic maps (Midgley *et al.*, 1994). A similar approach was used to map the 1949 quaternary catchments in the early 1990s, however, 1:250 000 topographic maps were used in that delineation in conjunction with rainfall-runoff distribution maps. This combined approach produced interlinked and hydrologically cascading fourth level quaternary catchments varying in size from 48 to 18 100 km^2 (average area is 650 km^2). An alpha-numerical coding system (i.e. adapted from the tertiary catchment) was used to label the quaternary catchments (Figure 1.1). Furthermore, digital boundary products were created for all catchment levels (Midgley *et al.*, 1994).

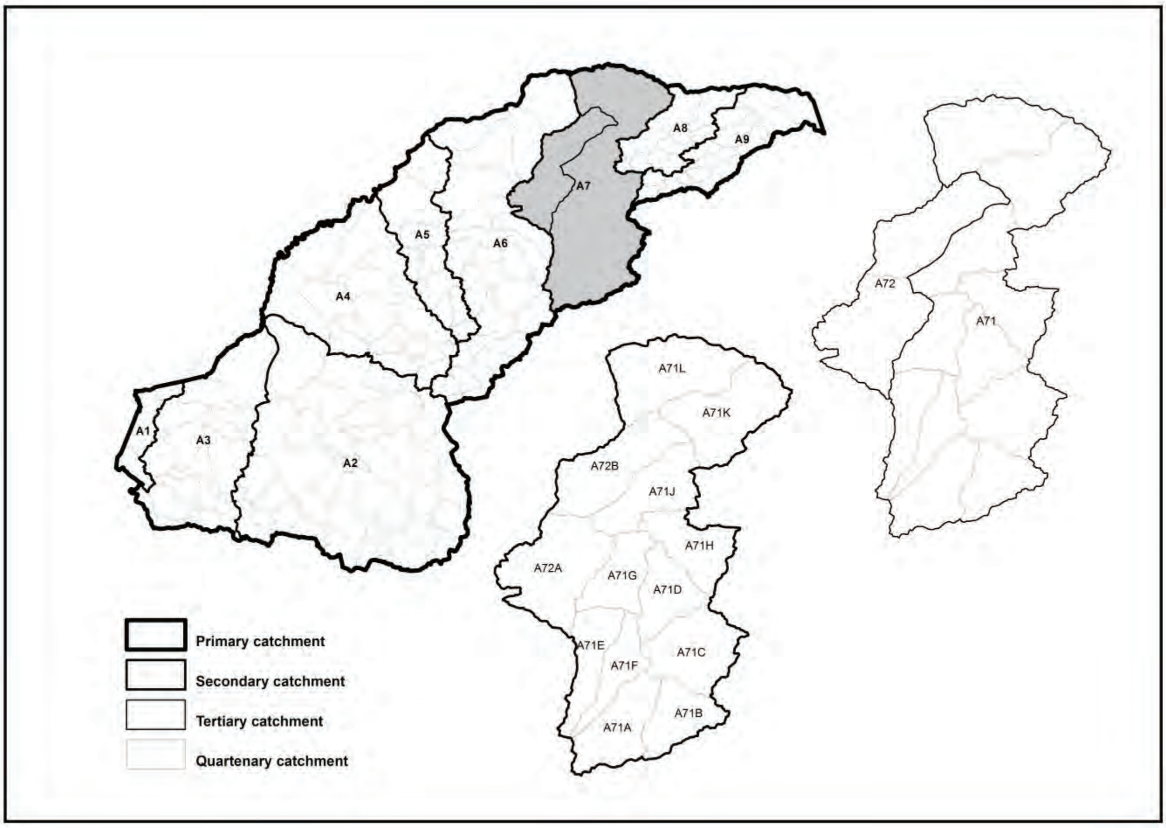

Figure 1.1: An example of the four level nested hierarchical catchment system with their naming conventions used in South Africa (after Midgley *et al*., 1994).

Until very recently, the DWA endorsed quaternary catchments constituted the most detailed spatial level for country wide operational decision making (Middleton and Bailey, 2008). They were used in a variety of applications which ranged from water resource management and conservation planning to environmental impact and risk assessments. However, these studies frequently highlighted the need for delineating catchments smaller than the quaternary scale. The more detailed the available catchment data, the more elaborated the water resource assessment that is possible (Hughes, 2004; Schulze and Horan, 2010; Nel *et al*., 2010b). Many quaternary catchments are fairly large spatial units within which the topography is highly heterogeneous. Hence, it is incorrect to interpolate quaternary catchment data to finer resolutions (Schulze, 2004a; Schulze *et al*., 2010b; Nel *et al*., 2011).

This is problematic for fields of study that require sub-quaternary scale information, such as environmental flow assessments (Tharme, 2003; Hughes, 2004; King and Brown, 2010), freshwater biodiversity planning (Linke *et al*., 2008; Nel *et al*., 2009; Smith-Adao *et al*., 2011) and climate change or hydrological modelling (Blignaut *et al*., 2010; Schulze and Horan, 2010; Schulze, 2011). Pre-cursors to a nationally accepted fifth level quinary GIS layer (the subject of this project) include altitudinal (Schulze and Horan, 2010; Schulze *et al*., 2010b) and catchment-based river network (Nel *et al*. 2009; Nel *et al*., 2011) quinary catchments. The altitudinally based quinary catchments representing hydrological and agricultural relatively homogeneous response zones (5 838 upper, middle and lower quinary catchments) emanated from two Water Research Commission (WRC) climate change reports, *viz*. 1562/1/10 and 1843/2/11 respectively. Moreover, a suite of data and information including daily rainfall, daily temperature, daily reference evaporation, baseline land cover and soils have also been developed for these altitudinal quinary catchments (Schulze *et al*., 2010b). The National Freshwater Ecosystem Priority Area (NFEPA) project (K5/1801), co-funded by the WRC, identified a national network of freshwater ecosystem priority areas (FEPAs). This project employed 9 417 sub-quaternary catchments (mean area of 135 km^2) as planning units to manage the water resource and the surrounding land. They were modelled in ArcHydro, an extension of ArcGIS 9.3, using a 50 m digital elevation model (CSIR, unpublished) and the 1:500 000 rivers used by the DWA. These quinary catchments maintain hydrological connectivity because they are delineated around entire river reaches within quaternaries. Both types of quinary catchments need to undergo rigorous refinement processes so that they can be endorsed by the DWA and used across the country (Nel *et al*., 2011). Currently, sub-delineation of catchments is being done piecemeal both locally and internationally. This is problematic for mainly three reasons. Firstly, consistent and standardized delineation methods and protocols for precision and accuracy are lacking, which cause difficulties for multi-jurisdictional collaboration. Secondly, comparison of assessment and monitoring information, as well as data sharing between sources, is hindered by conflicting boundary extractions. Lastly, the final products stemming from delineation are not endorsed or agreed upon by any government authority, making their usage and implementation challenging (Berelson *et al*., 2004; Nel *et al*., 2011).

1.2 Project aims

The project aims:

- to develop a nationally accepted river network quinary catchment GIS layer and metadata for South Africa, Swaziland and Lesotho,
- to populate these quinary catchments with associated hydrological data and
- undertake an assessment of its reliability.

The daily hydrological information (discussed in Section 2.2) is intended for hydrological modelling and the hydrological information given is daily climatic data as well as soils and land cover information per river network quinary. It must be noted that the hydrological information in Sections 2.2 and 2.3 has been extracted from Chapter 7 “Methods 2: Development of the Southern African Quinary Catchments Database”, WRC Report No. 1562/1/10 (Schulze *et al*., 2010b). The inputs of those authors are duly acknowledged.

Furthermore, the hydrological data and information have been disaggregated for altitudinal quinary catchments, and these disaggregated data will now be used to derive hydrological information for the river network quinary catchments.

CHAPTER 2: METHODS

2.1 Delineating river network quinary catchments

The river network quinary catchments delineated in this project are defined as hydrological catchments around the river reach of the 1:500 000 DWA river network and major dams, nested within the updated quaternary catchments from WRC Project K5/1908 (Weepener *et al*., In press).

The boundaries of quaternary catchments were refined in an aligned WRC project (K5/1908) that aimed at preparing a hydrologically improved DEM for southern Africa between 19ºS and 35ºS and 12ºE to 36ºE. A brief literature review revealed that the Shuttle Radar Topography Mission (SRTM) dataset is currently the most appropriate dataset to use as a baseline. A continuous Digital Elevation Model (DEM) was successfully created by filling voids inside RSA with elevations from 20 m contour lines and outside RSA with the Advanced Spaceborne Thermal Emission and Reflection Radiometer Digital Elevation Model (Aster GDEM) dataset. The 1:500 000 river systems (by the Directorate: Resource Quality Services of the Department of Water Affairs) were burned into the 'raw' DEM at certain threshold values (Weepener *et al*., in press). This process was then followed by automated hydrological correction. The latter process saw to it that DEM-derived flow paths followed real world river systems diligently. The improved gap-filled DEM described in this study represents the hydrologically soundest dataset for the study area to date. DEM derived products included nested hierarchical catchments (primary, secondary, tertiary and quaternary), local drain direction, slope, aspect, a hillshade and upstream number of cells. Hydrology experts from the DWA defined quaternary pour points from tributary intersections or dam walls. It must be noted that these points were chosen in such a way that they did not deviate excessively from the previously defined quaternaries (Weepener *et al*., in press).

The river network quinary catchments delineated in this project are defined as nested hydrological catchments around the river reach of the 1:500 000 DWA river network and major dams. The recommended average areas for different levels of catchments for the United States was used to guide the area of quinary catchments delineated for South Africa. The areas of the catchments for United States are shown in Table 2.1. The areas of the updated catchments for South Africa delineated in the WRC Project K5/1908 are shown in Table 2.1 In order to calculate the average area, only those quaternary catchments were included where the majority of the area fell within the boundaries of South Africa. This was to exclude the large quaternary catchments delineated in Namibia, Botswana, Zimbabwe and Mozambique.

Table 2.1: Average areas for different levels of catchments delineated for the United States (after USGS & USDA, 2009) and the updated South African quaternary catchments from WRC Project K5/1908.

United States			**South Africa**		
Name	**Level**	**Average Area (km^2)**	**Name**	**Level**	**Average Area (km^2)**
Region	1	460 000	Primary	1	53 000
Subregion	2	43 500	Secondary	2	8 000
Basin	3	27 500	Tertiary	3	4 300
Subbasin	4	1 800	Quaternary	4	650
Watershed	5	600			
Subwatershed	6	100			

2.1.1 Rules used for delineating river network quinary catchments

The river network quinary catchments were nested within the DWA quaternary catchments. The DWA quaternary catchments were delineated in the WRC project K5/1908. The same digital elevation model (DEM) that was used to model the quaternary catchment boundaries was used to model the quinary catchments. The DEM used was the SRTM90m flow path improved DEM with sinks filled. The DEM was extracted into seven regions in order to allow quicker processing.

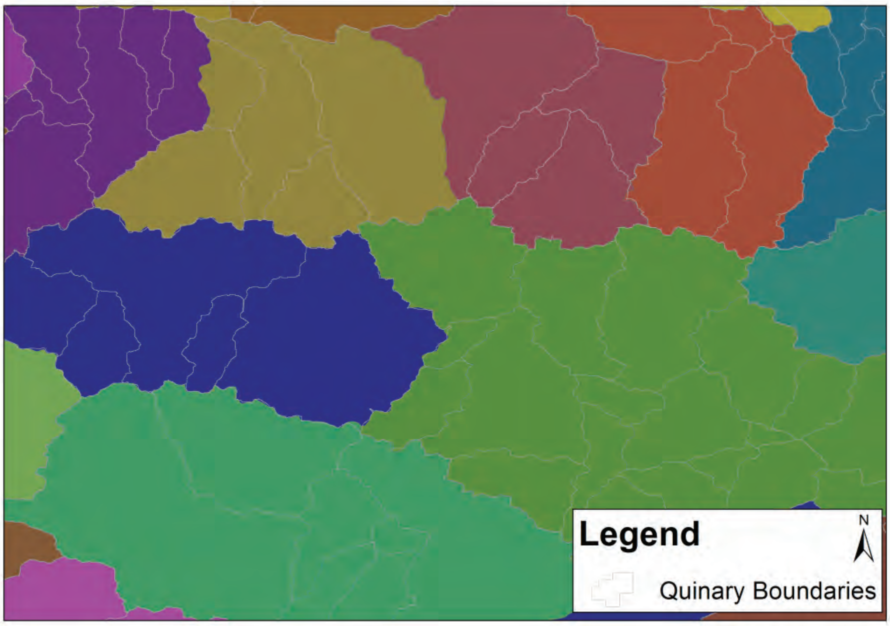

Figure 2.1: Quinary catchments are nested within quaternary catchments which are shown in the figure with different colours. [Note: quinary boundaries be made bolder]

A river network quinary catchment was delineated around each 1:500 000 river reach, defined as the stretch of river from the source to another tributary, or from a tributary to another tributary (i.e. the stretch of river between nodes on the 1:500 000 river network layer).

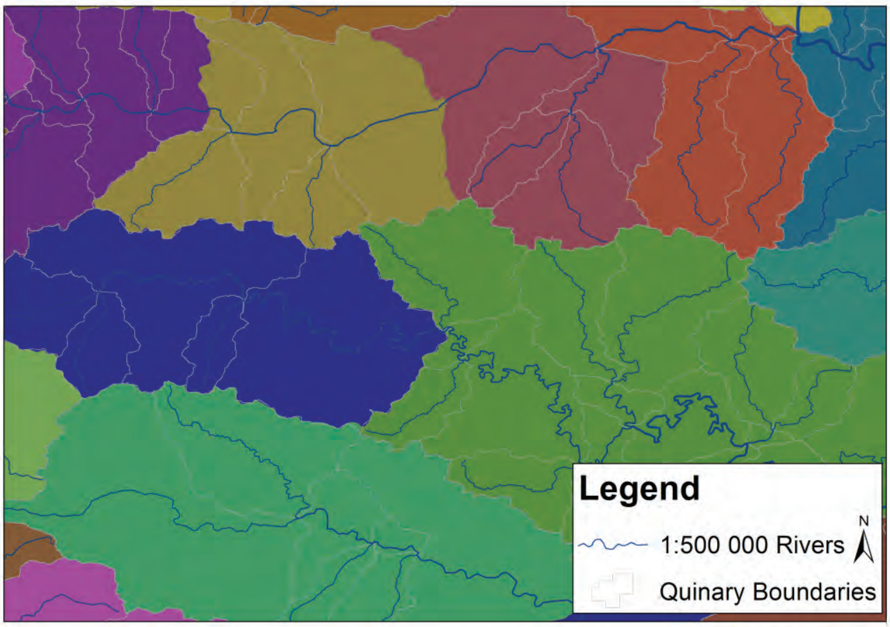

Figure 2.2: A river network quinary catchment contains a 1:500 000 river reach, from the source to the mainstem or another tributary.

Quinary catchments which do not drain into the estuary mouth were merged into a quinary catchment which drains into the coast. This rule was set so that the runoff into the estuary mouth could be calculated more accurately as requested by estuarine specialists. This "dead" land thus drains into the coast as shown in Figure 2.3.

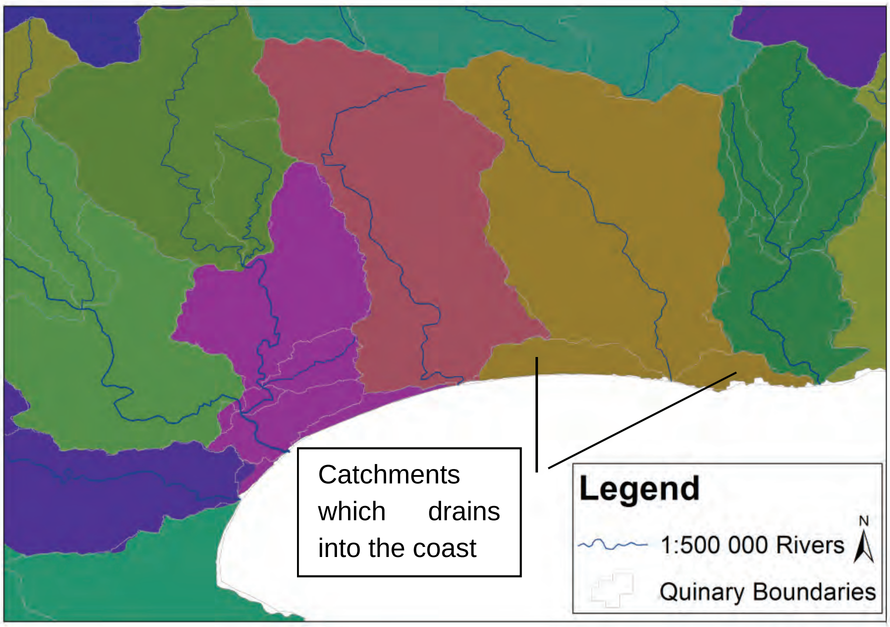

Figure 2.3: Quinary catchments which do not contribute to the runoff for the estuary mouth were merged into a catchment which drains to the coast, as shown in the figure.

Because the SRTM90 DEM extends beyond the border of South Africa, entire transboundary catchments were modelled and then clipped to the border of South Africa, based on the quaternary catchment GIS layer.

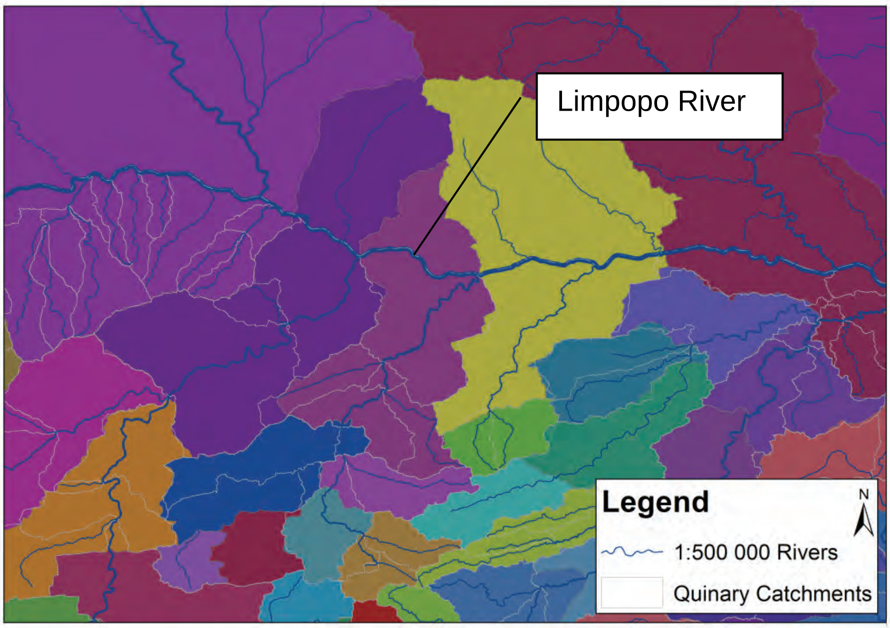

Figure 2.4: Quinary catchments were delineated for entire primary catchments even if they extended beyond the borders of South Africa, and then clipped to the border of South Africa based on the DWA quaternary catchments

Where a major dam exists or a pour point, Quinary catchments will be modelled so that a catchment is upstream of a major dam as shown in Figure 2.5. Major dams were considered as "nodes" or pour points in the 1:500 000 river network GIS layer such that the area upstream of a dam was modelled as a separate quinary catchment even if there was no tributary confluence present. The DWA major dams GIS layer (pers com Dr Mike Silberbauer) was used to define major dams. Major dams and monitoring nodes were used by Weepener *et al*. (in press) in their updating of the quaternary catchment GIS layer.

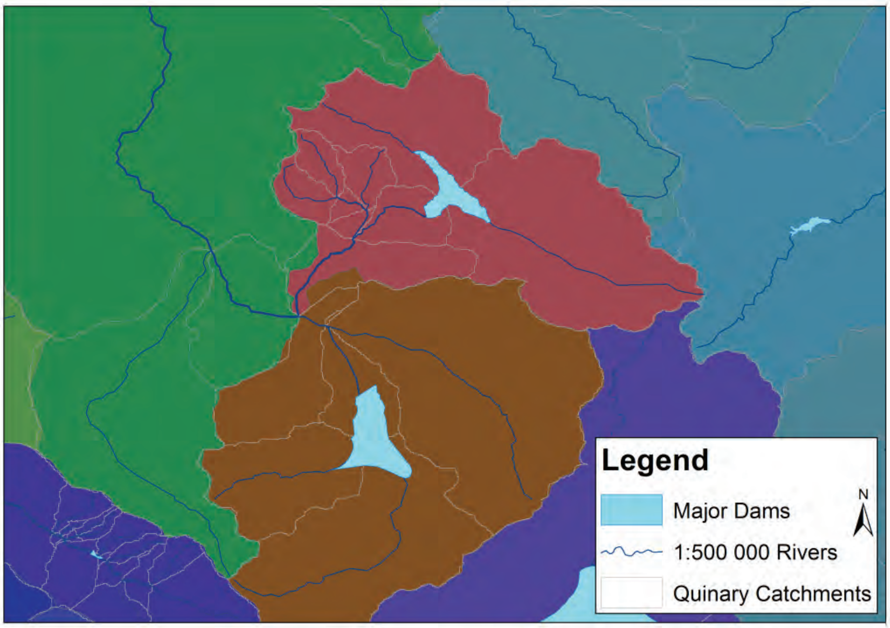

Figure 2.5: Quinary catchments were delineated so that catchments are modelled upstream of major dams

GRASS, a raster-based analysis package (ref), is better able to model watersheds in flat areas than ArcHydro. Where no obvious drainage channel exists, a large exterior basin threshold was used to delineate quinary catchments, guided by the USGS guidelines and the generated shape of the GRASS delineated watershed. Figure 2.6 shows the difference in catchment modelling using two different thresholds. Figure 2.6(a) shows the catchment delineation in the Northern Cape using an exterior watershed basin of 50 000 cells (average area of 560 km^2), and Figure 2.6(b) shows the catchments delineated using an exterior watershed basin threshold of 25 000 cells (average area of 263 km^2). Where appropriate, quinary catchments were made to follow the boundaries delineated by NFEPA (Nel *et al*., 2011) and the altitudinal quinary catchments (Schulze and Horan 2010) boundaries.

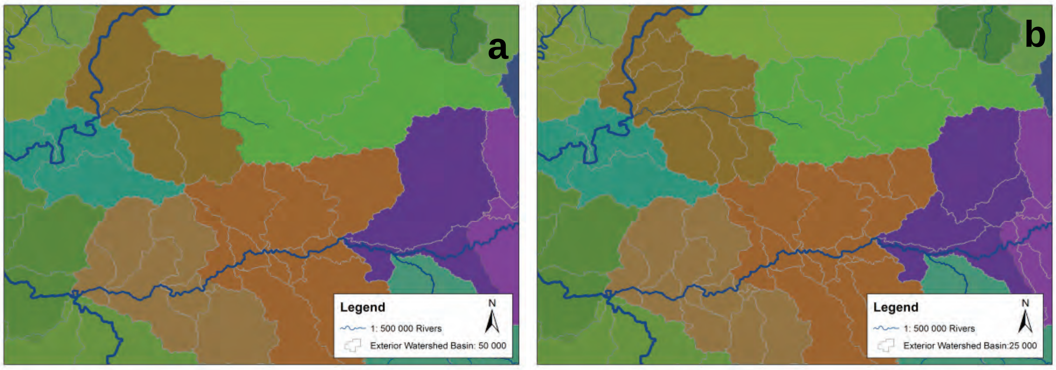

Figure 2.6: Catchment delineation with different basin thresholds. (a) Catchments delineated with a large exterior basin threshold of 50 000 cells (average area of 560 km^2), and (b) Catchments delineated with a large exterior basin threshold of 25 000 cells (average area of 263 km^2).

2.1.2 Initial watershed delineation in GRASS

Prior to the watershed delineation in GRASS 6.4.2, the updated quaternary catchment boundaries were used to build walls into the DEM in ArcHydro Tools 2.0 (ESRI, 2011) in ArcGIS 10. This was performed for all the DEMs. The DEMs were exported as GeoTIFFs and imported into GRASS. Using the r.watershed command in GRASS (GRASS, 2012), the Exterior Basin Threshold was adjusted to obtain sub-catchments of various sizes. Table 2.2 and Figure 2.7 display the various sub-catchments which are delineated using various exterior basin thresholds as a variable parameter in GRASS as well as the associated areas of the sub-catchments delineated.

Table 1.2: The exterior basin threshold and the average sub-quaternary catchments delineated.

Exterior Basin Threshold	Average Sub-catchment area (km^2)
50 000	560 km^2
25 000	263 km^2
5 000	33 km^2
1 000	12 km^2
500	6 km^2

Based on input from the project's Reference Group, an exterior basin threshold of 5 000 was used in order to generate a primary dataset of river network quinary catchments for South Africa. This threshold was based on the rationale that the *ACRU* hydrological model is best able to model catchments of a size of roughly 30 km^2. Based on the definition of a river network quinary catchment being associated with a 1:500 000 river reach, the preliminary river network catchments required extensive cleaning in ArcMap 10.

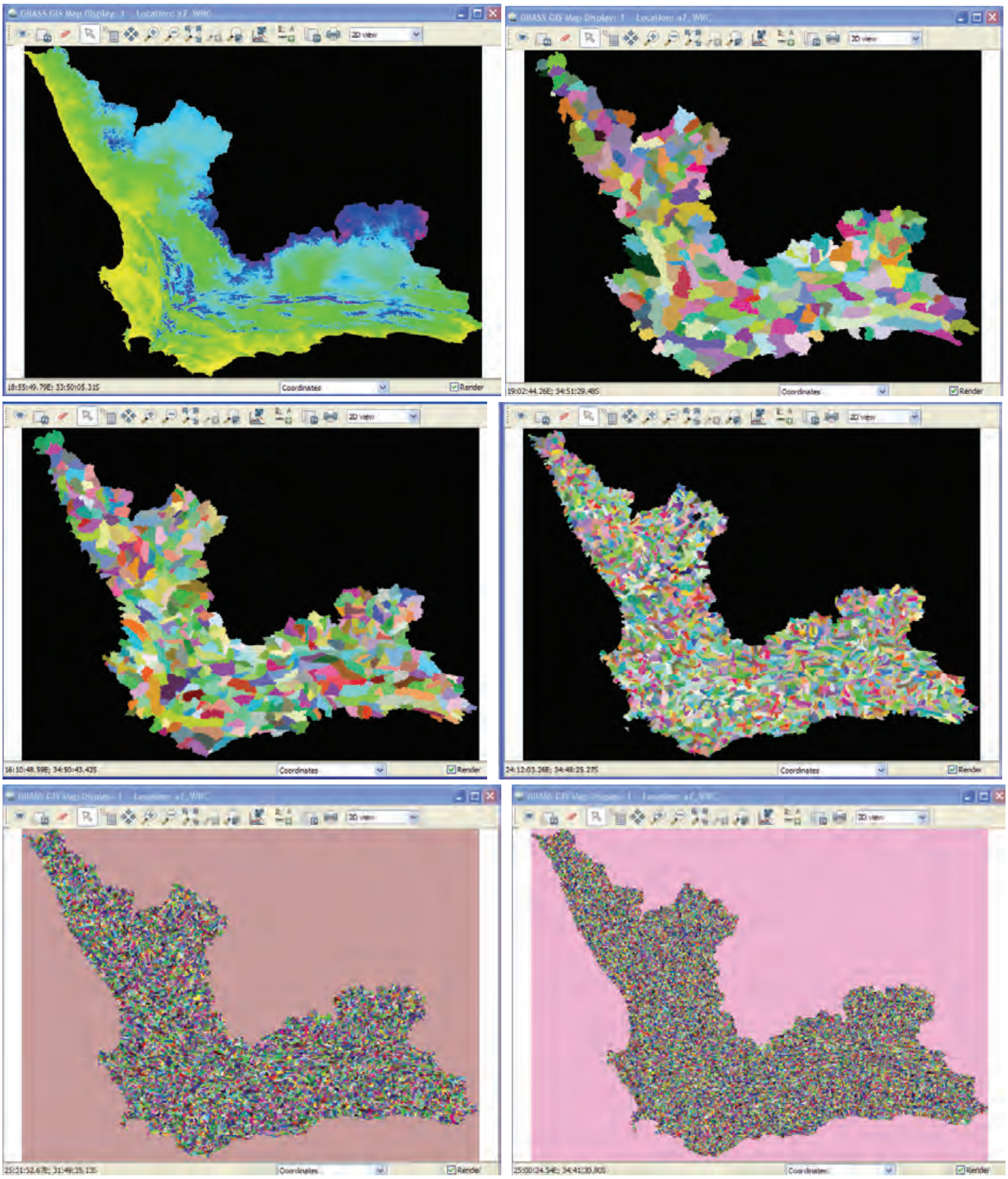

Figure 2.7: The various sub-catchments for the Western Cape generated using variable exterior basin watershed thresholds. The top left figure shows the DEM, top right shows an exterior watershed of 50 000 cells, middle left of 25 000 cells, middle right of 5000 cells, bottom left of 1000 cells and bottom right of 500 cells.

2.1.3 Cleaning of initial river network quinary catchments in GIS

The individual raster watersheds generated in GRASS were exported as GeoTIFFS and converted to polygons with smoothing of the polygons taking place. Using the ELIMINATE command in ArcGIS, all polygons with an area of less than 1 km^2 were eliminated and joined to the adjacent catchment. Spatial joining of the sub-catchments to the river network and dissolving according to river reach proved unsuccessful in cleaning the river network layer. Instead, sub-catchments were manually merged around the 1:500 000 river reaches, and polygons were split, based on catchments generated by the exterior basin threshold of 1 000 and 5 000. For the interior of the country, where large catchments have to be generated in order to contain a single river reach, catchments were split and merged using the 25 000 exterior basin threshold as the base GIS layer.

2.2 Quantifying the hydrological rivers, variables and parameters for the river network quinary catchments

2.2.1 Introduction

The daily hydrological information is intended for hydrological modelling, with the hydrological information given being daily climatic data in addition to soils and land cover information per river network quinary. The hydrological information described in this section has been summarised from Chapter 7 “Methods 2: Development of the Southern African Quinary Catchments Database”, WRC Report No. 1562/1/10 (Schulze *et al*., 2010b). The authors of that report are duly acknowledged. Furthermore, the hydrological information of that WRC Report had been disaggregated for application with altitudinal quinary catchments, and this disaggregated data/information will now form the basis to derive hydrological information for the river network quinary catchments.

Since their inception the DWA quaternary catchments (QCs) have been the standard assessment basis for much hydrological research, particularly through the advent of mainstream GIS and their release in 1994 as a major spatial component of *Surface Water Resources of South Africa 1990* (WR 90; Midgley *et al*., 1994). Many assessments of hydrological and agricultural responses over southern Africa have been made using the DWA quaternary catchments database, or QDB (e.g. Schulze and Perks, 2000; Gush *et al*., 2002; Schulze *et al*., 2005). This QDB has been described in detail by Schulze *et al*. (2008), and the daily time step conceptual-physical and multi-purpose *ACRU* model (Schulze, 1995 and updates) has been linked to it. The QDB had its origins in the late 1980s and since then it has been revised, reconstructed and expanded upon in a series of iterations (e.g. Dent *et al.*, 1989; Meier, 1997; Perks *et al*., 2000; Hallowes *et al*., 2004; Schulze *et al*., 2005).

2.2.2 Former levels of spatial dis-aggregation used in hydrological studies

For operational decision making, South Africa has been delineated into 22 primary catchments, each of which has been sub-divided into interlinked secondary, thereafter into tertiary and, at the fourth level, into hydrologically cascading quaternary catchments of which 1 946 make up the contiguous area of South Africa, Lesotho and Swaziland (**Figure 2.8**). When modelling hydrological responses, each QC had, until the advent of the altitudinal quinary catchments, been assigned a single set of catchment representative rainfall and reference potential evaporation time series values. In addition, a single set of soils attributes, usually area-averaged, had also been assigned for the entire quaternary catchments.

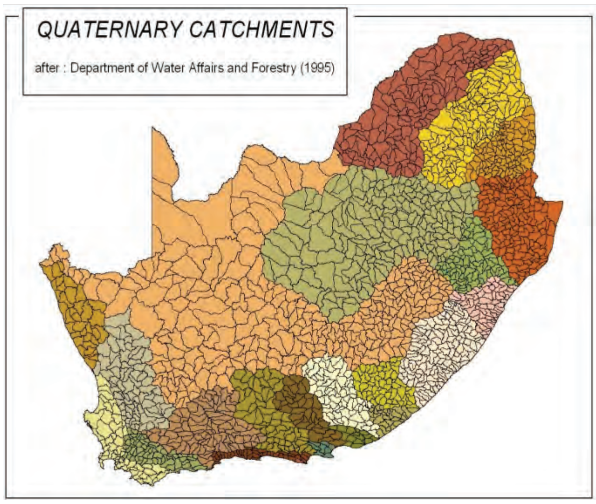

Figure 2.8: Primary and quaternary catchments covering South Africa, Lesotho and Swaziland (after DWAF, 1995).

2.2.3 The need for further spatial dis-aggregation of quaternary catchments for hydrological purposes

There exists within many of the quaternary catchments considerable physiographic heterogeneity. For example, statistical analysis has shown that intra-quaternary catchment variability of one arc minute (~1.7 x1.7 km) gridded altitude and rainfall values is high enough for approximately 1 000 of the 1 946 QCs to require subdivision into smaller, more homogeneous, response units on the grounds of natural hydrological variability alone (Schulze, 2004a). This is illustrated in Figure 2.9 in which differences in gridded altitude values between the 90th and 10th percentiles are shown for each quaternary catchment. Many of the quaternary catchments have altitudinal ranges within them in excess of 400 m which may need to be discretised further when based solely on the influence that altitude has on drivers of runoff such as rainfall, and on buffers to runoff such as soils properties and potential evaporation (Schulze, 2004a). A large percentage of the quaternary catchments with high variability occur in the high rainfall regions of the country which are then also the critical high runoff producing areas.

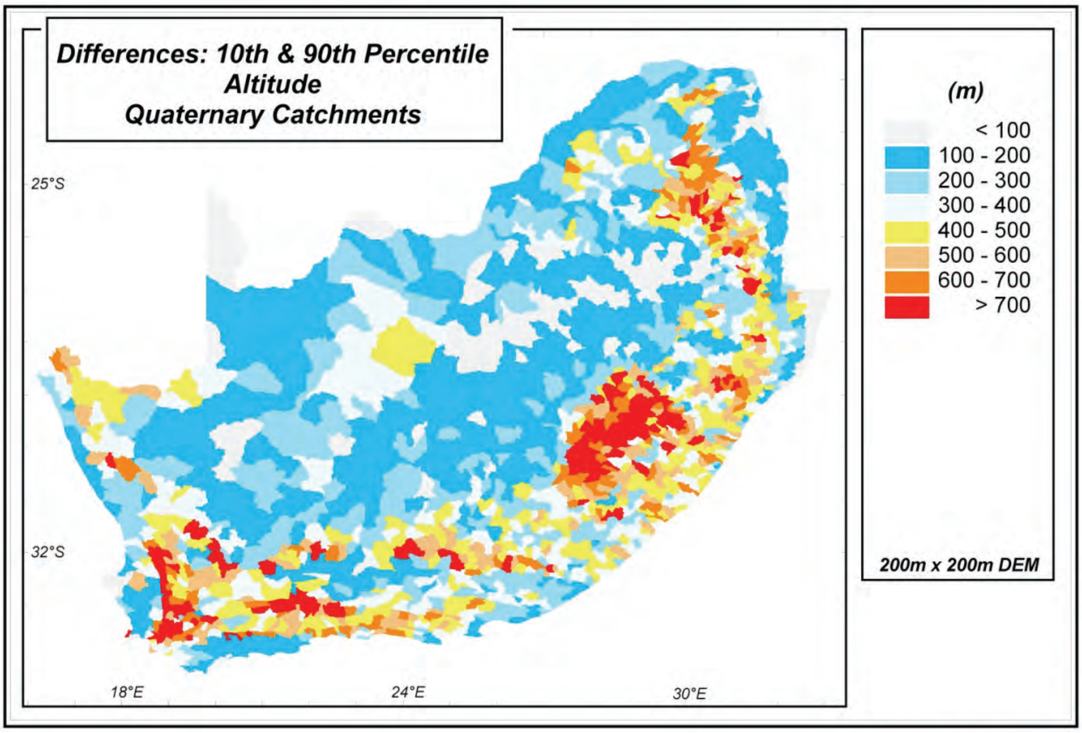

Figure 2.9: Differences in gridded altitude values for the 90th and 10th percentiles for each quaternary catchment (Schulze and Horan, 2010; based on Schulze, 2004a).

2.2.4 Delineating altitudinal quinary catchments

Numerous means of dis-aggregating fourth level quaternary catchments into hydrologically more homogeneous response areas were investigated in a now completed Water Research Commission project titled *Methodological Approaches to Assessing the Eco-Hydrological Responses to Climate Change in South Africa* (Schulze *et al.*, 2010a). None of the methods investigated was deemed suitable as a workable, automated and consistent methodology for southern Africa.

In order to achieve a consistent methodology of sub-delineating fourth level quaternary catchments into fifth level quinary catchments according to altitude criteria, each quaternary was therefore sub-divided consistently into three quinary catchments, i.e. an upper, middle and lower quinary, of unequal area but of similar topography and altitude. This was done using the Jenks' Optimisation procedures available within the ArcGIS software suite. The individually determined breaks between adjacent quinary catchments were then edge-matched to ensure a seamless coverage of quinary polygons. However, because the three quinary catchments within each quaternary catchment are delineated by natural altitude breaks, a specific quinary catchment may be made up of one or more discrete spatial units, i.e. polygons, as in the example of the upper quinary in Figure 2.10 (middle). These polygons are nevertheless conceptualised as ***one single spatial entity*** for purposes of hydrological simulations, with all runoff generated from those polygons flowing into the next downstream quinary catchment.

The individual polygons were then given a unique identity number, and the individual quinary catchments (sometimes incorporating more than one polygon) were given unique sub-catchment numbers and new alphanumeric identifiers based on the original DWA quaternary catchment number (Midgley *et al*., 1994). This system involved maintaining the original DWA number, e.g. V11A, and then adding a 1, 2, or 3 to the number to indicate upper (e.g. V11A1), middle (e.g. V11A2) or lower (e.g. V11A3) quinary catchment.

The concept is illustrated in Figure 2.10 for two quaternary catchments, with altitude shown in the left hand map, the three-fold delineation by natural breaks of altitude by Jenks' procedures in the middle map and the flowpaths of runoff from the upper to middle and middle to lower quinary catchment in the right hand map.

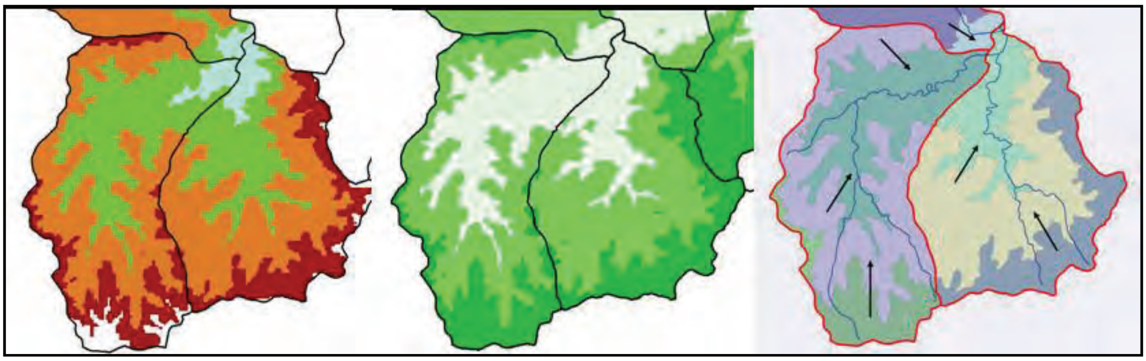

Figure 2.10: Sub-delineation of quaternary catchments from altitude (left) into three quinaries by natural breaks (middle) with flow paths of water (right) (Schulze *et al.*, 2010).

There are essentially two types of quaternary catchments, *viz*. "external" quaternary catchments that have no inflows from other catchments, and "internal" quaternary catchments which are fed by one or more upstream quaternaries. Irrespective of whether a quaternary catchment is internal or external, the outflow of the lower quinary catchment of a quaternary catchment (e.g. V11C3), does ***not*** enter the upper quinary catchment of the next downstream quaternary catchment (e.g.V11D1), because that upper quinary catchment (V11D1) may be at a higher altitude than the lower quinary catchment (V11C3) of the upstream quaternary catchment. Therefore, the outflow of the lower quinary catchment (V11C3) has been configured to rather enter the downstream quaternary catchment at its exit. A schematic of the flow path configuration between quinary catchments and quaternary catchments, taken from the Upper Thukela Catchment, is given in Figure 2.11. The integrity of the flow paths between one quaternary and its downstream neighbour is not affected.

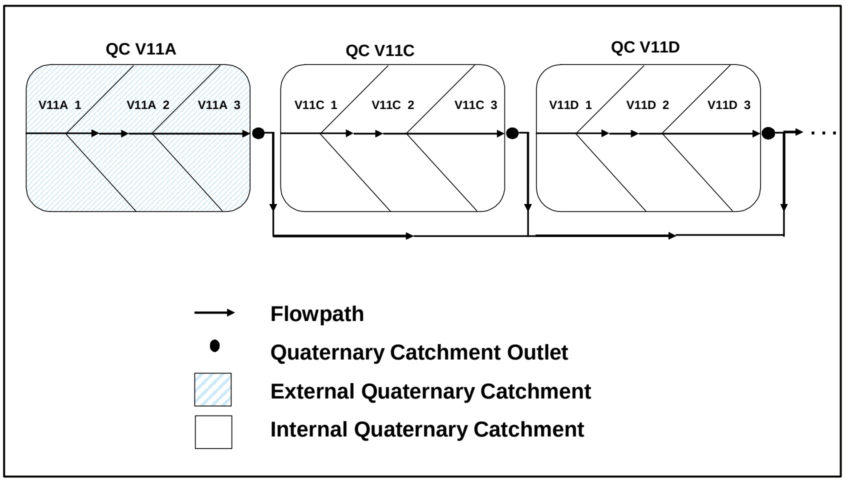

Figure 2.11: Example of flowpaths between quinary and quaternary catchments in the Upper Thukela Catchment (Schulze and Horan, 2007).

2.2.5 Results of sub-delineation to altitudinal quinary catchments

The sub-delineation of quaternary into altitudinal quinary Catchments had four hydrologically relevant and critical outcomes:

- South Africa, Lesotho and Swaziland were delineated into 5 838 hydrologically interlinked and cascading quinary catchments (Figure 2.12). The established quinary catchments cascade from the exterior sub-catchments, via the flow network, through interior sub-catchments with water eventually flowing out to sea, or into neighbouring countries (such as Mozambique), or into international border rivers (such as the Limpopo or the Orange). The interconnections between the sub-catchments allowed for more detailed hydrological modelling to be undertaken.
- Quinary catchments were shown, by statistical comparison, to be considerably more homogeneous than their parent quaternary catchments with respect to their altitudinal range. This is illustrated clearly when comparing the much lower altitudinal ranges of the quinary catchments shown in Figure 2.13 with the much higher ones of the quaternary catchments in Figure 2.9.
- The differences between hydrologically relevant attributes of the three quinary catchments within a quaternary catchment can be highly significant, especially in higher altitude runoff-producing quaternary catchments. This is illustrated in Table 2.2 in which differences in mean annual precipitation (to which runoff responds curvilinearly), slope (a variable in peak discharge estimation), reference potential evaporation (a determinant of soil moisture) and soil profile thickness (which is a control variable of recharge to groundwater and runoff generation) are markedly different between the three quinary catchments making up a quaternary, and would therefore yield markedly different hydrological responses than the parent quaternary catchment from which they were originally derived.
- Quinary catchments are better indicators of changes in vegetation, or potential growing areas on perturbed landscapes than the parent quaternary catchment. The reason for this is that altitude is often a determinant of vegetation types and a driver of change from one vegetation type to another (Acocks, 1988). Natural land cover and human induced land uses within an altitudinal quinary catchment therefore tend to be more homogeneous than within the attitudinally heterogeneous parent quaternary catchment. In the Thukela study, (Schulze and Horan, 2007) much of

the degraded land areas were found to be situated in the lower altitude quinary catchment, whereas pristine grassland dominated in the other upper and middle quinary catchments.

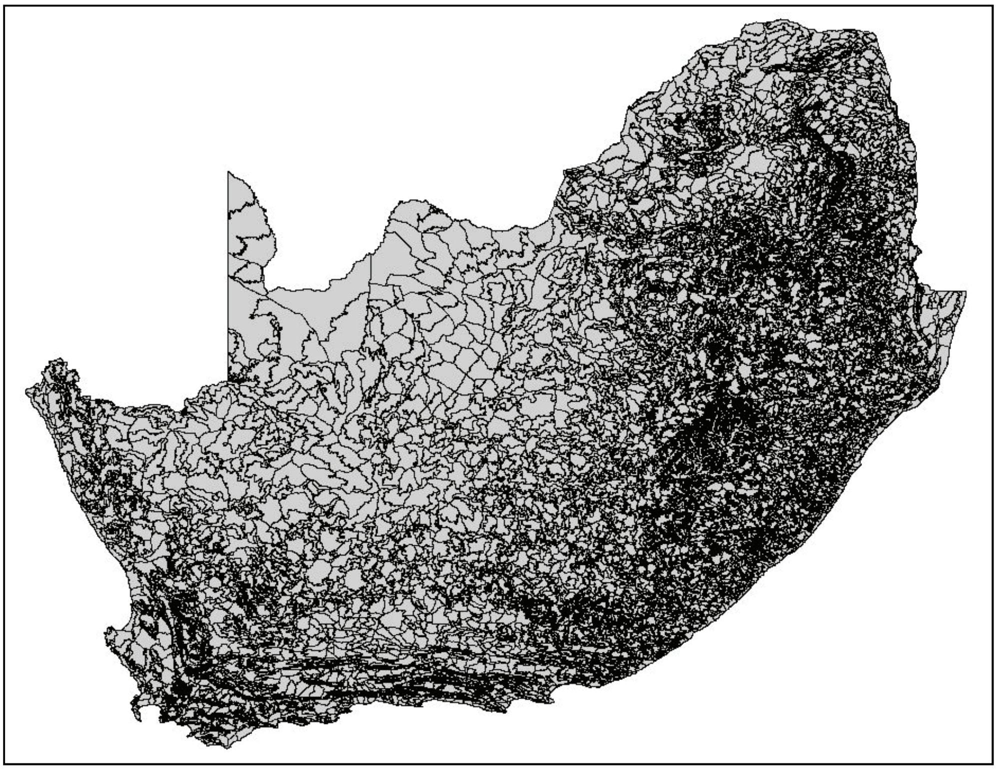

Figure 2.12: Generated altitudinal quinary catchments (Schulze and Horan, 2010).

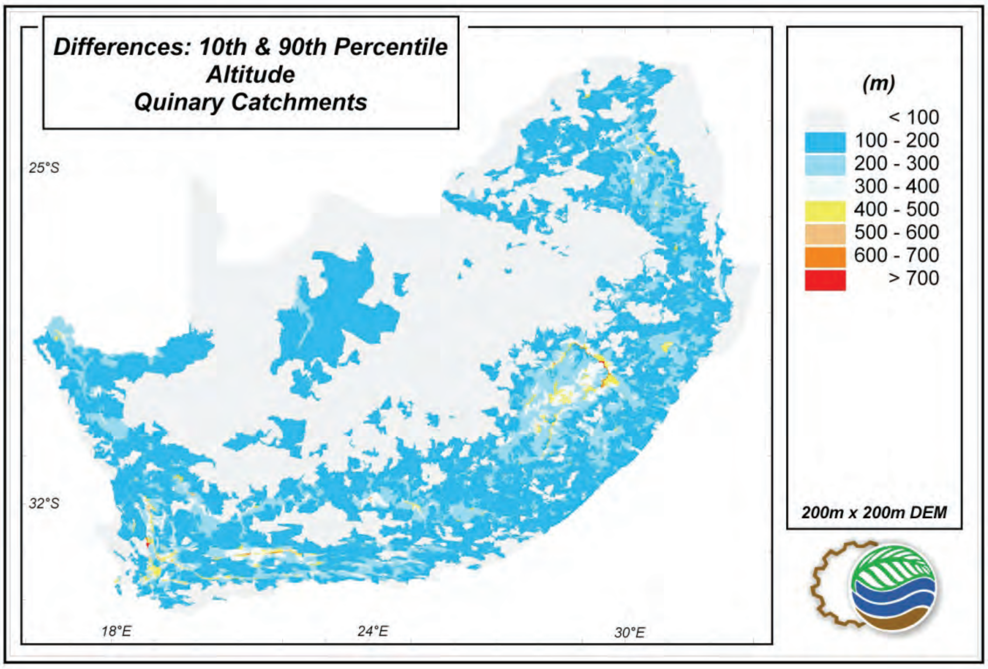

Figure 2.13: Differences between the 10th and 90th percentile values of one arc minute gridded altitudes per quinary catchment (Schulze and Horan, 2010).

Table 2.2: Differences between upper, middle and lower quinary catchment characteristics within nine quaternary catchments in the Upper Thukela area, KwaZulu-Natal (Schulze and Horan, 2007).

Quaternary Catchment	Quinary Number	Flows Into	Area (km^2)	MAP (mm)	Altitude (m)	Slope (%)	T_{max} (Jan)	T_{min} (Jul)	A-pan (Jan)	Soil Thickness (m)
V11A	1	2	20.47	1290	2790	37.9	17.7	-0.7	124	.40
	2	3	73.44	1156	2009	28.2	23.2	1.2	176	.53
	3	9	113.09	1006	1508	15.8	26.3	0.8	208	.69
V11B	4	5	49.51	1484	2724	49.0	14.6	-3.9	109	.37
	5	6	91.59	1430	2058	31.6	21.9	0.7	160	.62
	6	15	119.91	1125	1625	21.1	25.1	1.2	188	.66
V11C	7	8	38.06	980	1767	24.8	24.5	1.3	188	.48
	8	9	21.45	1026	1504	17.4	25.6	1.6	197	.61
	9	12	126.25	905	1294	6.6	27.8	0.5	223	.83
V11D	10	11	7.14	1020	1600	22.5	25.0	3.5	194	.57
	11	12	25.83	998	1396	17.3	26.6	2.3	205	.71
	12	27	190.32	816	1243	4.3	28.0	1.8	217	.77
V11E	13	14	52.55	1176	2019	18.5	22.5	1.8	168	.73
	14	15	37.12	1213	1580	22.4	25.8	1.5	195	.62
	15	27	77.61	1023	1286	10.2	27.3	1.6	209	.73
V11F	16	17	9.88	943	1533	15.9	25.4	1.6	198	.49
	17	18	52.94	795	1308	7.8	27.3	1.8	210	.73
	18	27	98.01	723	1200	2.9	28.1	2.1	217	.83
V11G	19	20	21.89	1668	2922	52.1	16.1	-2.6	115	.40
	20	21	169.30	1452	1998	26.3	22.0	0.5	160	.74
	21	24	90.87	1196	1558	21.5	25.0	1.3	185	.63
V11H	22	23	9.59	1288	1878	32.9	23.0	2.3	172	.59
	23	24	21.35	1216	1488	19.5	25.6	2.2	190	.69
	24	27	79.80	885	1281	9.1	27.3	1.9	205	.73
V11J	25	26	15.47	968	1461	15.9	26.5	2.3	201	.73
	26	27	18.33	877	1289	13.4	27.2	2.4	208	.65
	27	Exit	95.69	742	1174	3.8	28.2	2.1	216	.84

2.2.6 Developing an altitudinal quinary catchment database

The technical information which follows is extracted from Chapter 7 of the WRC Report No. 1562/1/10. The authors of that report, *viz*. RE Schulze, BC Hewitson, KR Barichievy, MA Tadross, RP Kunz, MJC Horan and TG Lumsden are duly acknowledged. The chapter authors of Chapter 7: "Methods 2: Development of a Southern African Quinary Catchments Database", *viz*. RE Schulze, MJC Horan, RP Kunz, TG Lumsden and DM Knoesen duly noted and acknowledged.

Following the delineation of South Africa, Lesotho and Swaziland into hydrologically interlinked quinary catchments, the previously developed quaternary catchment database (Schulze *et al*., 2005) was expanded to an altitudinal quinary catchments database. Much of the methodology utilised in the establishment of the quaternary catchment database was repeated to obtain the quinary catchment hydrological variables required for the majority of hydrological models. This included, but not exclusively, rainfall, potential evaporation, crop growth and transpiration parameters, soil attributes, stormflow response variables, and daily and monthly temperature information. All information generated was based on simulations **under baseline climatic conditions**.

2.2.7 Estimations of daily rainfall values

Lynch (2004) compiled a comprehensive database (1950 - 2000) of quality controlled (and infilled where necessary) rainfall data consisting of > 300 million rainfall values from 12 153 daily rainfall stations in southern Africa. From this database, a rainfall station had to be selected for each of the 5 838 quinary catchments, with that station's data considered representative of the daily rainfall of that quinary catchment.

This was achieved by assuming that the previously selected station representing the rainfall of the parent quaternary catchment in the quaternary catchment database would also represent the three quinary catchments within the parent quaternary catchment. The selection of the stations representing the quaternary catchments was described in Schulze *et al.* (2005) and involved first determining the centroid of each of the quaternary catchments. The Daily Rainfall Extraction Utility (Kunz, 2004) was then used to extract the 10 closest rainfall stations to each catchment's centroid. These ten stations were ranked by the Kunz (2004) utility using ten reliability criteria, with the best ranked station being subjected to further manual evaluation. In total, 1 244 stations were selected, with their associated daily rainfall values used to model the hydrology of the 1 946 quaternary catchments. Reliability tests (Warburton and Schulze, 2005) showed the average reliability of the rainfall stations selected to be 79.2 %, with the highest reliability of a chosen station being 100% and the lowest reliability of a chosen rainfall station being 23.9%. Nearly 50% of the selected rainfall stations had a reliability of 95% or higher (Warburton and Schulze, 2005), with poorest reliability found to be in Lesotho, the Western Cape fold mountains region and along the north-eastern border of South Africa with Mozambique. By implication, one rainfall station often was used to model the hydrology of more than one quaternary catchments.

In response to further research during the course of WRC project K5/1562 (Schulze *et al*., 2010b), the representative station for 11 quaternary catchments was changed in order to improve the representation of rainfall in those catchments. This resulted in the total number of representative stations reducing from 1 244 to 1 240. These 1 240 stations were then used to generate the daily rainfall of the 5 838 quinary catchments according to the assumption made above, *viz*. that the representative rainfall station for each quaternary catchment would also represent the rainfall of the associated three quinary catchments.

Multiplicative rainfall adjustment factors were then determined for each quinary catchment and applied to the daily records of the representative rainfall station in order to render the station's daily rainfall more representative to that of the quinary catchment. In this way a unique 50 year daily rainfall record was created for each of the 5 838 quinary catchments for application in hydrological simulation modelling. The adjustment factors were derived by first calculating the 12 spatial averages of all the one arc minute (~1.7 x 1.7 km) gridded median monthly rainfall values, as determined by Lynch (2004), within a quinary catchment. The ratio of these catchment average median monthly rainfalls to median monthly rainfalls of the representative rainfall stations was then calculated to arrive at 12 monthly adjustment factors.

2.2.8 Daily estimates of maximum and minimum temperatures

Daily maximum and minimum temperature values facilitate estimations to be made, implicitly or explicitly, of solar radiation, vapour pressure deficit and potential evaporation (Schulze, 2008), and with those variables plus rainfall as input into hydrological models such as *ACRU*, the generation of soil moisture content, runoff and/or irrigation demand becomes possible.

Procedures outlined in detail by Schulze and Maharaj (2004) enable the generation of a 50 year historical time series of *daily* maximum and minimum temperatures at any unmeasured location in South Africa, Lesotho and Swaziland at a spatial resolution of one arc minute of latitude/longitude (~1.7 x 1.7 km) for the 429 700 grid points covering the region. In summary, the underlying temperature database was made up of daily, quality controlled records from > 970 temperature "control" stations, extended to a common 50 year period, *viz*. 1950 - 1999 (Schulze and Maharaj, 2004). Infilling and/or extension of records to the common 50 year period at each of the control stations took account of independent month-by-month maximum and minimum temperature lapse rates (i.e. rates of change of temperature with altitude) from 12 lapse rate regions identified in southern Africa (Schulze, 1997), and from carefully chosen target stations at which similarities in the variability of daily temperature values with those from the control station was the key criterion. At each of the 429 700 grid points the maximum and minimum temperatures were computed for each day of the 50 year data period from two selected, independent (i.e. in different quadrants), temperature stations. The daily values from these two stations were then averaged in order to modulate any biases (e.g. from lapse rates or station data) emanating from either of the two stations' generated records.

Representative grid points from the study of Schulze and Maharaj (2004) were determined, to represent each of the 5 838 quinary catchments covering the study area. The selection of the representative grid points was achieved by first calculating the mean altitude of each quinary catchment from a 200 m DEM. Grid points with altitudes similar to those of the catchment means, and located as close as possible to the catchment centroids (grid points preferably within the catchment), were then selected to represent each of the quinary catchments.

In summary, the above determination of daily maximum and minimum temperatures for the quinary catchments was accomplished using a two-step approach. The first step was to generate a 50 year daily maximum and minimum temperature dataset at 429 700 raster points from > 970 control stations (with data quality checked and infilled). Secondly, individual grid points to represent each quinary catchment were selected. Based on the results of tests performed, the algorithm applied to select grid points in the second step incorporated an exponential decay in the influence of altitude with distance from the point of interest, rather than the linear decay employed when selecting target stations for infilling of missing values at the control stations (control stations were used in the first step when generating the temperature grid).

The resulting 50 year series of daily maximum and minimum temperatures for each quinary catchment was then also used in the generation of daily estimates of solar radiation and vapour pressure deficit. From these, daily values of reference potential evaporation and potential crop evapotranspiration were computed on a quinary catchment-by-catchment basis).

2.2.9 Daily estimates of solar radiation

Variations in the amount of solar radiation (R_s) in time and over space causes all atmospheric movement and change, and solar radiation is thus ultimately the generator of all weather and climate. Additionally, agricultural (i.e. higher order) plants utilise the visible portion of the solar radiation to produce carbohydrates (dry matter, or yield) out of water and CO_2 during the process of photosynthesis, and thus solar radiation is a major determinant of crop development and yields. It is therefore a major input variable in commonly used crop yield models such as CERES-Maize (Ritchie *et al*., 1998). Hydrologically, of the three factors determining the processes of evaporation and transpiration, *viz*. solar radiation, vapour pressure deficit and wind, solar radiation is under most conditions the dominant factor, frequently explaining up to 80% of the variation in potential evaporation. It is therefore the major input variable to physically-based methods for estimating potential evaporation, such as the Penman (1948) method and its variant, or the Penman-Monteith method (Monteith, 1981), which has internationally become the *de facto* standard technique for estimating crop potential evapotranspiration.

In the absence of an adequate network of solar radiation stations with long quality controlled records, as is the case over much of southern Africa, R_s may be estimated from daily maximum (T_{mxd}), and minimum (T_{mnd}), temperatures (Richardson and Reddy, 2004). Under clear sky conditions high solar radiation loadings reach the earth's surface, resulting in rapid *warming* of the surface/atmosphere (i.e. high T_{mxd}), but with clear sky conditions also allowing terrestrial infrared (longwave) radiation to escape into space at night, enabling rapid *cooling* of the surface/atmosphere (i.e. low T_{mnd}), which in turn results in a large temperature range, T_{ra} (i.e. T_{mxd} - T_{mnd}). Conversely, cloudy conditions and rainfall reduce day time surface solar radiation (because of a lower T_{mxd}), with the clouds also absorbing and re-radiating more terrestrial radiation at night, thereby moderating the cooling rate, resulting in a lower T_{ra} (i.e. T_{mxd} - T_{mnd}). Hence T_{mxd} and T_{mnd}, particularly also when expressed through T_{ra}, are highly suitable surrogate variables for use in estimating R_s.

Because it is fundamentally sound, the Bristow and Campbell (1984) equation was used as a point of departure to estimate solar radiation in southern Africa from temperature. This equation essentially describes solar radiation as an exponential asymptotic function of daily T_{ra} as follows:

$$R_s = aR_a\,[1 - exp\,(- bT_{ra}^{\;c})]$$

where

R_a	=	extraterrestrial radiation,
	=	f (the solar constant, the earth's radius vector, latitude and solar declination, i.e. an expression of time of year),
a	=	clear sky atmospheric transmissivity of R_a ,
	=	0.75 in the Bristow and Campbell equation, and which accounts for the depletion of R_a due to scattering by atmospheric aerosols and the pure atmosphere (Rayleigh extinction), as well as absorption by water vapour,

while

b, c	=	empirical constants governing the depletion of the solar beam due to cloudiness and rainfall, and for which daily T_{ra} is used as an estimator on the premise that cloudy/rainy conditions are associated with high atmospheric humidity and hence a low diurnal T_{ra} while under clear skies high temperature ranges prevail.

However, two modifications were made to the Bristow and Campbell equation by Schulze and Chapman (2008a) to improve estimates of R_a in southern Africa, the first being a modification of the clear sky transmission constant 0.75 by a water vapour related extinction function in the form of

$$1 - 1/T_{ra}^{a}$$

based on the premise that the higher the water vapour content (and by inference the lower the temperature range), the more the clear sky extinction would be. Clear sky solar radiation was thus expressed as

$$R_s = 0.75\ R_a\ [1 - 1/T_{ra}^{a}]$$

with the exponent 'a' optimised from > 8 000 clear sky solar radiation observations from four defined solar radiation zones across southern Africa (Schulze and Chapman, 2008a).

The second modification accounted for intra-annual and regional variations in the Bristow and Campbell (1984) extinction expression for cloudy and rainy days (i.e. $[1 - exp\ (- bT_{ra}^{c})]$) by optimising the empirical constants '*b*' and '*c*' using > 40 000 daily solar radiation observations from 24 southern African stations each with quality checked R_s data. A month-by-month modification of *b* and *c* for each of southern Africa's four solar radiation zones resulted in marked improvements in estimates of R_s on cloudy and rainy days (Schulze and Chapman, 2008a).

With a well verified temperature based method of estimating daily values of solar radiation, the 50 year daily maximum and minimum temperature series generated at each of 429 700 grid points over southern Africa could then be used to estimate 50 years of daily R_s values at each of those points. For baseline hydrological simulations with the Quinary Catchments Database (Schulze *et al*., 2010b) the same representative points that were selected for daily temperature estimates (Section 2.2.8) were used and the daily R_s values at those points were then input into the database.

2.2.10 Daily estimates of vapour pressure deficit

Daily values of vapour pressure deficit (*VPD*) are required when modelling potential evapotranspiration using the Penman-Monteith equation (Penman, 1948; Monteith, 1981). By definition,

$$VPD = e_a - e_d$$

where	e_d	=	actual vapour pressure (kPa),
and	e_a	=	saturated vapour pressure (kPa)
		=	0.6108 exp [17.27 T / (T + 237.3)] according to Tetens (1930), and
with	T	=	air temperature (°C).

In estimating daily values of *VPD* the actual VP, e_d, which has been shown to be a conservative climate element (Chapman, 2004) and which may be derived at any specified location in southern Africa from well verified monthly regression equations (Schulze and Chapman, 2008b) based on four spatial variables (*viz.* latitude, longitude, distance from the ocean, altitude) plus one temporal variable (daily temperature range), is held constant at that location for a given month. The fluctuating day-to-day daily temperature values at that location are then used with the Tetens (1930) formula given above to calculate a daily saturated VP, e_a. From e_d and e_a daily values of *VPD* can then be computed.

Using the above equations and approach, the 50 year daily maximum and minimum temperature series generated at each of 429 700 grid points over southern Africa could then be used to estimate 50 years' daily *VPD* at each of those points. For baseline hydrological simulations with the Quinary Catchments Database (Schulze *et al*., 2010b) the same representative points that were selected for daily temperature estimates were used and the daily *VPD* values at those points were then input into the database.

2.2.11 Daily estimates of reference potential evapotranspiration

The capacity of air to take up water vapour (with this capacity increasing with temperature and decreasing with humidity), the amount of energy available for the latent heat used in the process of evaporation (with the energy provided mainly by solar radiation) and the degree of turbulence in the lower atmosphere (related to wind) are the three factors which create an *atmospheric demand* and when this demand can be met fully, e.g. when soils are wet and vegetation covers the ground completely and is growing actively, *potential evapotranspiration* (E_p) occurs. There are many methods of estimating E_p, ranging from complex physically based equations to simple measurements and even simpler surrogates based on single variables such as temperature. These methods all yield different answers under different climatic conditions, and a *reference potential evaporation*, E_r (with its inherent advantages and defects), therefore has to be selected as that evaporation against which other methods must be adjusted appropriately. In simulating the hydrological landscape with a vegetative cover and/or under irrigation, the physically based FAO (1992) version of the Penman-Monteith equation (Penman, 1948; Monteith, 1981) has now become the *de facto* international standard of what is termed *reference crop evapotranspiration*, replacing the A-Pan and other techniques. It is defined as

> *"The rate of evapotranspiration from a hypothetical crop with an assumed crop height of 0.12 m, a fixed canopy resistance of 70 s.m^{-1} and albedo of 0.23, which would closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and not short of water" (p.12).*

The estimates of the Penman-Monteith equation as used in the Quinary Catchments Database (Schulze *et al*., 2010b) are based on

- daily maximum and minimum temperatures, and hence daily saturated vapour pressures, generated over southern Africa on a 1' x 1' (~ 1.7 x 1.7 km) raster for 50 years, based on research by Schulze and Maharaj (2004) which has been summarised in Section 2.2.8,
- month-by-month gridded values of vapour pressure deficit for southern Africa, summarised in Section 2.2.10, and
- daily gridded values of solar radiation determined for southern Africa by modifications to the Bristow and Campbell (1984), as described by Schulze and Chapman (2008a) and summarised in Section 2.2.9.

The original form of the Penman-Monteith equation (Monteith, 1981) may be written as

$$\lambda ET_o = \frac{\Delta(R_n - G) + \rho c_p (e_a - e_d) / r_a}{\Delta + \gamma(1 + r_c / r_a)}$$

where λET_o = latent heat influx of evaporation (kJ/m^2/s),
R_n = net radiation flux at surface (kJ/m^2/s),
G = soil heat flux (kJ/m^2/s),
ρ = atmospheric density (kg/m^3),
c_p = specific heat moist air (kJ/kg/°C),
$(e_a - e_d)$ = vapour pressure deficit (kPa),
r_c = crop canopy resistance (s/m),
r_a = aerodynamic resistance (s/m),
Δ = slope of the vapour pressure curve (kPa/°C),
γ = psychrometric constant (kPa/°C), and
λ = latent heat of vaporisation (MJ/kg).

Adapting the above equation to the given definition of reference crop evapotranspiration, and multiplying out constants according to derivations and formulae given in FAO (1992), the above equation may be simplified to the following formula:

$$E_{rpm} = \frac{0.408\Delta . R_n + Y \frac{900}{T_{xd} + 273} u_2 (e_a - e_d)}{\Delta + Y(1 + 0.34 u_2)}$$

where	E_{rpm}	=	reference crop evaporation (mm/day),
	R_n	=	net radiation at the crop surface (MJ/m^2/day),
	T_{xd}	=	average daily air temperature (°C) at screen height, and
	u_2	=	daily mean windspeed at 2 m height (m/s), defaulted (in the absence of measurements) to 1.6 m/s,

with the other variables defined as above.

What remains is for T_{xd}, Δ, γ, $R_{n,}$, e_d and e_a to be formulated. The formulations are a combination of the simplifications of FAO (1992) derived equations and empirical expressions developed specifically from southern African research. Thus,

T_{xd}	=	mean daily air temperature (°C)
	=	$(T_{mxd} + T_{mnd}) / 2$, with
T_{mxd}	=	daily maximum temperature (°C) (cf. Schulze and Maharaj, 2004; summary in Section 2.2.8)
T_{mnd}	=	daily minimum temperature (°C) (cf. Schulze and Maharaj, 2004; summary in Section 2.2.8),
e_a	=	saturated vapour pressure (kPa)
	=	$0.6108\ exp\{(17.27\ T_{xd})(T_{xd} + 237.3)\}$,
e_d	=	actual vapour pressure (kPa)
	=	empirically derived for South Africa on a month-by-month basis (cf. Schulze and Chapman, 2008b; with summary in Section 2.2.10),
Δ	=	delta, i.e. slope of vapour pressure curve (kPa/°C)
	=	$[4098\{0.6108\ exp((17.27\ T_{xd}) / T_{xd} + 237.2)\}] / (T_{xd} + 237.3)^2$,
γ	=	psychrometric “constant” (kPa / °C)
	=	$0.665 / (10^3\ P_a)$, with
P_a	=	atmospheric pressure (kPa), determined from altitude, *viz*.
	=	$101.3[(293 - 0.065z) / 293]^{5.26}$, with
z	=	altitude (m) above mean sea level,
R_n	=	$R_{sn} - R_{lw}$, with
R_{sn}	=	net shortwave (solar) radiation (MJ/m^2/day)
	=	(1 - 0.23) R_s, with albedo of short grass assumed to be 0.23, and
R_s	=	$0.75\ R_a(1 - 1/T_{ra}^{2.5})[1 - exp(- bT_{ra}^{c})]$, with
R_a	=	extraterrestrial solar radiation, from tables or standard formulations (cf. Schulze and Chapman, 2008a; summarized in Section 2.2.9),

Using the above equations, the 50 year daily maximum and minimum temperature series generated at each of 429 700 grid points over southern Africa could then be used to estimate 50 years of daily reference crop evapotranspiration by the Penman-Monteith technique at each of those points. For baseline hydrological simulations with the altitudinal Quinary Catchments Database (Schulze *et al*., 2010b) the same representative points that were selected for daily temperature estimates (Section 2.2.8) were used and the daily Penman-Monteith values at those points were then input into the database.

2.2.12 Hydrological soils attributes

Hydrological models require soils information as input. Being a threshold based model, *ACRU* (Schulze, 1995 and updates) needs input values on the following soils variables:

- thicknesses (m) of the topsoil and subsoil;
- soil water contents (m/m) at
  - saturation (porosity),
  - drained upper limit (also commonly referred to as field capacity), and
  - permanent wilting point (i.e. the lower limit of soil water availability to plants);
- rates of “saturated” drainage from topsoil horizon into the subsoil, and from the subsoil horizon into the intermediate groundwater zone, and the
- erodibility of the soil.

Values of these variables have been derived by Schulze and Horan (2008) using the AUTOSOILS decision support tool (Pike and Schulze, 1995 and updates) applied to the ISCW soils database (SIRI, 1987 and updates) for each of the soil mapping units, called Land Types, which cover South Africa, on the basis that the hydrological properties of all the soil series making up an individual Land Type were area-weighted. For each quinary catchment the values of the hydrological soils variables required by the *ACRU* model were derived from the Land Types identified in that quinary catchment, again on an area-proportioned basis.

2.2.13 Hydrological attributes of baseline land cover types

In any hydrological impact study, the hydrological attributes of baseline land cover types are required in order to simulate any changes in hydrological responses when the baseline land cover is converted to new land uses or new forms of land management. For South Africa, Lesotho and Swaziland the 70 Acocks Veld Types (Acocks, 1988) are a recognised baseline (i.e. reference) land cover for application in hydrological impact studies (cf. Schulze, 2004b; 2008).

Based on a set of working rules for determining the water use coefficient, interception per rainday, root distribution, a coefficient of infiltrability, an index of suppression of soil water evaporation by a litter/mulch layer and a soil loss related vegetal cover factor, month-by-month values of these attributes given in Schulze (2004b; 2008) were incorporated into the altitudinal Quinary Catchments Database for each of the 70 Acocks Veld Types covering southern Africa. For each of the 5 838 quinary catchments in the database the spatially most dominant Veld Type was then selected as the representative baseline land cover.

For studies on present-day or anticipated future hydrological responses which are impacted upon by anthropogenic changes in land use and management (e.g. afforestation, land degradation, urbanisation, enhanced tillage or tillage practices), hydrological attributes of such land uses need to be input into models such as *ACRU*. In addition to the 70 Acocks baseline land covers, month-by-month values of the water use coefficient, leaf area index (where available), interception per rainday, root distribution, a coefficient of infiltrability and a soil loss related vegetal cover factor, have been assigned to each category of the National Land Cover (2000), a 49-fold classification of land use, in a hydrologically consistent manner.

2.3 Developing a river network quinary catchment database

One of the aims of this project was to establish a database for the newly-developed river network quinary catchments similar to the altitudinal quinary catchments database. The methodologies for the spatial establishment of each data set have been described in this report Sections 2.3.2 to 2.3.3 and Sections 2.1.2 to 2.1.3 respectively. This section describes the method for deriving the river network quinary catchments database using the concepts and data established for the development of the altitudinal quinary catchments database.

2.3.1 Feasibility of assigning altitudinal quinary catchment data to river network quinary catchments using spatial overlap

The Reference Group of this project suggested an investigation into the assignment of the relevant hydrological and climatological information to the newly established river network quinary catchments. The proposed approach was to "marry" the existing altitudinal quinary catchment information (Schulze *et al*., 2010b) with the newly developed river network quinary catchments by spatial location. The assumption was made that if the majority of a new river network quinary catchment fell within an existing altitudinal quinary catchment, or if the centroid of the river network quinary catchment was proximal to the centroid of a specific altitudinal quinary catchment, then the values of the particular altitudinal quinary catchment could be assigned to the new river network quinary catchment. However, Figures 2.14 and 2.15 visually highlight the pitfall in this approach.

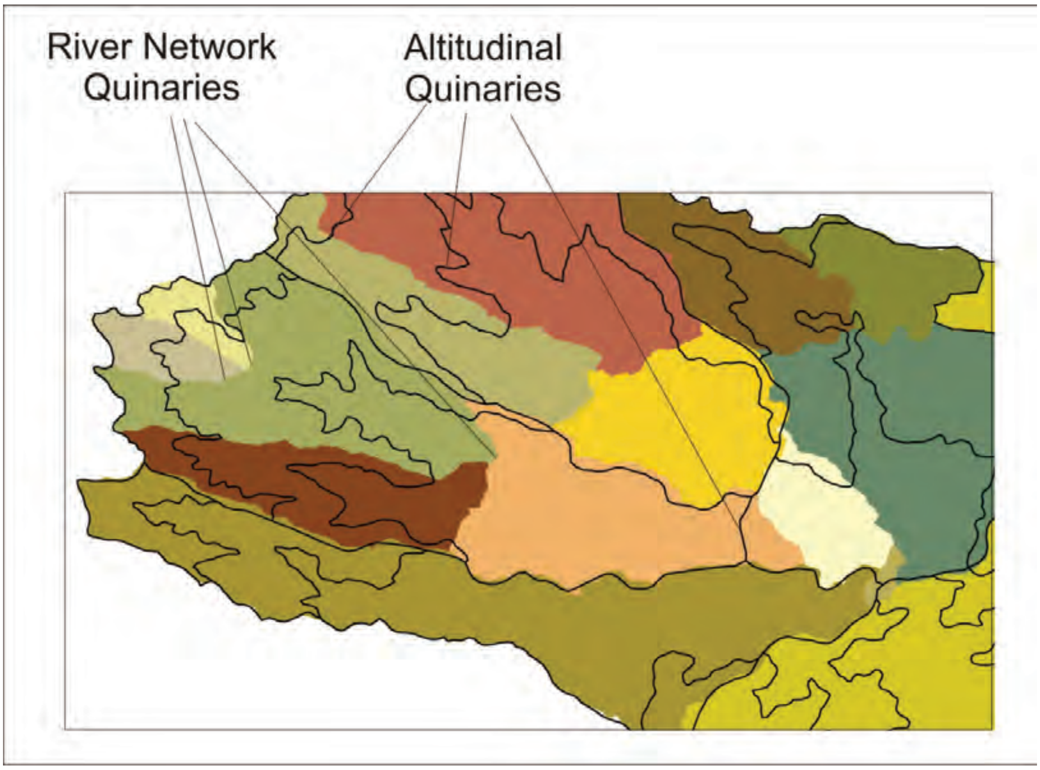

Figure 2.14: Comparison between the existing altitudinal quinary catchments (depicted by black lines) and the river network quinary catchments (depicted by the colour shading).

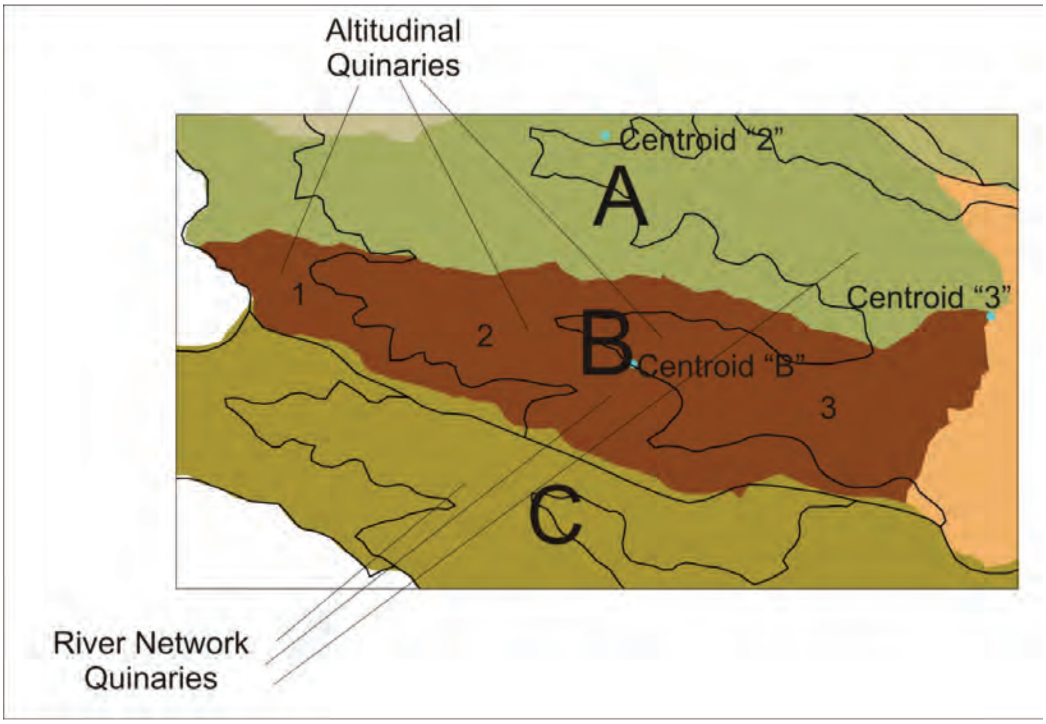

Figure 2.15: Close up comparison between the existing altitudinal quinary catchments shown in black lines and labelled numerically (1, 2 and 3) and the river network quinary catchments shown in coloured polygons and labelled alphabetically (A, B and C). The centroid for river network quinary catchment B is labelled (Centroid "B"), as are those for altitudinal quinary catchments 2 and 3 (Centroid "2" and "3").

Figure 2.14 is a reminder that river network quinary catchments tend to run parallel to hydrological flows, while altitudinal quinary catchments tend to run across the hydrological flows. This means that river network quinary catchments and altitudinal quinary catchments are generally spatially quite incongruent. Using the example in Figure 2.15, it becomes apparent that neither of the two nearest centroids in the altitudinal quinary catchments are close to, or representative of, the river network quinary catchment. Thus, assigning data to the river network quinary catchments using a nearest centroid approach is inappropriate. In addition, the areas of the altitudinal quinary catchments that overlap with a river network quinary catchments often extend well beyond those of the river network quinary catchment. Assigning data to the river network quinary catchments based on the use of the data associated with the altitudinal quinary catchment that makes up the majority of the area within the river network quinary catchment is also inappropriate because the area of this altitudinal quinary catchment can extend well beyond that of the river network quinary catchment and may thus not be representative.

The situation described in Figure 2.15 was similar to many other examples studied in primary catchment U, thus coming to the conclusion that assigning hydrological parameters and variables from the pre-existing altitudinal quinary catchments was not viable. The adjustments made in terms of rainfall, evaporation, temperature, solar radiation, as well as the zoning of soils and vegetation were found to be so highly dependent upon altitude (Sections 2.2.7. through 2.2.12), that it was considered scientifically unsound to attempt to allocate variables derived in this way, to a spatial unit determined using a different natural phenomenon.

2.3.2 Approach adopted for developing a river network quinary catchment database

In light of the preceding findings, the hydrological research team based at UKZN agreed, in consultation with the Reference Group of this project, to approach the allocation and assignment of the hydrological information to the new river network quinary catchments by returning to base information and excluding the information (but not the knowledge) obtained in the establishment of the altitudinal quinary catchments (Schulze *et al*., 2010b).

2.3.3 Daily estimates of rainfall

The rainfall driver station selected to represent the quaternary catchments, as described in detail in Schulze *et al.* (2005) and in Section 2.2.7 of this report, were retained as the representative rainfall station for this research. Any quinary catchment established from a parent quaternary was therefore assigned the parent quaternary catchment's rainfall station. Analysis of the applicability and reliability of the selected stations is detailed in Section 2.2.7 and in Warburton and Schulze (2005).

A process of perturbing the observed rainfall by multiplicative adjustment factors, which has been well documented (Schulze *et al*., 2005, Schulze *et al*., 2010b), was applied to the rainfall station records to account for the spatial variability of the rainfall within each river network quinary catchment and in doing so, to account for the point to area reduction factors. The adjustment factors were derived by first calculating the 12 spatial averages of all the one arc minute (~1.7 x 1.7 km) gridded median monthly rainfall values (determined by Lynch, 2004) within a river network quinary catchment. The ratio of these catchment average median monthly rainfalls to the representative station's median monthly rainfalls was then calculated to arrive at 12 monthly adjustment factors. These factors were then multiplied by the daily rainfall values of the driver station to adjust them to be more representative of the spatial unit of the river network quinary catchment.

2.3.4 Daily estimates of maximum and minimum temperature

The creation of new quinary catchment boundaries by assignment, based upon river networks as opposed to altitude, has caused not only the development of new boundaries, but also of new centroids. With the establishment of the river network quinary catchments, new mean altitudes for each quinary, as well as the location of the new centroids had to be determined. For each river network quinary catchment, a representative altitude was computed from a 90 m DEM and for this altitude the grid points of the same or very similar altitude were selected, preferably within the catchment. The point closest to the centroid of the river network quinary catchment was then selected from the subset of those with a similar altitude to that of the catchment. The 50 year series of daily maximum and minimum temperatures was generated for that latitude and longitude to best represent the daily temperatures of the river network quinary catchment.

The resulting 50 year series of daily maximum and minimum temperatures for each river network quinary catchment could then be used in the generation of daily estimates of solar radiation and vapour pressure deficit and from those, daily values of reference crop evapotranspiration could then be computed on a quinary catchment-by-catchment basis, as summarized below.

2.3.5 Daily estimates of solar radiation

The generation of the daily solar radiation values for all the 429 700 grid points covering Southern Africa has been documented in Section 2.2.9 of this report and in Schulze and Chapman (2008a). In order to determine the values of the hydrological information required, the same representative points that were selected for daily temperature estimates (Section 2.3.5) were used and the daily R_s values at those points were then input into the river network quinary catchment database.

2.3.6 Daily estimates of vapour pressure deficit

Daily values of vapour pressure deficit (*VPD*) are required when modelling potential evapotranspiration using the Penman-Monteith equation (Penman, 1948; Monteith, 1981). The detailed information as to the development of the 50 year daily data set for each of the 429 700 points of the vapour pressure deficit is contained in Section 2.2.10 and in Schulze and Chapman (2008b). To determine the hydrological variables for the river network quinary catchment database, the same representative points that were selected for daily temperature estimates (Section 2.3.5) were used and the daily *VPD* values at those points were then computed and input into the database.

2.3.7 Daily estimates of reference potential evapotranspiration

The estimates of the Penman-Monteith equation as used in the river network quinary catchments database are based on

- daily maximum and minimum temperatures, and hence daily saturated vapour pressures, generated over southern Africa on a 1' x 1' (~ 1.7 x 1.7 km) raster for 50 years, based on research by Schulze and Maharaj (2004) which has been summarised in Section 2.2.8,
- month-by-month gridded values of vapour pressure deficit for southern Africa, summarised in Section 2.2.10, and
- daily gridded values of solar radiation determined for southern Africa by modifications to the Bristow and Campbell (1984), as described by Schulze and Chapman (2008a) and summarised in Section 2.2.9.

Using the above drivers and the equations and methods detailed in Section 2.2.11, the 50 year daily maximum and minimum temperature series generated at each of 429 700 grid points over southern Africa could then be used to estimate 50 years' daily reference crop evapotranspiration by the Penman-Monteith technique at each of those points. For the river network quinary catchments database the same representative points that were selected for daily temperature estimates (Section 2.2.4) were used and the daily Penman-Monteith values at those points were then input into the database.

2.3.8 Hydrological soils attributes

The same method used to derive the hydrological soils attributes for the altitudinal quinary catchments (Section 2.2.12) was applied to river network quinary catchments. For each river network quinary catchment, the values of the hydrological soils variables required by the *ACRU* model were derived from the Land Types identified in that quinary catchment, on an area-proportioned basis.

2.3.9 Hydrological attributes of baseline land cover types

The same method used to derive the hydrological attributes of baseline land cover types for the altitudinal quinary catchments (Section 2.2.12) was applied to river network quinary catchments. For each of the river network quinary catchments in the database the spatially most dominant Acocks Veld Type was then selected as the representative baseline land cover, and the values of water use coefficient, interception per rainday, root distribution, a coefficient of infiltrability, an index of suppression of soil water evaporation by a litter/mulch layer and a soil loss related vegetal cover factor, relating to that Veld Type were input as the relevant attributes.

CHAPTER 3: RESULTS AND DISCUSSION

3.1 Description of quinary catchment GIS layer

One of the major constraints in generating a river network quinary layer is the rule that the catchments need to be generated around the 1:500 000 river reach. The 1:500 000 river network `is not a homogenised spatial layer. It was originally generated for purposes of cartography and as a result there are complications in using it to generate river network catchments around the river reach. Despite the 1:500 000 rivers being burned into the DEM, the catchments derived always required significant manual cleaning. In some cases where the pour points obtained from DWA were manually moved, the generated catchments from GRASS aligned very poorly with the borders of the updated quaternary catchments.

Three primary catchments were selected in order to describe the quinary river network catchment. The first catchment is situated in KwaZulu-Natal. The catchment is made up of the uMvoti, uMngeni and uMkomazi river systems and contains the towns of Durban and Pietermaritzburg.

3.1.1 Primary catchment U: uMvoti to uMkomazi

Primary catchment U is situated in KwaZulu-Natal. The catchment is made up of the uMvoti, uMngeni and uMkomazi river systems and contains the towns of Durban and Pietermaritzburg. The U catchment is made up of 62 quaternary catchments. The total area for the catchment is 18 285 km^2. The minimum area for a quaternary catchment is 60 km^2, the maximum area is 680 km^2 and the mean area is 295 km^2. The catchment contains a total of 176 river network quinary catchments. The smallest quinary has an area of less than 1 km^2 and the largest has an area of 405 km^2. The mean area for the river network quinary catchments is 104 km^2. The minimum number of river network quinary catchments nested in a quaternary is one, i.e. where the entire river reach of the 1:500 000 river network remains unchanged through the length of the quaternary catchment. The greatest number of river network quinary catchments nested in a single quaternary catchment is nine. This is in catchment U10J, where the areas of the river network quinary catchments range from <1 km^2 for a short mainstem river between two confluences, to a maximum of 194 km^2. The average and the median number of river network quinary catchments nested within a quaternary catchment are three.

The NFEPA sub-quaternary catchments (Nel *et al.*, 2011) total 196 for the same primary catchment, with a mean area of 98 km^2. The reason that NFEPA has a higher number of sub-quaternary catchments is that the 1:500 000 rivers network GIS layer downloaded off the DWA website was used in the cleaning of the NFEPA sub-quaternary catchment GIS layer. The 1:500 000 rivers have since been updated for this area. This can be seen in the south of primary catchment in Figure 3.1 where more than one river segment is found along the coast within the originally delineated river network quinary catchments. The rivers were added because of the estuaries located at the river mouths. These changes have since been included into the 1:500 000 river network.

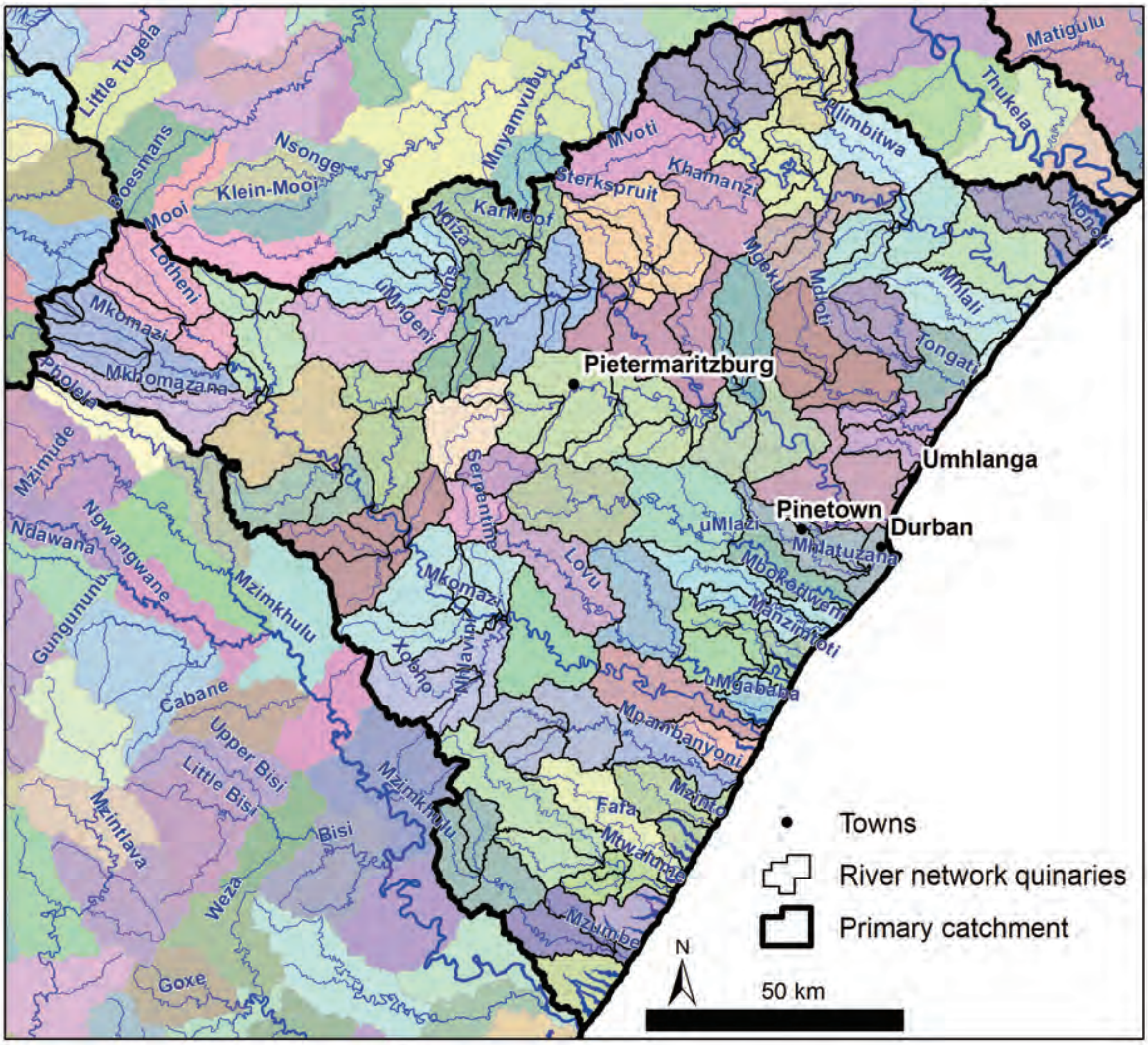

Figure 3.1: Primary catchment U and the river network quinary catchments delineated (after cleaning) in thin black lines, while the coloured polygons represent the updated quaternary catchments.

3.1.2 Primary catchment J: Gouritz

The second primary catchment analysed is the J Catchment, i.e. the Gouritz Water Management Area (Figure 3.2). The Gouritz WMA comprises the Karoo in the north and the Klein Karoo in the middle of the catchment. The Karoo and the Klein Karoo are separated by the Swartberg Mountains. The Langeberg Mountain is the southernmost limit of the Klein Karoo through which the Gouritz River drains, as shown in Figure 3.2**.**

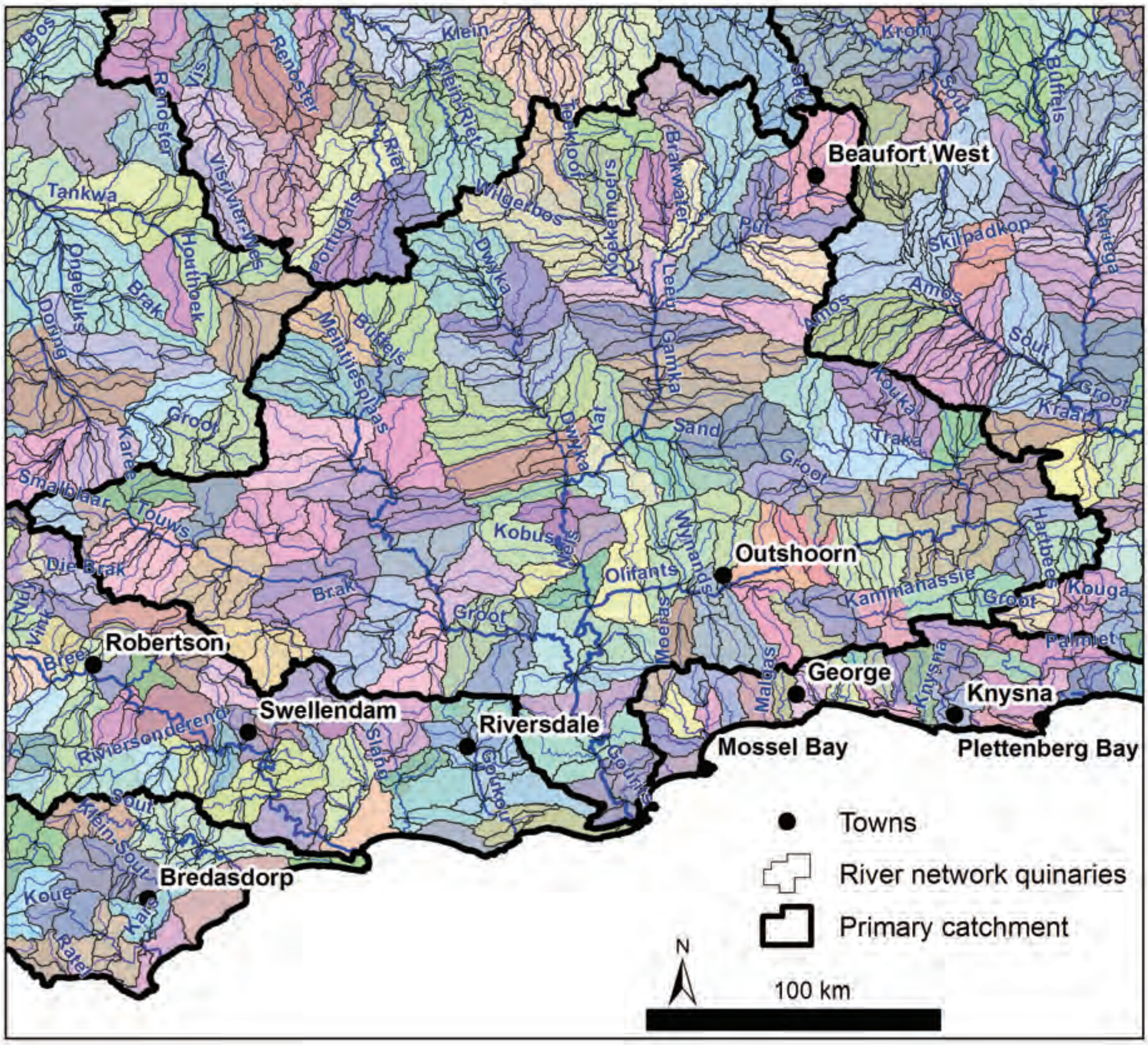

Figure 3.2: Primary Catchment J, the Gouritz Water Management Area, and the river network quinary catchments delineated (after cleaning) in the thin black lines while the coloured polygons represent the updated quaternary catchments.

Primary catchment J contains 92 updated quaternary catchments with a mean quaternary catchment area of 490 km^2. The smallest quaternary catchment is 171 km^2 and the largest quaternary catchment is 1 188 km^2. The total size of the primary catchment is 45 101 km^2. After the river network quinary catchments were cleaned in ArcMAP, a total of 444 river network quinary catchments were delineated for the Gouritz primary catchment. The smallest river network quinary has an area of less than 1 km^2 and the largest river network quinary has an area of 523 km^2. The mean area of the river network quinary catchments for primary catchment J is 100 km^2. A total of 453 NFEPA sub-catchments were delineated for primary catchment J with a mean area of 100 km^2 and a maximum area of 421 km^2. The maximum number of river network quinary catchments nested within a quaternary catchment is 15 quinary catchments. The median number of river network quinary catchments nested within a quaternary catchment is 4 and the average number of nested river network quinary catchments is 5. There is a very good correspondence between the catchments delineated from the SRTM DEM and the DEM used for the NFEPA project.

3.1.3 Primary catchment E: Olifants-Doring

Primary catchment E, the Olifants-Doring catchment in the Western Cape, has a total of 75 quaternary catchments with a mean quaternary area of 652 km^2. The total area of the catchment is 48 891 km^2, with a minimum quaternary catchment area of 123 km^2 and a maximum area of 2 761 km^2. The total number of river network quinary catchments delineated and cleaned for primary catchment E is 455 with a mean area of 107 km^2. The minimum area of a river network quinary is less than 1 km^2, and the maximum area is 1 168 km^2.

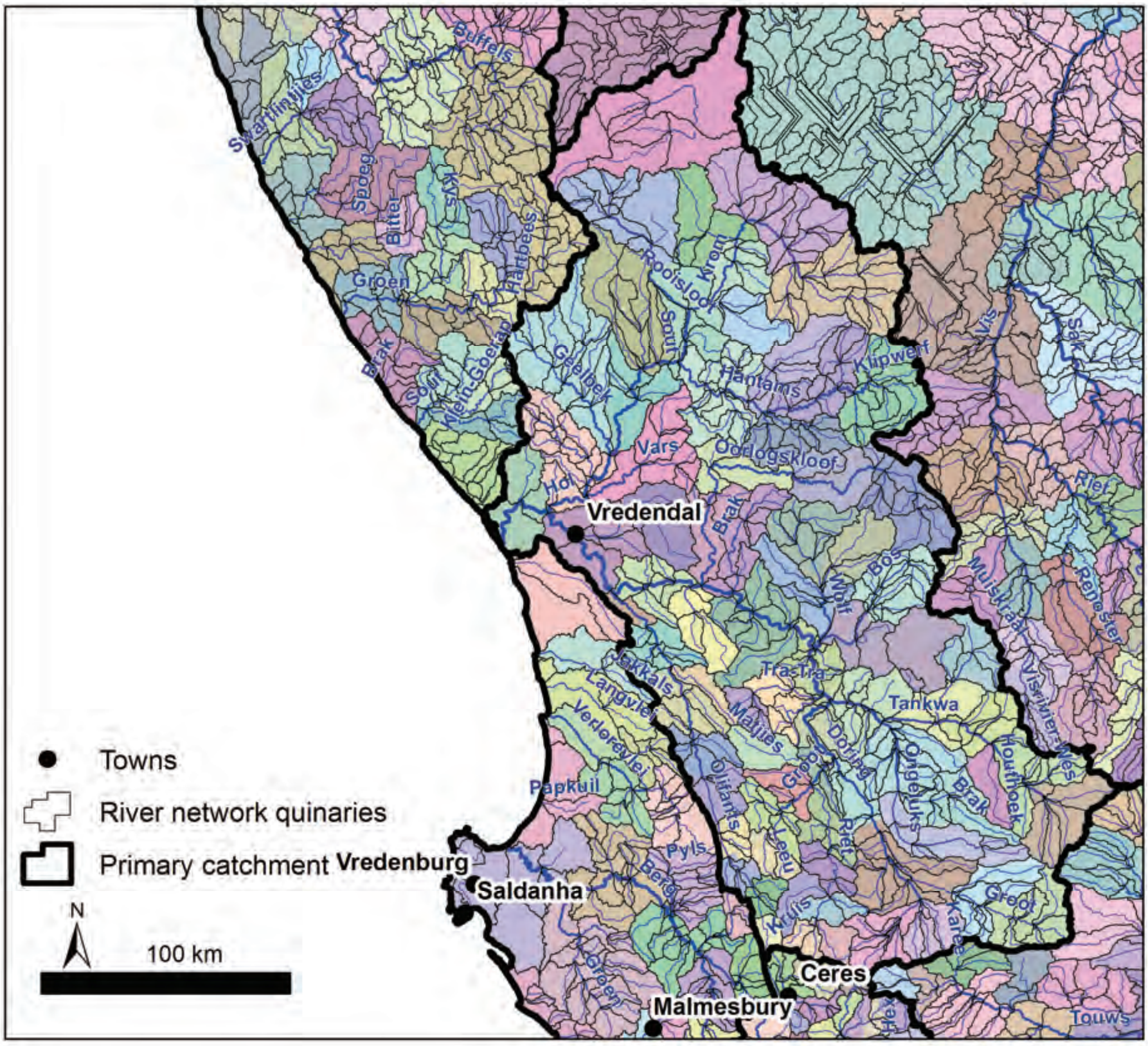

Figure 3.3: Primary Catchment E, the Olifants-Doring Catchment in the Western Cape, and the river network quinary catchments delineated (after cleaning) in the thin black lines while the coloured polygons represent updated quaternary catchments.

A total of 467 NFEPA sub-quaternary catchments were delineated for the NFEPA project with a mean area of 105 km^2 and a maximum area of 1 553 km^2. There are a maximum of 16 river network quinary catchments nested within a quaternary catchment. For primary catchment E there are a median of 5 and an average of 6 nested river network quinary catchments per quaternary catchment. In general, this catchment has more river reaches per quaternary catchment than primary catchments U and J and as a result there are a greater number of river network quinary catchments per quaternary catchment.

The summary statistics for primary catchments U, J and E are shown in Table 3.1. The total areas of the primary catchments are given as well as the statistics for the quaternary and river network quinary catchments. The average number of river network quinary catchments per quaternary catchments varies across the country because of number of river reaches of the 1:500 000 river network per quaternary catchment varies.

Table 2.1: Summary statistics of quaternary and river network quinary catchments for Primary Catchments U, J and E.

	Catchment U	Catchment J	Catchment E
Total Area	18 285 km^2	45 101 km^2	48 891 km^2
Number of quaternary catchments	62	92	75
Average size of quaternary catchment	295 km^2	490 km^2	652 km^2
Number of river network quinary catchments	176	444	455
Average size of river network quinary	104 km^2	102 km^2	107 km^2
Average number of river network quinary catchments per quaternary catchment	3	5	6

3.2 Importance of Daily Rainfall in Modelling

For operational modelling of many elements of Integrated Water Resource Management, simulations should be undertaken at daily time steps. The day, and diurnality, is a *universal natural time step* (which neither the second, minute, hour, week or month are). The next natural time step up would be the season, and that displays no universality as the difference between seasons varies across the world (Schulze, 2004a). Diurnality encapsulates, albeit not perfectly, many hydrologically related processes (e.g. evaporation, transpiration and many discrete rainfall events; Schulze, 2004a). Furthermore, many operational decisions are made according to daily conditions (e.g. irrigation, tillage, reservoir operations).

There are, however, two other major reasons for promoting daily time step modelling. The first is the availability of data:

- South Africa, for example, has daily rainfall records of over 20 years' duration for nearly 4 000, and for over 40 years' duration for over 1800 stations, while for the same durations autographically recorded data for time steps < 1 day are available for only 97 and 8 stations respectively (Smithers and Schulze, 2000a; 2000b).

- Similarly, daily values of maximum and minimum temperatures in South Africa are available for over 1300 stations and for pan evaporation from over 600 stations.
- The station networks with daily data are, thus, relatively dense (although not in all hydrologically critical areas) and have records of relatively long duration.
- Furthermore, for climate change studies downscaled daily climate values are now available for present (1971-90) and CO_2 enhanced (2046-65; 2081-2100) scenarios from a wide range of GCMs.

Secondly, daily time step models provide a vast array of potential and realistic and, in the context of the National Water Act and IWRM, highly relevant output which (say) monthly models do not (Schulze, 2004a), e.g. on

- modes of irrigation scheduling
- peak discharge
- event based sediment yields
- phosphorus/nitrate yields
- near real-time catchment states
- impacts of land management
- climate change impacts with CO_2 transpiration feedbacks
- reservoir operations
- instream flow requirements
- wetlands functions
- flow routing through channels / reservoirs
- reservoir status
- crop yields (dryland and irrigated) or
- explicit generation of stormflow, interflow and baseflow.

There are, nevertheless, limitations to modelling at a daily time step. These include

- problems of missing data (Smithers and Schulze, 2000a);
- daily raingauges being read at 08:00 when discrete rainfall events may span more than one day or cross the 08:00 observational time and then be modelled as more than one event;
- the rainday spanning 08:00 to 08:00 while daily streamflow records are given from midnight to midnight (However, techniques are available to shift rainfall and streamflow into phase with one another; Smithers and Schulze, 1995);
- large areas having no rainfall stations; or
- rainfall intensities not being accounted for explicitly.

In regard to the lack of intrinsic ‘knowledge’ on rainfall intensity from daily values at individual points there are, nevertheless, seasonal and individual event indicators which can be used in daily models to account, in some measure, for intensity. The advent of quality controlled daily integrated radar and satellite derived rainfall values is likely to improve distributed hydrological modelling in South Africa, with major benefits to many facets of IWRM.

CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

Huge progress has been made in developing skills to automate the delineation of nested sub-catchment boundaries for South Africa, stemming from: (i) the release of the updated quaternary catchments GIS layer and associated ancillary GIS layers, such as hydrologically corrected DEMs, flow direction paths and catchment pour points (Weepener *et al*., in press), and (ii) the piloting of different software packages (e.g. GRASS, ArcGIS) and rules for sub-catchment delineation within this project. In addition, the project team has harnessed much knowledge that has been developed over the years through related WRC projects on how to scientifically develop estimates of daily hydrological, daily climatic and land cover data and summarize these into different sub-catchment boundaries (Schulze and Horan, 2010).

The river network quinary catchments delineated in this project are defined as nested hydrological catchments around the river reach of the 1:500 000 DWA river network and major dams. Because the 1:500 000 river network is a cartographic product and is not at the same resolution throughout the country, the delineation and GIS cleaning of the river network quinary catchments layer has proved to be problematic and time consuming. While much attention was given to the manual GIS cleaning of coastal primary catchments, further work is needed on improving the river network quinary catchments located in the primary catchments in the interior of the country (i.e. the primary catchments that do not drain into the sea). The interior catchments were delineated using an exterior basin threshold of 5 000 cells, giving rise to many quinary catchments that do not contain 1:500 000 river reaches. A consensus must be reached among DWA water resource planners and decision-makers whether it is useful to retain these quinary catchments or to merge them. In addition, a naming convention for the different quinary catchments should be developed, so that data can be gathered by researchers in a consistent manner, and joined to the attribute database using a standard and unique quinary catchment identifier.

This project was begun with the idea of serving two separate quinary GIS layers to DWA: an altitudinal quinary catchment GIS layer, and a river network quinary catchment GIS layer. During the course of this project, the project team came to the recommendation that, while these two layers are informative in their separate formats, their potential application would be improved for detailed hydrological modelling purposes if a sub-catchment delineation which contains a combination of the two concepts were developed (i.e. river network quinary catchments sub-delineated according to altitude). This is a strong recommendation in moving forward with developing a final DWA endorsed suite of nested sub-catchments.

The river network quinary catchments reported on in this document should therefore be viewed as an intermediate product which can be taken to DWA in order to engage with the hydrologists and relevant parties, so that a DWA endorsed layer of river network and altitudinal quinary catchments can be finalised. This should be seen as an important next phase of this project.

4.2 Recommendations

In a scientifically defensible way, the next step is to merge the concepts of nested hierarchal river network quinaries and altitudinal quinaries to create a finer scale catchment which more accurately reflects the topographic, rainfall and land use, as well as resultant runoff changes, within a quaternary catchment. Changes in land use usually occur where there is a change in rainfall, and the latter often represents an amplification of 2-6 times in South Africa when any change in rainfall is converted to a change in the stream flow (e.g. Schulze, 2008). The resultant land use change also impacts the river condition, where rivers often start to become modified from their relatively natural state as a result of the land use changing from natural vegetation to human use landscapes that support activities such as agriculture, forestry, and urban and rural settlements. A key recommendation is that up until the quinary level the nested hierarchical catchments are watershed delineated such that flow path integrity is preserved, but that at the sixth catchment level, altitudinal response zones are used to sub-delineate the fifth level so that sixth level catchments reflect relatively homogenous response zones, based on land use, elevation and rainfall changes, and hence stream flow changes.

The concepts of the methods developed for altitudinal and river network quinary catchments need to be used as a key point of departure for a follow-on project to produce a merged layer of relatively homogenous response zones (in terms of hydrology, soils and land use). Altitudinal and river network quinary catchments, as they currently stand, have a few limitations. For example, altitudinal quinaries, which have more than one pour point as an exit, can be further revised to take into account the extent of altitudinal gradients in different regions of the of the country. Further, the hydrological information and the methodology used to model hydrology for each sub-catchment could be improved based on the methods and concepts previously developed. Rules for splitting up the river network quinary catchments into a sixth level altitudinal quinary would need to be identified and tested scientifically. The rules would need to take into account the change of altitude within a quaternary, for example, a quaternary with a high variation in altitude would have a high variation in rainfall resulting in a greater number of relatively homogenous response zones. For the river network quinary catchments, these were based on the existing 1:500 000 river network which has an inconsistent density of rivers and as a result a quinary, due to the length of the river reach, may be spatially highly variable in terms of rainfall, soils, other climate variables and land use, and hence runoff. Further work would need to examine the splitting of these quinary catchments based on a consistent river network GIS layer.

As a standalone layer, the altitudinal quinary catchments and the river network quinary catchments are limited in their application, but if the layers are merged they can form a powerful tool for many applications around water resource planning and management, and assessment of ecosystem services.

The concepts of the methods for altitudinal and river network quinary catchments need to be used as a point of departure for a follow-on project and be used to produce a merged layer of relatively homogenous response zones (in terms of hydrology, soils and land use). As a standalone layer, the altitudinal quinary catchments and the river network quinary catchments are limited in their application, but if the layers are merged they can form a powerful tool for many applications around water resource planning and management, and assessment of ecosystem services.

The confidence that can be afforded to the hydrological data is highly dependent on the proximity of the rainfall stations to catchments, as well as effective monitoring of trends at the rainfall stations. Strategic decisions need to be taken on which rainfall stations are a priority to maintain in the national monitoring network of sampling stations, as well as to identify potential gaps in the network where new rainfall stations should be sited.

Endorsement and naming conventions need to be established to facilitate the attachment of additional research data to the quinaries. Examples of additional data sets currently collected at a quaternary level, for example, include alien vegetation, FEPAs, ecosystem service data and baseflow data.

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