Developing an Elementary Tool for Ecological Reserve Monitoring in South Africa's Freshwater Ecosystem Priority Areas (FEPAs): A Pilot Study in the Koue Bokkeveld

Report to the
WATER RESEARCH COMMISSION

by

BRUCE PAXTON, LOUISE DOBINSON, MARTIN KLEYNHANS & GERALD HOWARD

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Obtainable from
Water Research Commission
Private Bag X03
Gezina,0031

orders@wrc.org.za or download from www.wrc.org.za

EXECUTIVE SUMMARY

1. Overview and background

Extensive research and development has gone into methodologies aimed at determining the Ecological Reserve in South Africa, i.e. into quantifying the volumes, timing and frequency of flows required to support ecosystem processes in local rivers. Considerably less attention has been accorded its operationalisation; with some managers alleging that Reserve determination methodologies have been developed in a vacuum without any serious consideration for their practicability. This study was undertaken in response to the need to develop simple tools to monitor the Reserve that can be broadly applied in rural catchments with limited water resource management capacity and monitoring, a de-centralised water storage and transfer infrastructure, but which have a high conservation and biodiversity value, i.e. Freshwater Ecosystem Priority Areas (FEPAs). One of the fundamental premises of this study is the notion that operationalisation of the Reserve in river catchments stands a better chance of succeeding if more knowledge and control is placed in the hands of Water User Associations (WUAs) (representing both established commercial and emerging farming sectors) since they play a critical day-to-day role in the management of local water resources. By providing a set of easily interpretable tools and the basic skills required to manage their water resources more efficiently, this project aims to play a role in their institutional development through providing a significant link at the science-management interface.

Aims and objectives

The primary aims of the FEPAs and Flows study are therefore to:

- establish rated cross-sections at flow monitoring sites for FEPA-listed rivers and their support areas at selected nodes in the Koue Bokkeveld sub-catchment;
- assimilate the latest data from the WRCS hydrology and reconcile this with Olifants and Doring Rivers;
- gather information on present day water use collected by field personnel assigned to the Cape Critical Rivers (CCR) Project;
- use the above information to provide specialist ecological, hydraulic and hydrological support to the CCR Project; and
- investigate elementary, cost-effective monitoring tools and protocols for monitoring the Reserve in catchments of high ecological importance that can be broadly

applied by non-technical personnel within CMAs, WUAs and conservation extension officers throughout South Africa.

General Approach and methodology

- *1) Hydrology* – Modelled hydrological data used in the recently completed Water Resource Classification Study for the Olifants-Doring catchment was derived for the period 1920 to 2004 using the most recent calibrated information wherever possible. The Natural and Present Day hydrology from the classification study was used for validating the WRCS data, together with updated information from existing DWS flow monitoring gauges and those which were installed during the course of this study. As part of the 'Methodological Approaches to Assessing Eco-Hydrological Responses to Climate Change in South Africa', hydrology has been modelled at the quinary catchment scale for the country. The team investigated the usefulness of this data for Reserve monitoring.
- *Hydraulics* – Accepted and locally developed methodologies were used to derive a rating curve relating river stage to discharge across a stable transect that exhibits uniform flow on the Twee and Riet Rivers. A rating curve was then fitted through the observed and modelled points to allow the conversion of discharge to depth and to other variables including average velocity and wetted perimeter. The hydraulic analysis produced the following information: (1) a time series of stage based on the time series of flow, (2) a cross-section plot showing the observed and modelled flows and stages, (3) a plot showing the rating curve, the rating curve equations, and (4) lookup tables of various hydraulic variables versus flow including maximum depth, average depth, average velocity and others.
- *Monitoring indicators* – The project team developed a set of monitoring indicators to aid with the monitoring of the Reserve in the Koue Bokkeveld. A relatively inexpensive, as well as easily communicated and interpreted environmental flow monitoring tool was developed from these indicators. Opportunities for engaging the Koue Bokkeveld WUA in applying the monitoring tools was investigated through the Cape Critical Rivers (CCR) Project.
- *Stakeholder participation and engagement* – engagement with the Koue Bokkeveld WUA, DWS and CapeNature was central to the intended outcomes of this study and the CCR Project.

2. Study Area

The Koue Bokkeveld study area falls within the Olifants-Doring catchment (Olifants-Doorn: Water Management Area 17). It is located at the southern end of the of this WMA where it forms the headwaters of the Doring River which flows in a northerly direction, draining the eastern flanks of the Cederberg mountains, before joining the Olifants River at the downstream end of quaternary catchment E24M near the town of Klawer. This study focussed on three main rivers within the Koue Bokkeveld catchment, namely: the Twee, Leeu and Riet Rivers which confluence with the Groot River before this river joins the Doring River at De Mond. The Mean Annual Runoff (MAR) for the Koue Bokkeveld has been estimated at 281.6 $Mm^3.a^{-1}$ – accounting for roughly 66% of the flows at the confluence of the Doring and Olifants Rivers (423 $Mm^3.a^{-1}$) and 33% of the flows at the mouth of the Olifants River (1073 Mm3/a). The runoff from this region therefore plays a critically important role in supporting the health of the mainstem of the Doring, as well as that of the estuary. The Koue Bokkeveld is one of the most intensively farmed areas in the Olifants-Doring Water Management Area (WMA), having the third highest registered surface water use (20.9%).

3. Discharge estimation at natural control sites

In this study we opted to broaden the flow gauging network in the Koue Bokkeveld using water level loggers housed in stilling wells and located at natural control sites at critical monitoring nodes on the Twee and Riet Rivers. The advantages of this approach are firstly, the low cost relative to the construction of more traditional crested weirs, and secondly the minimal impact on the river and its biota – particularly the fact that natural controls don't alter migratory corridors. Rather than necessitating the constructing an artificial weir, natural control methods make use of the natural shape of the river for discharge estimation. Two flow monitoring sites were selected – one on the Riet River (Node R43) and one on the Twee River (Node R41). A similar methodology to the one that is generally used for Environmental Water Requirements (EWR) studies in South Africa was employed to derive a rating curve for the sites on the Twee and Riet Rivers. Five cross-sections were surveyed relative to local benchmarks on the Riet River and eleven at the initial site on the and Twee River through the geomorphic units of interest (riffle, pool and run). The water surface slope and macro channel slope were also surveyed at both sites. Discharge was measured which corresponded to the water level measured on the cross-section at the time of the survey. Random spot velocities were also collected in the reach and along each of the cross-sections on five separate occasions on each River. On repeat site visits, water levels on the cross-sections, water surface slopes, the discharge and velocities were collected. These data were then used to determine a rating curve for each cross-section and water levels recorded at 30 minute intervals could then be translated into water volume (cumecs) at each site.

4. Hydrology of the Koue Bokkeveld

Observed daily average flows from existing DWS gauging weirs on the Leeu and Doring Rivers (E2H007 and E2H002: Nodes R41 and R37 respectively) are available for download from the DWS website. Data from gauging weir E2H007 was available from 1980 to present and data from gauging weir E2H002 is available from 1923 to present. Flow data for the Riet River is available between 1935 and 1948, after which the gauging weir became unserviceable. These data were supplemented by data from additional water level gauges located at natural control sites on the Riet and Twee Rivers (Nodes R43 and A1 respectively). The monitoring nodes were therefore as follows:

- Gauging weir E2H007 on the Leeu River (R41),
- Gauging weir E2H002 on the Doring River at Aspoort (R37),
- at the stage logger site on the Riet River (R43),
- and at the stage logger site on the Twee River (A1).

Modelled hydrological data used in the WRCS study for the Olifants-Doring catchment was derived for the period 1920 to 2004 using the WR2005 database and verified with the most recent calibrated information wherever possible. The most detailed work has been completed in the Upper Olifants and parts of the Doring, while the remaining areas of the Olifants-Doorn WMA has been updated from WR90 in the recent WR2005 study. The use of the ACRU quinary catchment configuration was investigated in this study since this would ensure that the scale of the hydrology would better correspond to FEPA catchments and that the methodology could be repeatable at any location within the country. Natural daily flows are available from the ACRU quinary database for the period 1950 to 1999. The WR2005 data is monthly whereas ACRU flow sequences are modelled at a daily level. The initial aim was to use the daily ACRU modelled flows to disaggregate the modelled monthly hydrology from the WRCS and to scale from quaternary catchment level to sub-catchment (quinary) level for selected nodes.

However, several problems deriving natural daily flows using the quinary configuration became apparent:

- The quinary database only includes rainfall for the period January 1950 to December 1999;

- The parameters describing the hydrological characteristics of the soil are regionalised and did not reflect the local characteristics of the smaller catchments in the Koue Bokkeveld that exhibited high rainfall variability;
- Many of the rainfall stations used in the quinary database have since been closed, which means that the simulated flows can't always be extended to a later date without using different rainfall stations. This necessitated replacing rainfall stations that were used in the original configuration with rainfall stations that are still open.

The team therefore reverted back to using the monthly data from the WR2012 database, a national study which has recently been completed as an update to both the WR90 and WR2005 databases and contains simulated monthly runoff and rainfall data for the period October 1920 to September 2010.

5. Developing an Ecological Reserve Monitoring Tool

We developed an elementary method – the STandardised REserve Analysis and Monitoring tool (STREAM) – for monitoring the Reserve in catchments characterised by run-of-river abstractions, limited flow monitoring infrastructure decentralised water resource infrastructure (i.e. rural catchments without large dams with release mechanisms and that control water by means of extensive reticulation systems). The proposed method assesses deviations from Reserve requirements at coarse spatial and temporal resolutions and does so retrospectively. It is not intended for monitoring real-time compliance in complex catchments with major water resource infrastructure, or for developing operating rules for dams. It has been developed with the budget and skills limitations in mind of managers in smaller catchments that have high conservation value.

As it currently stands, STREAM comprises a series of Excel spreadsheets incorporating a combination of data entry templates, mathematical and logical functions, together with pivot tables and graphic outputs that require basic Excel skills to generate. The steps are as follows:

Preparatory steps:

- Ecological Reserve Management Areas: secondary or quaternary catchment management areas within IUAs are identified based on biophysical, socio-economic or infrastructural congruency, as well as on the location of gauging stations.

- Assimilating and preparing rainfall records: for each management area, a set of indicator rainfall stations is identified and records are assimilated for the period under review.
- Rainfall-runoff relationships: historical rainfall records for each Ecological Reserve management area are assimilated from the WR2012 database and linear and non-linear regressions are used to estimate relationships between total monthly observed rainfall and simulated runoff over the historical period (from previously simulated data e.g. WR2012, or from the latest hydrology). This initial step is necessary to set the model up and requires a familiarity with regression analysis. However, once the model is set up, STREAM can be run with limited expert input aside from periodic reviews.

Analysis:

- Calculate aggregated catchment rainfall on a monthly basis: the monthly rainfall data for the period under review which is assimilated in (b) above is entered into STREAM and catchment rainfall is aggregated for each Reserve management area.
- Estimating natural flows: The regression equations developed in (c) above are used to estimate natural flows in monthly volumes for the evaluation period – either monthly, biannually or annually depending on agreed upon assessment intervals.
- Convert natural flows to EWR equivalents: the Reserve rule curves obtained from the gazetted flows, are then used to convert the natural flow volumes into EWR volumes and these are then compared to the observed flows.
- Calculate monthly time-series observed flows: observed flow data from monitoring stations – DWS gauging stations or natural control sites – are assimilated and monthly flow volumes are calculated from these.
- Plot the deficit/excess of observed flows vs EWR flows on monthly and annual basis: The model then outputs simple bar charts indicating whether the observed flow volumes are above, below or equal to the EWR flows for the evaluation period on an annual and month-by-month basis.

6. Supporting and promoting Ecological Reserve Monitoring in priority catchments

STREAM is not intended to assess whether the Reserve is being legally complied with in terms of the National Water Act. The issue of compliance needs to be interrogated beyond the simple fact of whether a certain hydrological value has exceeded a threshold or not, i.e. whether non-compliance equates to ‘anything below the Reserve’. As an alternative to ‘compliance’, the Reserve be approached as a ‘working hypothesis’ that requires monitoring in order to assess whether it is achieving the state desired for the system at the outset of the classification process. Rather than a threshold, the Reserve be assessed by tracking trends, setting Thresholds of Potential Concern (TPCs), testing outcomes against realistic management interventions and adjusting these where necessary within the framework of an iterative, adaptive management approach.

Advantages and opportunities of STREAM:

- STREAM is a modest attempt to address the fact that while water resource modelling is widely used for planning, it is less often used in an operational context.
- The model can be set up by someone with limited expertise in hydrological modelling, but who has some experience of regression modelling and a good knowledge of the basic principles of environmental flow science.
- Once the model is set up for a certain catchment, it simply requires updating on an annual or quarterly basis when new rainfall and flow data become available. This task can be undertaken by personnel with moderate skills levels within WUAs, CMAs, regional DWS offices, conservation authorities or NGOs.
- STREAM is capable of supporting water allocations in the catchment which can be issued with greater confidence in the sustainability of outcomes. The consequences of the directives – or contraventions of them such as illegal dams, water abstractions or transfers within the catchments – can be monitored and remedied more readily.
- With repeated use, confidence with respect to the response of aquatic ecosystems to flow change would be significantly improved and would provide valuable benchmark against which RQO monitoring protocols and Ecostatus models could be calibrated.
- Although there is a significant amount of uncertainty in STREAM with regards to natural flow estimations, the advantage of STREAM, or similar models, is that it is objective, repeatable and its outputs can be interrogated and reviewed when more accurate data become available. This means that the identification of year-on-year trends is possible and that inherent uncertainties will reduce over time and with increased use and review.

Limitations and constraints of STREAM:

- Real-time monitoring of the reserve is not possible with STREAM, rather, the Reserve is reviewed retrospectively at quarterly, six-monthly or annual intervals.
- Daily flow monitoring is not achievable given the limitations of hydrological models in the catchment and their ability to estimate natural flows – especially low flows – in real time. STREAM therefore assess monthly volumes (which have the advantage of aligning with DWS planning units) and these are combined with a set of monthly 'minimal flow' indicators.
- STREAM does not currently assess the number of floods required for each month.
- The model consists of a simple Excel spreadsheet with a combination of formulas, logical functions, pivot tables and chart outputs with step-by-step instructions of how to proceed with an analysis. It is therefore vulnerable to errors resulting from incorrect user inputs.
- It is important to note that this model would not be effective as a basin-wide tool, or for dam operating rules. It is best suited for smaller, tertiary- or quaternary-scale catchments where targeted interventions may be necessary, but where budgets and capacity may be limited.
- The cost of rainfall data from the South African Weather Services (SAWS) is a major impediment to monitoring the Reserve and water resources management in general in South Africa.
- The model relies on rainfall-runoff regressions of observed rainfall and simulated hydrology and is therefore prone to the inherent uncertainties contained in the simulated data and the regression equations
- STREAM should be used in conjunction with monitoring protocols for the Resource Quality Objectives (RQOs) set for the catchment.
- The easily interpretable, visual representation of Reserve flows provided by STREAM, made the task of communication of water resource issues in the Koue Bokkeveld a lot easier. Stakeholders responded to and engaged with the figures and were able to suggest ways in which they may, in future, address water resource issues in problem catchments.

Quarterly, or biannual review of the Reserve using STREAM or a similar monitoring methodology in an adaptive management framework and in line with the principles of Integrated Water Resource Management (IWRM) is recommended.

Recommendations and further research:

- Improving hydrological certainty and regularly reviewing and updating rainfall-runoff relationships should be an important component in further application or development of this and any other similar model.
- Concomitant efforts to reinforce and expand rainfall monitoring infrastructure will go a long way towards achieving the former objective.
- Should software be considered in the future, the possibility then exists of increasing the sophistication of the integrated rainfall-runoff model.
- In terms of immediate research and development needs, a priority is to continue testing the model in an adaptive management framework in the Koue Bokkeveld, to develop monitoring and response protocols around its use and to test these in a different catchment with a different set of water resource challenges.
- STREAM does not currently assess high flows (floods), but should these be included in future versions. High flow requirements must be made explicit in the gazette, this includes their classes, expected and required frequencies, as well as their timing.
- This study has demonstrated that perceptions that operationalisation of the Reserve is impossible, are false. While there are limits, it is not completely unachievable if good quality and up-to-date data is at hand, that appropriate tools are available and that these are effectively applied in an adaptive management context.
- In high conservation priority catchments (i.e. FEPAs or Fish Sanctuaries), where hydrological routing has been used to determine the EWR, these data should be interrogated and reviewed and suitable methodologies applied to increase the confidence in EWR outputs.
- Water resources management is a complex field private landowners and public institutions will continue to require considerable support to ensure that adaptive management systems are functional and sustainable.

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LIST OF ABBREVIATIONS

ACRU	Agricultural Catchments Research Unit
Adjimp	Adjacent impervious area
CAPE	Cape Action Plan for People and the Environment
CCR	Cape Critical Rivers
CMA	Catchment Management Agency
Cofru	Baseflow response coefficient
DWS	Department of Water and Sanitation
EC	Ecological Category
EWR	Ecological Water Requirement
EWT	Endangered Wildlife Trust
FDC	Flow Duration Curve
FEPA	Freshwater Ecosystem Priority Area
IUA	Integrated Unit of Analysis
IUCN	International Union for the Conservation of Nature
IWRM	Integrated Water Resource Management
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MC	Management Class
NFEPA	National Freshwater Ecosystem Priority Area
NWA	National Water Act
PPTCOR	Precipitation Correction factor
Qfresp	Stormflow response coefficient
RHAM	Rapid Habitat Assessment Method
RQO	Resource Quality Objective
SAM	Strategic Adaptive Management
SAWS	South African Weather Service
Smddep	Fraction of soil depth contributing to stormflow
SPATSIM	Spatial and Time Series Information Modelling
STREAM	STandardised REserve Analysis and Monitoring

TPC	Threshold of Potential Concern
TWQR	Target Water Quality Range
WARMS	Water Authorisation Registration and Management System
WMA	Water Management Area
WRC	Water Research Commission
WRCS	Water Resource Classification System
WReMP	Water Resources Modelling Platform
WUA	Water User Association

1 OVERVIEW AND BACKGROUND

1.1 Introduction

The Ecological Reserve (referred to here as the 'Reserve') as stipulated in South Africa's National Water Act (Act 36 of 1998) requires that a portion of the flow in all the country's rivers be retained in order to support their ecological functioning in a condition agreed upon by all users. This condition – its class – is determined during the course of a consultative classification process – the Water Resource Classification System (WRCS) (DWAF 2006). In terms of the National Water Act (NWA, No. 36 of 1998, Chapter 3, Part 1, Section 2(a)) classification is required to be carried out for all significant water resources in South Africa's primary Water Management Areas (WMAs). This is the first step in a process that ultimately leads to the determination of the Reserve and thereby the desired future state of any inland water body.

In their assessment of water resources research and policy in South Africa over the preceding two decades, King and Pienaar (2011) identified a number of challenges that faced water management in the country including *inter alia*, the need for:

1) monitoring of and compliance with the Reserve;
2) backing up compliance monitoring with a cost-effective hydrological monitoring network covering mainstem and tributary sites;
3) independent validation of assumptions and indices contained within WRCS models and
4) integrating the WRCS with national biodiversity planning initiatives – in particular the National Freshwater Priority Areas (NFEPA) programme.

In terms of the National Water Act, the Reserve comprises both the quantity (magnitude, duration and timing), was well as the quality of the water resource. Extensive research and development has gone into methodologies aimed at determining the water quantity component of the Reserve, i.e. into quantifying the volumes, timing and frequency of flows required to support ecosystem processes in local rivers (Hughes 2005; Hughes et al. 2012; Hughes and Hannart 2003; Brown and King 2000; Brown et al. 2007; Arthington et al. 2003; King et al. 2004; King and Louw 1998; O'Keeffe et al. 2002). Considerably less attention has been accorded its operationalisation; with some managers alleging that Reserve determination methodologies have been developed in a vacuum without any serious consideration for their practicability (Pollard and Du Toit 2011). With a few notable exceptions, therefore, there is limited understanding, or monitoring of the Reserve in South African catchments (Pollard and Du Toit 2011) – this despite the fact that environmental flows are recognised as one of the principal climate change mitigation strategies worldwide (World Bank 2010; Schlüter et al. 2013; Matthews et al. 2014; Aldous et al. 2011).

A number of solutions of varying sophistication and complexity have been proposed to meet this challenge locally, but thus far, few have had a broad uptake. Once the policy documents, the specialist deliberations, the reports and models have been finalised, the challenges of translating these to actual river flow become all too clear – limited local capacity or understanding of the Reserve, minimal commitment to its implementation, declining monitoring infrastructure and competing multi-sectorial demands on a finite resource. But what strikes the water resource practitioner wanting to effect real-world change in terms of water resource management most, is the complexity of managing a dynamic, mobile resource that exhibits high levels of spatial and temporal variability. Notwithstanding these challenges, the importance of managing and protecting water resources was highlighted in a recent World Economic Forum report which ranked looming water crises as being among the highest risks to stability worldwide, with water scarcity having far-reaching societal as well as environmental ramifications (WEF 2015). These realities should hold no less true for South Africa, where mean annual temperatures have increased 1.5 times the global average over the past fifty years and the effects of global climate are expected to be felt especially acutely (Ziervogel et al. 2014). This study was therefore undertaken with these challenges in mind, together with the budgetary and skills limits of local water management bodies and the challenges faced by water resource managers. In this chapter, existing initiatives for Reserve monitoring are briefly reviewed, their limitations and challenges discussed and the general approach to the study introduced.

1.2 Basic principles of Reserve monitoring

Central to all Reserve monitoring approaches is the Flow Duration Curve (FDC) which plots flow – either daily average, or instantaneous discharges ($m^3.s^{-1}$) (Figure 1.1) or monthly volumes ($Mm^3 = m^3 \times 10^6$) (Figure 1.2) – against the proportion of time (percentile) that the flow of a certain magnitude is exceeded. The FDC shows how frequently a flow of a certain magnitude can expect to occur in a river. For the water user, it is useful for assessing levels of assurance – how often extremely low flows are likely to recur. FDCs also provide means of converting natural simulated flows to Reserve flows and comparing these with actual gauged flows.

Figure 1.1 shows an FDC for the month of October on a river where the simulated daily average discharge on a day at the 40th percentile is expected to be 10.5 $m^3.s^{-1}$ (a). The gauged flow (b) at the 40th percentile (4.3 $m^3.s^{-1}$) is shown to be higher than the corresponding Reserve flow of 2.9 $m^3.s^{-1}$. Lower magnitude flows that are exceeded for more than 55% of the time fall below the Reserve FDC (shown by the arrow). For flows which are exceeded 70% of the time, e.g. at (a) (5.9 $m^3.s^{-1}$), the corresponding Reserve flow at (e) (2.1 $m^3.s^{-1}$) is higher than the recorded discharge at the same percentile (1.1 $m^3.s^{-1}$) (f). For the period under investigation at this site therefore, the Reserve requirements are not being met in October for 45% of the time.

Figure 1.2 shows an FDC for the month of October for converting natural monthly volumes (as opposed to $m^3.s^{-1}$ shown in Figure 1.1) into Reserve flows. The October natural monthly volume of 12.6 Mm^3 is exceeded roughly 30% of the time and the corresponding Reserve value at that percentile is 5.4 $M.m^3$ – showing that the Reserve was met during October of that year. During the second year, however, the gauged flow (e) is shown to be considerably lower than the Reserve flow (d). The advantage of using monthly volumes for monitoring purposes is that these are the units that are published in Government Gazettes and therefore readily available to managers and water resource authorities. Monthly volumes are also better understood by farmers and managers who are accustomed to working in volumetric units.

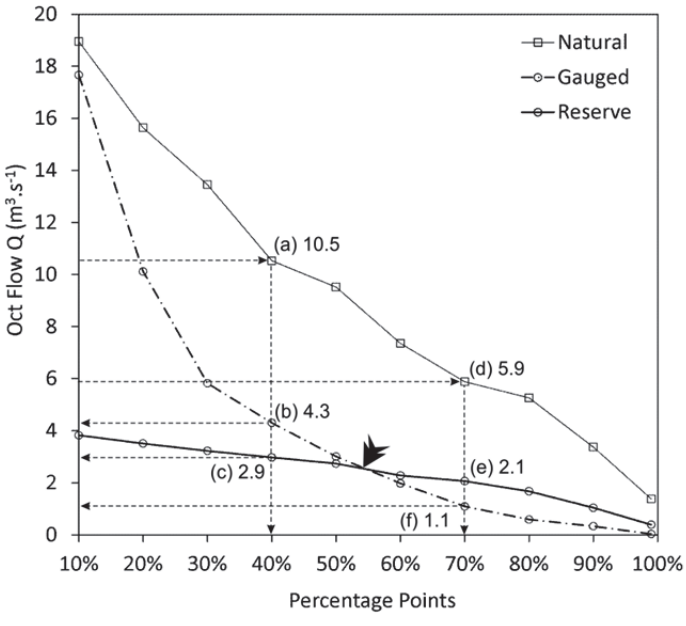

Figure 1.1 Flow Duration Curves (FDCs) in daily average discharge ($m^3.s^{-1}$) for: (a) natural flow at the 40th Percentile, (b) corresponding gauged flow, (c) corresponding Reserve flow, (d) natural flow at the 70th Percentile, (e) corresponding Reserve flow, (f) corresponding gauged flows. The arrow indicates the flow percentile at which gauged flows drop below the required Reserve flows.

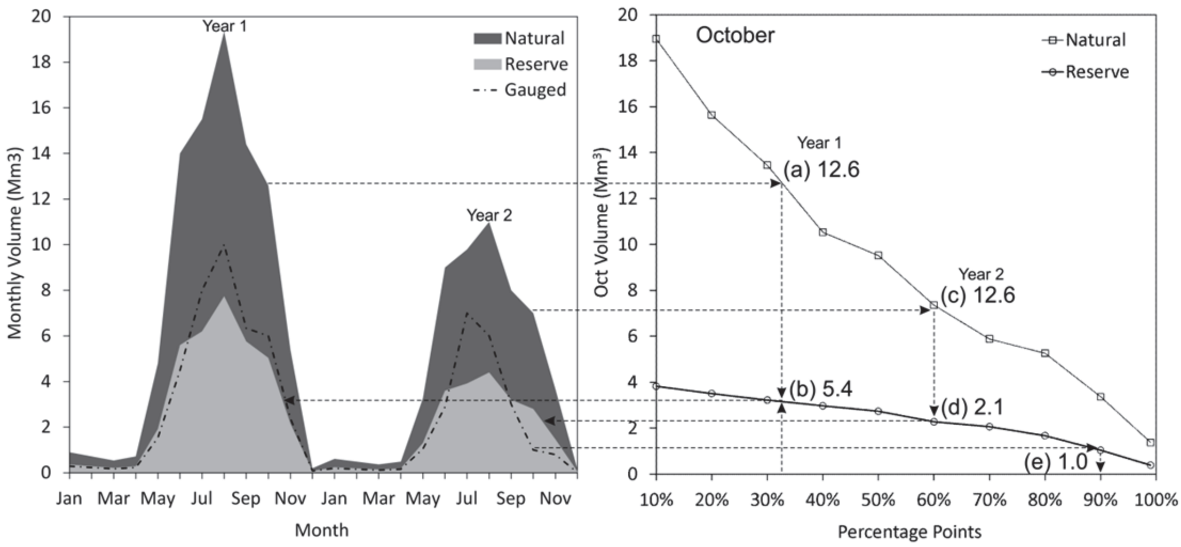

Figure 1.2 Converting monthly volumes (Mm^3) from natural flows to Reserve flows for year one (a) October natural volume, (b) corresponding Reserve flow and year 2 (c) and (d).

Monthly volumes, however, are less suitable from an ecological standpoint since hourly and daily flow durations are masked – the same volume of water could be distributed across a matter of hours or days (i.e. a flood) or across a whole month with very different ecological outcomes for each scenario. Monitoring the Reserve by means of monthly volumes should therefore be combined with the gauged data to assess adherence to other indicators such as minimum flows – which are provided for the driest months of the year in the gazetted hydrological Resource Quality Objectives (RQOs) – or the number of high flow events in the month of interest which would provide an indication of how bulk volumes were distributed through time.

1.3 Reserve monitoring approaches in South Africa

Tools for assisting with Reserve monitoring in South Africa range from the elementary – for example by comparing Reserve with gauged flows – to more sophisticated real-time catchment-scale decision support systems that incorporate the ability to simulate dam releases and produce complex operating rules that include curtailments and restrictions (Hughes and Mallory 2008; Mallory 2009; Pollard et al. 2012; Riddell et al. 2013; Hughes et al. 2008).

Hughes et al. (2008) tested a real-time monitoring software for the Thukela River – the '*Real Time Reserve Management Model*'. This model was developed as a component within the Spatial and Time Series Information Modelling (SPATSIM) framework. While Reserve implementation was a central objective of the study, it was contained within a broader, real-time water management system based on a water resource systems yield model. The methodology makes allowance for scenarios where storage infrastructure is available to regulate flows, as well as for situations where users are reliant on run-of-river abstraction, i.e. where management may depend on water use curtailments or restrictions.

Hughes et al.'s (2008) model encompasses two procedures. The first procedure involves developing and calibrating the real-time operational system which is contained within the SPATSIM framework and requires specialist input. This first procedure begins with the preparation of a real-time Pitman model that simulates natural flows from hydrologically-relevant catchment parameters and converts these to Reserve flows. This requires the selection of appropriate rainfall stations which, preferably, have records for a minimum of twenty years and which are representative of the range of rainfall variations across the catchment. However, satellite-derived rainfall estimates can also be used. The rainfall data are patched and averaged across several rainfall gauges, the Pitman model is then recalibrated and the revised simulations are checked against the outputs of the original Reserve Determination study. Using a systems yield model, a set of operating rules can then be determined for each Reserve management area, the boundaries of which are delineated on the basis of quaternary catchments, the presence of Reserve sites and operational management infrastructure. Five sets of rules for are determined for each unit:

- *Ecological Water Requirement (EWR) Targets*: monthly EWR requirements for ten levels of assurance for each monitoring site. Where releases from dams can be made, the rules would be determined using the systems yield model.
- *Reservoir releases for users*: for users supplied by a dam through managed releases upstream of the monitoring site. Restrictions are based on reservoir water levels.
- *Reservoir release rules*: for users supplied directly by the dam. Restrictions are based on reservoir levels.
- *Run-of-river curtailment rules*: for run-of-river abstractors during periods of limited water availability determined through the system yield model.
- *Monthly curtailment factor*: allows for seasonal variations in restriction rules using monthly factors.

Hughes et al. (2008) acknowledge that obtaining real-time data (rainfall or flow) for triggering high flow releases was problematic. In particular the timing of releases to coincide with natural flow events from tributaries would require a predictive methodology

– such as thresholds of daily rainfall over the preceding 24 hours – to forecast high flow events.

These models require a specialist hydrological consultant with knowledge of the software to set up and calibrate, as well as a considerable degree of commitment on the part of water management authorities and water users to run consistently. As Hughes et al. (2008) point out – this will have financial implications for implementation. In smaller catchments, of lower strategic, but higher biodiversity value, these methods are unlikely to be affordable or implementable.

Mallory (2009) has made the point that a catchment cannot be managed for the Reserve alone and that any operating rules should take the needs of the users themselves into account such that sustainability targets are achieved through curtailments and restrictions without compromising economic viability. With Hughes et al. (2008), Mallory (2009) acknowledges that the lack of real-time data within catchments is a major impediment to the rigorous operationalisation of the Reserve and suggests that simple tools are required which don't rely on real-time data.

For their study, Mallory (2009) based operating rules on the natural flow at key points in the catchments – either a dam or an EWR site. The Water Resources Modelling Platform (WReMP) was used to determine the catchment-wide near-real time operating rules of four pilot catchments in South Africa: the Letaba, Luvuvhu, Kat and Upper Komati Rivers. These operating rules could be implemented either through restrictions, i.e. temporary reductions in water use, or curtailments, i.e. permanent reductions in water demand – for example by reducing the area under irrigation and by implementing compulsory licencing. The operating rules were based on two modelling processes: the first to determine the natural hydrology at any point in the system, and a second that determined the operating rules themselves using WReMP. These models were developed for fairly extensive catchments with large scale water resources infrastructure and complex water transfers and therefore required considerable technical expertise to set up and run. Mallory (2009) emphasised that on-going support to catchment managers would likely be necessary.

An alternative to real-time monitoring is to assess compliance retrospectively. Riddell et al. (2013) used Flow-Duration Curves (FDCs) to analyse compliance in the Crocodile River, Mpumalanga for three historical periods using assurance rules produced during the course of a comprehensive Reserve determination study undertaken for that river. The EWR rule curves for their study were derived from natural flows contained in existing hydrological databases developed for the country – the 2005 Water Resources of South Africa Study (Middleton and Bailey 2008) (WR2005).

Riddell et al. (2013) used FDCs to compare natural WR2005, Reserve and observed flows of average daily discharge on a month-by-month basis to retrospectively assess Reserve compliance on the Crocodile River. They assessed the percentage time, the total number of months, the seasonality, as well as the magnitude of non-compliance. They also assessed contiguity, i.e. flows that were non-compliant for several successive months were deemed a severe infringement on river sustainability. They considered these elementary comparative methods adequate for compliance monitoring and showed a deterioration of compliance since the 1960s in terms of the extent (percentage of time), magnitude and contiguity of non-compliant flows.

Simple retrospective techniques like the former are much more likely to be taken up in catchments with limited resources, but would require some initial support to set up. The principal disadvantage of retrospective assessments of Reserve compliance is that transgressions cannot be identified timeously, addressed and corrected (Pollard et al. 2012). However, in the absence of more sophisticated real-time models, retrospective assessments can guide decisions with respect to future allocations, curtailments and restrictions, as well as guide water use licensing and future water allocation agreements.

1.4 The challenge of estimating natural flows

One of the principal challenges in monitoring the Reserve is the difficulty of distinguishing whether flow in any river system across any time interval (instantaneous, daily, monthly or annual) is the result of natural hydrological variability, or the result of flow regulation and abstraction. South African rivers exhibit some of the highest variability on daily, monthly, seasonal and inter-annual time scales observed anywhere in the world (McMahon 1979). As opposed to a fixed quantity against which compliance can be judged therefore, the Reserve is instead a moving target, dependent upon both natural and anthropogenic antecedent conditions. To some degree, natural variability has been built into the gazetted Reserve assurance rules which provides flows for 'maintenance' (normal) and for 'dry' years. However, without observed or simulated estimates of natural runoff, it is not possible to decide whether the observed patterns under consideration are the result of 'normal' or a 'dry' scenario.

The principal source of simulated hydrological data in the country is the 1990 *Surface Water Resources of South Africa* (WR90 – Midgley et al. 1994) which generated hydrological information at the quaternary catchment level for a 70-year time series of naturalised monthly streamflow volumes for the time period 1920 to 1989. This was done for the 1,946 catchments in South Africa, Lesotho and Swaziland. Following on from this study, the 2005 *Water Resources of South Africa* Study, commissioned by the WRC in 2004 (WR2005 – Middleton and Bailey 2008) updated and improved on the WR90 study. In the WR2005 model the interactions between ground and surface water were included and further consideration was given to afforestation and alien vegetation (Pitman 2011). These data and hydrological information have subsequently been updated to WR2012 which includes additional water resources data and water resource models updated to 2010.

The above models simulate hydrological data at the scale of the quaternary catchment. However, the usefulness of the data generated at this scale is limited for Reserve monitoring, freshwater biodiversity planning and climate change studies because quaternary catchments tend to be fairly large and hydrologically heterogeneous (Nel et al. 2011a; Maherry et al. 2013). A study commissioned by the WRC to develop a fifth level of hydrological information – the quinary scale – has recently been completed (Maherry et al. 2013; Schulze and Horan 2011). Quinary catchments are sub-quaternary, altitudinally-based hydrological and agricultural zones modelled using a 50 m digital elevation model and the national 1:500 000 rivers layer (Schulze et al. 2011b). The quinaries are nested within the quaternaries and defined as a 1:500 000 river segment between its source and the next tributary, or between two 1:500 000 tributaries. The suitability of using quinary scale hydrology for Reserve monitoring is discussed further in Section 4.2.

The hydrological databases described above are widely available, but their usefulness for Reserve monitoring and management is constrained by the fact that they are historical and only updated at five-year intervals. An assessment of whether the Reserve is being met currently depends on knowing the quantity of water that would have occurred in a river before abstraction on the day, over the last week, month or, at most, the last year if any meaningful management interventions are to be effective. Real- or semi-real time modelling is therefore required. The chief impediment to the role-out of real-time hydrological models, however, is the limited availability and high cost of hydrological modelling, together with the limited number of functional rainfall driver stations in the South Africa – and of these, many more are facing closure by the South Africa Weather Service (SAWS) (Pollard et al. 2012). Furthermore, this rainfall data has become too costly for local research and natural resource management budgets. These scenarios are transpiring at a critical juncture in South Africa’s water history when global climate change may fundamentally alter the availability and distribution of water across the country, making the widespread availability of rainfall data to managers and researchers all the more critical.

In the absence of reliable and affordable rainfall data, there remains two alternative sources of model input including: flow indicator sites, i.e. (1) a flow gauge located in an undeveloped portion of the catchment and (2) satellite-based radar-rainfall estimation methods. Both these approaches have limitations. In the case of flow-gauged indicator sites, high rainfall variability across a catchment limits the usefulness of a single indicator site. Furthermore, the absence of undeveloped reference sites, i.e. sites that are subject to minimal disturbance, in heavily utilised catchments restricts the number of sites where such gauges could be located. With respect to satellite-based radar-rainfall estimation methods, these may not currently be reliable enough for hydrological modelling purposes (Schröter et al. 2011; Pollard et al. 2012) and such models are not yet widely available in South Africa. While the most desirable option for Reserve monitoring, real-time hydrological modelling is therefore not at this point considered a viable option for widespread roll-out in less strategic, but ecologically important catchments such as FEPAs.

1.5 Freshwater Ecosystem Priority Areas (FEPAs) and the Ecological Reserve

The National Freshwater Ecological Priority Areas (NFEPA) programme provided the first comprehensive assessment of South Africa’s freshwater and estuarine ecosystems in terms of their conservation worthiness and importance for providing ecosystem services (Nel et al. 2011a). Freshwater Priority Areas (FEPAs) were selected by applying systematic conservation planning software (MARXAN) to sub-quaternary catchments in each of the 19 delineated WMAs in South Africa. The resulting FEPA maps which delineate planning units at the sub-quaternary catchment scale provide a strategic conservation framework intended to support water resource management, conservation and bioregional planning (Nel et al. 2011a). The FEPAs represent the spatial dimension of freshwater conservation planning; the temporal dimension – i.e. that of flows – has been largely ignored. Since river flow (its quantity and timing) is considered the ‘master variable’ in freshwater ecosystems (Poff et al. 1997), the exclusion of the flows from conservation targets in these systems is a major oversight. The integration of NFEPA with the Reserve is therefore currently viewed as a potentially innovative approach for moving Integrated Water Resources Management (IWRM) forward in South Africa (Nel et al. 2011b; King and Pienaar 2011).

Because of their conservation value, FEPAs are accorded by the WRCS high Recommended Ecological Categories (RECs) and require more faithful compliance with provisions contained in Reserve (Driver et al. 2011). However, as we have pointed out, there are a number of obstacles to achieving this. Chief among these are (1) the absence of a broad-based hydrological monitoring network and (2) the limited capacity among emerging Water User Associations (WUAs) and local conservation authorities to understand the implications of and to implement on-the-ground monitoring of the Reserve. A further concern are the data-deficiencies and the inherent uncertainties associated with the WRCS process itself – which uses hydrological scaling without biological input – and in many instances may require independent validation of assumptions.

1.6 Aims and objectives of this study

In examining the factors constraining the operationalisation of the Reserve in the Lowveld region of South Africa Pollard and du Toit (2011) summon the principle of *requisite simplicity* (Holling 2001) which Stirzaker (Stirzaker et al. 2010) defines as the necessity to 'discard some detail, while retaining conceptual clarity and scientific rigour'. This study was undertaken in response to the need to develop simple tools that can be broadly applied in rural catchments with limited water resource management capacity and monitoring or storage infrastructure, but with high conservation and biodiversity value.

One of the fundamental premises of this study is the notion that operationalisation of the Reserve in river catchments stands a better chance of succeeding if more knowledge and control is placed in the hands of WUAs (representing both established commercial and emerging farming sectors) since they play a critical day-to-day role in the management of local water resources. WUAs face significant challenges with respect to monitoring and protecting the resource, at the same time as ensuring an equitable allocation among users. By providing a set of easily interpretable tools and the basic skills required to manage their water resources more efficiently, this project aims to play a role in their institutional development through providing a significant link at the science-management interface. In this way it is hoped that more active intervention and engagement in monitoring will encourage WUAs to actively regulate use and improve irrigation efficiency. It is intended that this project provide the tools that will be necessary to work towards the goal of sustainable river management rather than strictly enforce compliance. As Pollard et al. (2012: pg 82) point out, strict enforcement of the Reserve may not be meaningful or appropriate in the short or medium term and that instead 'effort and progress towards meeting the intentions of the NWA including the Reserve' should rather by demonstrated by landowners and WUAs.

This study aims to use the Koue Bokkeveld as a case study for investigating the feasibility of operationalising the Reserve in catchments with a decentralised water infrastructure, i.e. farm dams and canals, in areas of high conservation importance (FEPAs) for assessing observance to conditions contained in the Reserve. The Koue Bokkeveld has been selected as the study area since it is one of the most intensively farmed areas in the Olifants-Doring catchment, having the third highest registered surface water use (20.9%) as well as one of highest water yields in the aforementioned catchment (Belcher et al. 2011). Irrigation of deciduous fruits for export and vegetables, constitutes 98% of the water use in the area. In addition, there is an ever increasing demand for agricultural expansion for established and emerging farmers. In light of this, it is considered critical to incorporate the principles of IWRM into current and future water resource planning in the area and that downstream users and ecosystems are not unnecessarily compromised. The Koue Bokkeveld has the distinction of having been used as a pilot catchment in the development and implementation of the WRCS. It was therefore ideally suited to lead the way in terms of operationalisation of the Reserve in the Western Cape through the WRCS.

The current WRC study is supported by the Endangered Wildlife Trust's (EWT) Cape Critical Rivers (CCR) Project, which commenced in February 2013. The broad aim of the CCR Project is to support water resource management in selected FEPAs throughout the Western Cape. The CCR Project provided an extension officer to assist the CMAs, WUAs and conservation authorities with water resource management during the project. The field officer also assisted with the installation of six water level gauges for monitoring river flow. This WRC study therefore linked closely with the CCR Project and provided the latter with hydrological and ecological monitoring support and data essential to its success.

The primary aims of the FEPAs and Flows study are therefore to:

1. establish rated cross-sections at flow monitoring sites for FEPA-listed rivers and their support areas at selected nodes in the Koue Bokkeveld sub-catchment;
2. assimilate the latest data from the WRCS hydrology and reconcile this with Olifants and Doring Rivers;
3. gather information on present day water use collected by field personnel assigned to the Cape Critical Rivers (CCR) Project;

4. use the above information to provide specialist ecological, hydraulic and hydrological support to the CCR Project; and
5. investigate elementary, cost-effective monitoring tools and protocols for monitoring the Reserve in catchments of high ecological importance that can be broadly applied by non-technical personnel within CMAs, WUAs and conservation extension officers throughout South Africa.

The knowledge generated in this study will inform key stakeholders within the selected catchments with regards to the current state of priority FEPAs and provide a basis for monitoring and assessing the efficacy – or otherwise – of water management interventions in those areas. It will provide a set of guiding principles and protocols for monitoring the operationalisation of the Reserve in these catchments. It is intended that this study provide lessons with regards to the challenges that will face the implementation of the Reserve in river systems throughout South Africa. An expanded hydrological monitoring network will also assist with climate change monitoring, modelling and adaptation.

1.7 General approach and methodology

It is important to note that at this stage and for the reasons already outlined in the preceding sections, real-time Reserve monitoring is not considered feasible in the Koue Bokkeveld. Also, the use of real-time rainfall data may not have the required resolution for smaller tributary sites. Since there are no release structures on dams, the necessity for real-time monitoring is diminished. It was therefore decided that, in this study, the Reserve be assessed retrospectively and that these assessments (six monthly or shorter) will provide better indications of the required restrictions to abstractions and storage by landowners and the WUA. The study comprised the following components:

1) Hydrology – Modelled hydrological data used in the recently completed WRCS study for the Olifants-Doring catchment ("Classification of Significant Water Resources in the Olifants Doorn Water Management Area", Belcher et al. 2012) were derived for the period 1920 to 2004 using the most recent calibrated information wherever possible. The most detailed work has been completed in the Upper Olifants and parts of the Doring, while the remaining areas of the Olifants-Doorn WMA has been updated from WR90 (Midgley et al. 1994) in the recent WR2005 study (Middleton and Bailey 2008). The Natural and Present Day hydrology from the classification study was used for validating the WRCS data, together with updated information from existing Department of Water and Sanitation (DWS) flow monitoring gauges and those which were installed during the course of this study. Hydrological data was assimilated from two active DWS gauging weirs located on the Leeu (E2H007) and Doring (E2H002) Rivers in the Koue Bokkeveld Integrated Unit of Analysis. These data were supplemented by data from additional water level gauges (Solinst Levelogger® Edge LT) installed on the Twee and Riet Rivers. No additional catchment modelling was undertaken and the natural hydrological sequences from WR2012 study were used.

As part of the '*Methodological Approaches to Assessing Eco-Hydrological Responses to Climate Change in South Africa*' project Schulze et al. (2011a) developed the quinary catchments for South Africa. The team investigated the usefulness of this data for monitoring the Reserve. Where this was not possible, hydrology at quaternary catchment level was scaled to the sub-catchment level. The sub-catchment scaling was based on catchment area and the latest available rainfall surface information.

(2) Hydraulics – Accepted and locally developed methodologies (Jordanova et al. 2004; Hirschowitz et al. 2007; Birkhead 2002; James and King 2010) were used to derive a rating curve relating river stage to discharge across a stable transect that exhibits uniform flow on the Twee and Riet Rivers. The stage-discharge relationship was developed from a minimum of three readings of discharge at different times of the year and magnitudes of flow. A rating curve was then fitted through the observed and modelled points to allow the conversion of discharge to depth and to other variables including average velocity and wetted perimeter.

The hydraulic analysis produced the following information: (1) a time series of stage based on the time series of flow, (2) a cross-section plot showing the observed and modelled flows and stages, (3) a plot showing the rating curve, the rating curve equations, and (4) lookup tables of various hydraulic variables versus flow including maximum depth, average depth, average velocity and others.

(5) Monitoring indicators – The project team developed a set of monitoring indicators that will aid with the monitoring of the Reserve in the Koue Bokkeveld. A relatively inexpensive, as well as easily communicated and interpreted environmental flow monitoring tool was developed from these indicators. Opportunities for engaging the Koue Bokkeveld WUA in applying the monitoring tools was investigated through the CCR Project.

(6) Stakeholder participation and engagement – Engagement with the Koue Bokkeveld WUA, DWS and CapeNature has been central to the intended outcomes of this study and the CCR Project. The engagement process was run as a component of the CCR Project,

but linked closely with the findings of this FEPAs and Flows WRC Project. The CCR Project engaged the Koue Bokkeveld WUA at the commencement of the study where the following issues were addressed: (1) the specific needs and concerns of the WUA will be identified; (2) the rationale behind the project and its intended outcomes; (3) opportunities for participation and collaboration. The CCR field officer continued to liaise throughout the project with the WUA, with the WRC Project team, as well as with individual landowners in the Koue Bokkeveld. Towards the end of the CCR Project, a dissemination meeting was held to explain the project outcomes.

2 THE KOUE BOKKEVELD STUDY AREA

2.1 General description

The Koue Bokkeveld study area falls within the Olifants-Doring catchment (Olifants-Doorn: WMA 17) (Figure 2.1). It is located at the southern end of the of this WMA where it forms the headwaters of the Doring River which flows in a northerly direction, draining the eastern flanks of the Cederberg mountains, before joining the Olifants River at the downstream end of quaternary catchment E24M near the town of Klawer (Figure 2.1). It is recognized as being one of the most important catchments in South Africa from a freshwater biodiversity and conservation perspective since it supports an unusually high number of endemic freshwater fish and invertebrate species (Skelton et al. 1995; Darwall et al. 2011; De Moor 2011). It forms part of the Greater Cederberg Biodiversity Corridor which is aimed at restoring ecological connectivity across landscapes of the region – considered a key strategy for climate change adaptation.

This study focusses on three main rivers within the Koue Bokkeveld catchment, namely: the Twee, Leeu and Riet Rivers which confluence with the Groot River before this river joins the Doring River at De Mond (Figure 2.2). The Mean Annual Runoff (MAR) for the Koue Bokkeveld has been estimated at 281 $Mm^3.a^{-1}$ – accounting for roughly 66% of the flows at the confluence of the Doring and Olifants Rivers (423 $Mm^3.a^{-1}$) and 33% of the flows at the mouth of the Olifants River (1073 $Mm^3.a^{-1}$). The runoff from this region therefore plays a critically important role in supporting the health of the mainstem of the Doring, as well as that of the Olifants River estuary. The rivers are noted not only for their water yield, but also for their high levels of aquatic biological diversity and endemism and of the 11 quaternary catchments, five contain sub-quaternary FEPAs. These FEPAs provide habitat for a number of threatened fish species including the: Clanwilliam sawfin (*Barbus serra*) (Endangered/International Union for the Conservation of Nature – IUCN), the Clanwilliam yellowfish (*Labeobarbus capensis*) (Vulnerable/IUCN), the Fiery redfin (*Pseudobarbus phlegethon*) (Endangered/IUCN), the Twee River redfin (*Barbus erubescens*) (Critically Endangered/IUCN) and the Clanwilliam rock catfish (*Austroglanis gilli*). The Doring River itself provides critical habitat for populations of endangered Clanwilliam sandfish (*Labeo seeberi*) (IUCN 2012). The Koue Bokkeveld is one of the most intensively farmed areas in the Olifants-Doring WMA, having the third highest registered surface water use (20.9%). Irrigation of citrus and deciduous fruits for export and vegetables constitutes 98% of the water use. Agriculture has been identified as the focus of future employment creation within the constraints of available land and water resources.

Figure 2.1 (a) Relief map of the Koue Bokkeveld in the Olifants-Doring catchment. Sub-catchments within the main Primary Catchment (E) – Upper and Lower Olifants, Doring and Koue Bokkeveld – are shown, (b) location of the sub-catchments within South Africa

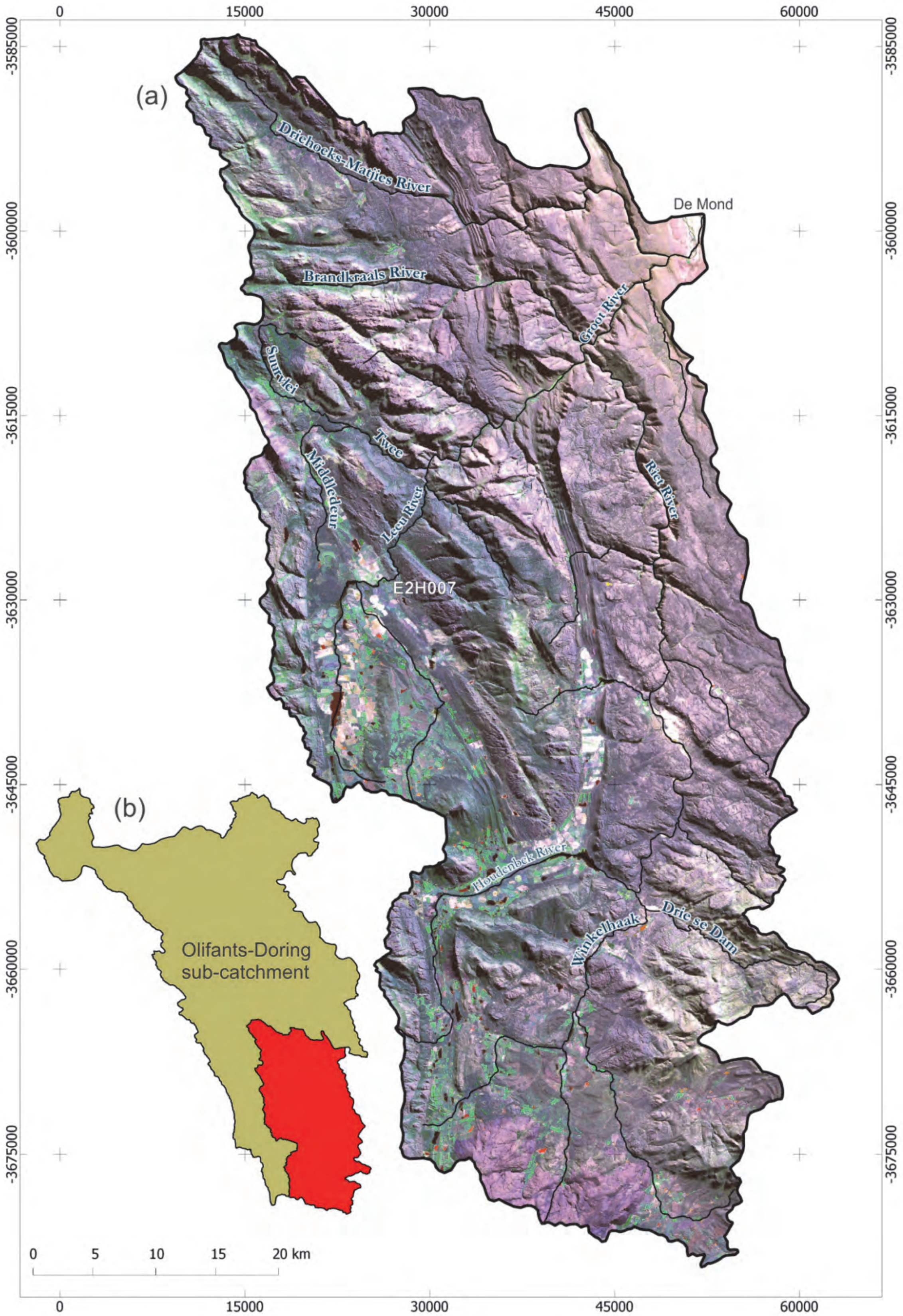

Figure 2.2 (a) Satellite image of the Koue Bokkeveld showing the main rivers within the study area. Light green areas indicate cultivated land, (b) location of the Koue Bokkeveld within the sub-catchment delineated in Figure 2.1.

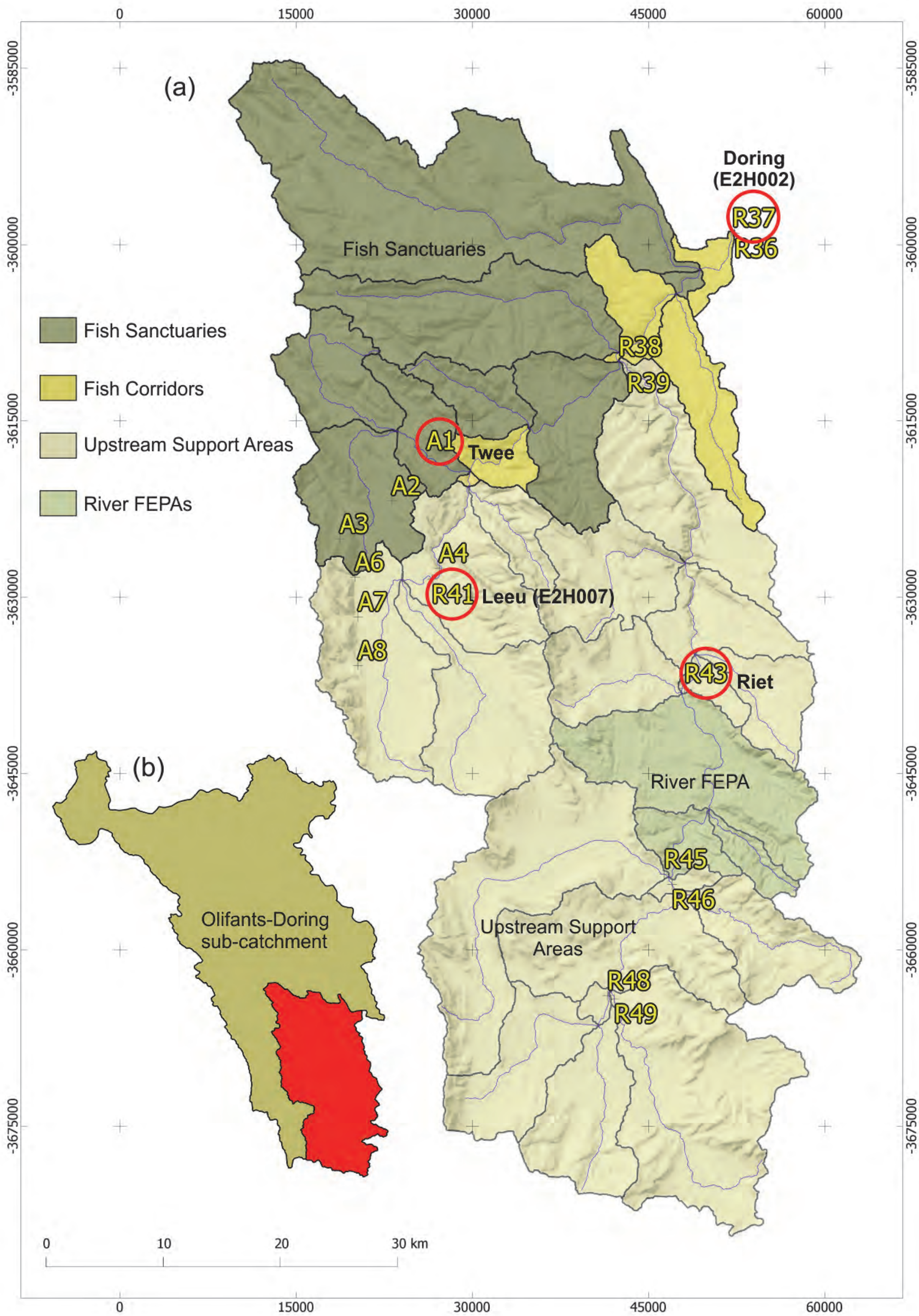

Figure 2.3 Koue Bokkeveld study region showing the FEPAs together with the hydrological nodes selected during the WRCS and RQO processes. The location of the water level loggers for the Riet and Twee Rivers, as well as the two DWS gauging weirs are circled in red, (b) location of the Koue Bokkeveld within the sub-catchment delineated in Figure 2.1

Improving water security is therefore seen as a critical developmental challenge (Witzenberg Municipality 2005). The focal monitoring sites in the catchment for this study were selected on the basis of criteria discussed further in Section 3.2 of this report. These monitoring sites are located at the river nodes identified during the WRCS process (Belcher et al. 2011b) with additional river nodes identified for assessing Resource Quality Objectives (RQOs). The sites include river nodes A1 on the Twee River, R41 on the Leeu River (DWS gauging weir E2H007), R43 on the Riet River and R37 on the Doring River (DWS gauging weir E2H007) (Figure 2.3). The sites are all downstream of the most intensively farmed agricultural areas and therefore reflect flows entering the mainstem Groot and Doring Rivers after abstraction in the upper catchment.

3 DISCHARGE ESIMATION AT NATURAL CONTROL SITES

3.1 Introduction

A significant impediment to Reserve monitoring as pointed out in previous chapters is the paucity of gauged flow data in South Africa. In the Western Cape – and no less so in the Koue Bokkeveld – most FEPAs are located on smaller tributaries where flow records have not been a focus for achieving broader water resource management objectives in the past. The two operational DWS gauging weirs in the Koue Bokkeveld – E2H007 (R41) on the Leeu River and E2H002 on the Doring River at Aspoort just outside the boundary of the catchment (R37) (Figure 2.3) – are of little value for gauging flows at critical sites on either Twee or the Riet Rivers – both of interest from an ecological point of view: the former because it falls within a FEPA fish sanctuary and supports endangered fish populations, and the latter because of its upstream support role for the mainstem Doring River. This reflects a fundamental problem with regards to the operationalisation of the Reserve, i.e. if the Reserve is being met at one site, can it be said that it is being met at all sites? (Pollard et al. 2012). Clearly not if water abstraction and infrastructure is distributed unevenly throughout the catchment. However, given a fairly good coverage of monitoring sites, some inferences can be drawn with respect to Reserve compliance at sites which are not monitored.

In the absence of gauged flow data, a linear function that scales runoff volume on the basis of the ratio of catchment areas (Hughes 2004), or runoff modelling using near real-time observations of rainfall data are potential alternatives. However, both real-time and retrospective monitoring using these methods are limited by high variability in rainfall, evaporation, soils geology and land-use. This is particularly in the case in the Koue Bokkeveld where rainfall on the western mountain source areas is extremely variable and complex to model, varying from 700 $mm.a^{-1}$ in the mountainous west to 150 $mm.a^{-1}$ in the more arid south-west. Without support and infrastructure, it is doubtful whether these models would be appropriate for smaller, isolated catchments like the Koue Bokkeveld where technical capacity is limited.

In this study therefore, we opted to broaden the flow gauging network in the Koue Bokkeveld using water level loggers housed in stilling wells and located at natural control sites at critical junctures on the Twee and Riet Rivers. The advantages of this approach are firstly, the low cost relative to the construction of more traditional crested weirs, and secondly the minimal impact on the river and its biota – particularly the fact that natural controls don't alter migratory corridors. Rather than necessitating the constructing an artificial weir, natural control methods make use of the natural shape of the river for discharge estimation. Barnard and Rooseboom (2004) have defined a natural control as any section of a watercourse where a unique relationship exists between water level (stage) and discharge. This unique relationship enables the discharge (volume per unit time) to be estimated from a measured water level. Barnard and Rooseboom (2004) recommend that a gauging site should be monitored in the long-term for any changes to the site as a result of floods and transportation of sediments. These natural controls have successfully being used at other sites in the Western Cape to monitor impacts on surfaces waters of proposed abstraction from the Table Mountain Aquifer (Ractliffe and Snaddon 2012).

3.2 Flow monitoring site selection and description

The United States Geological Surveys (USGS 1982), cited in Barnard and Rooseboom (2004) list a number of factors that need considered when selecting a suitable natural control site for discharge measurement. Together with ease of access, they list the following factors:

1. The general course of the river should be straight for approximately 100 m upstream and downstream of the site;
2. the total river flow to be measured must be contained in the main channel
3. the streambed should be stable;
4. an unchanging natural control must be present;
5. a pool must be present upstream from the control at low flows to ensure the recording of stage at these flows and to a avoid high velocities in the approach channel during high flows;
6. should a suitable site be situated between two tributaries, it should be far enough downstream from the upper tributary so that flow is fairly uniformly established across the entire width of the river and far enough upstream from the lower tributary to avoid variable backwater effect;
7. the control section should be far enough upstream from bridges, dams etc. that could influence the water level at the control section through backwater effects.

The location of the water level measurement position materially effects the calculated discharge (Barnard and Rooseboom 2004). A critical control is defined as an area where flow passes from subcritical (slow and deep) to supercritical (fast and shallow). Critical controls result in a unique depth being established called the critical depth from which discharge can be calculated. If the water level is taken too close to the control section the water surface profile forms a drawdown curve and pressures are not hydrostatic. If it is taken too far upstream from the control section the frictional forces produce a water surface slope towards the control section. Barnard and Rooseboom (2004) suggest that stage measurements at a critical control should therefore be taken in the deepest and most tranquil part of the pool section, at least twice the maximum head expected upstream of the critical section, but not further than three times.

Barnard and Rooseboom (2004) investigated various types of natural controls that could be used as flow gauging sites. These included: step-pool controls, horizontal constriction controls and uniform controls. Out of the three types of controls, it was found that step-pool controls were very robust and provided efficient critical controls for a wide range of flows.

Many tributary systems in the Western Cape, including those in the Koue Bokkeveld, are well suited to discharge estimation by means of natural controls because of their bedrock morphology. Nevertheless, suitable sites which account for all the above factors are difficult to find. Of particular concern to the site selection on the Twee and Riet Rivers was the predominance of braided reaches where both accessibility and complex bed morphologies were major hindrances. A second limiting factor was accessibility – both rivers flow through mountainous terrain where vehicular access is limited. These were then the two primary considerations that governed the site selection process for this study. The Twee and Riet sites are relatively accessible and located at areas where the river is constricted through a relatively narrow channel as opposed to broader braided sections which is commonly found in the rivers of the Cederberg.

3.2.1 Riet River flow monitoring site

The Riet River flow monitoring site is a step-pool control close to EWR monitoring node R43 (Figure 3.1). The logger is located in a pool which lies on a 90 degree bend in the Riet River. Thus the first factor, as defined by the USGS (1982) is not satisfied. However, all other factors have been satisfied and due to the size of the pool and location of the logger behind a large boulder sheltered from turbulence, it is unlikely that the bend poses a major issue except in floods. The pool is controlled by a stable bedrock shelf of varying cross-section at low to medium flows and possibly by a boulder field further downstream during very high flood events.

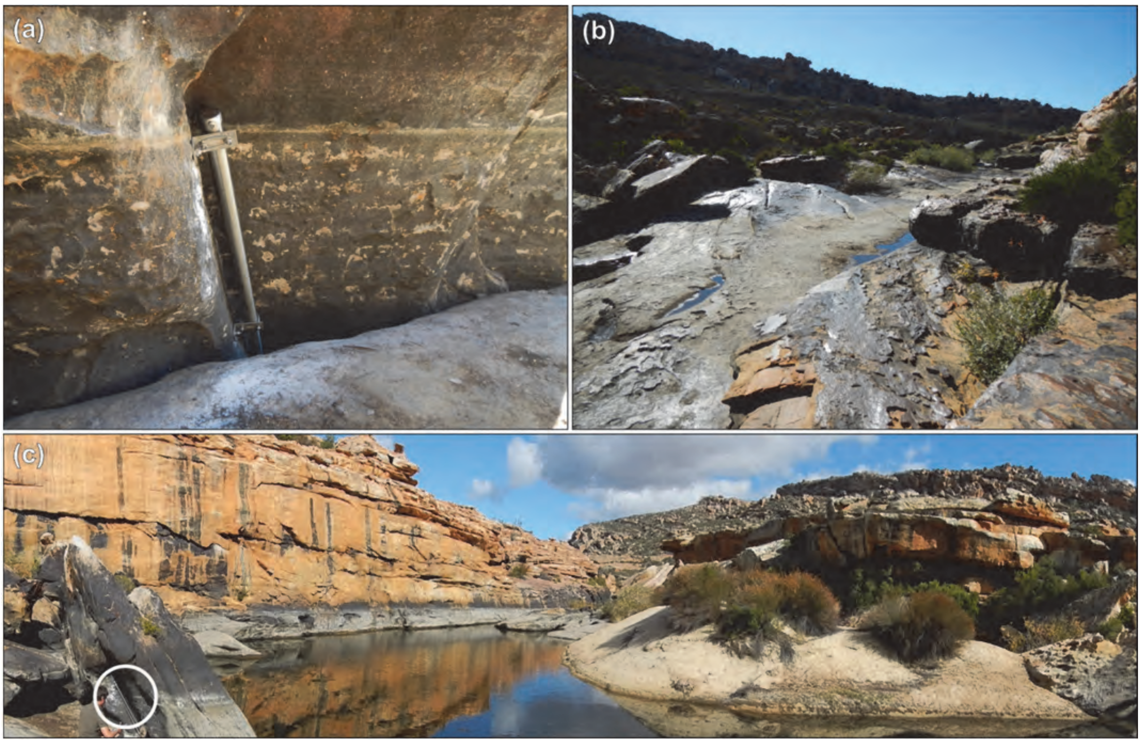

Figure 3.1 (a) Stilling well bracketed to a boulder at the Riet River flow monitoring Site R43, (b) the view of the hydraulic control downstream, (c) view of the site looking upstream – the white circle indicates the location of the logger.

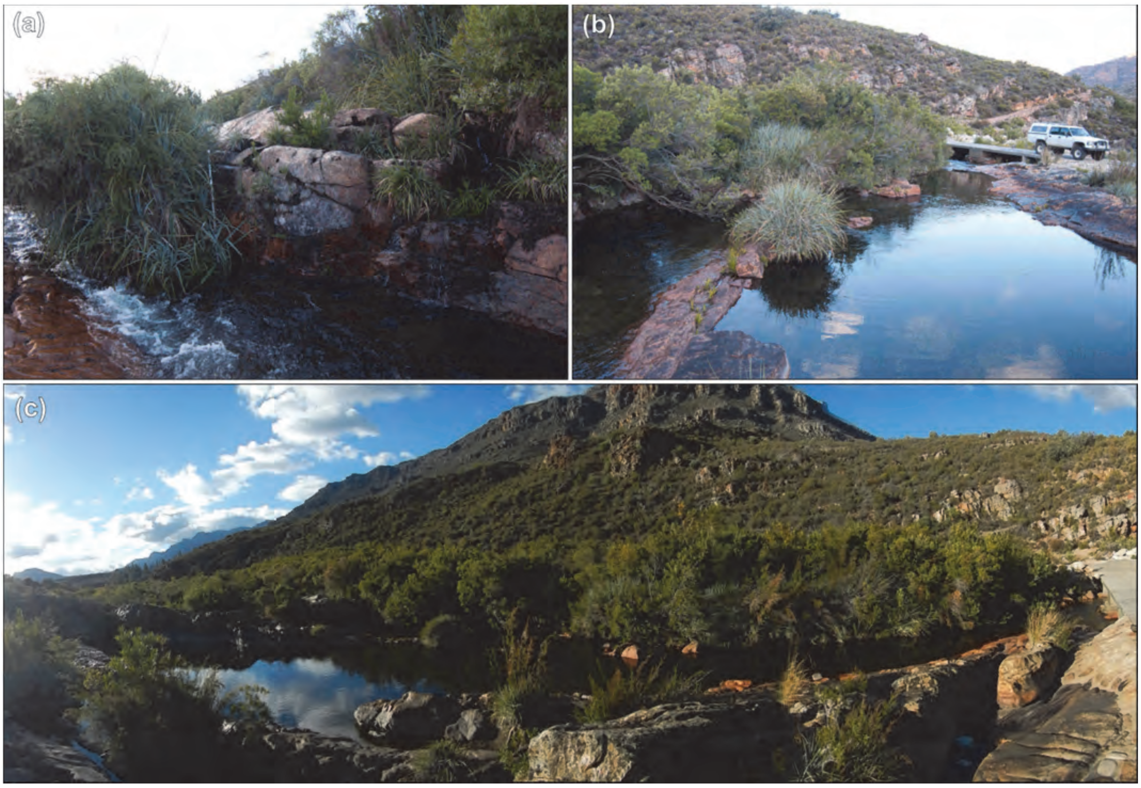

Figure 3.2 (a) Location of the stilling well and water level logger on the Twee River flow monitoring Site A1, (b) the view of the hydraulic control downstream, (c) view of the site looking upstream.

The logger is located approximately 10 m upstream of the control point, although critical depth will only occur there at low flows. The site is extremely stable due to most parts of the channel reach being bedrock and only after a very large flood could one expect significant changes to occur that could influence water levels at the logger. There is a sand bank located in the pool but this should not have a significant influence on water levels at the logger as it does not cause a constriction at the control section and it is likely that the sand bank is a fairly stable feature over the long term.

3.2.2 Twee River flow monitoring site

The flow monitoring site (Site A1-a) on the Twee River is a step-pool control site at low flows, but at higher flows the control probably moves to a culvert located further downstream and in floods the control moves to the large waterfall located even further downstream (Figure 3.2). The logger was located near a small waterfall upstream of a culvert, which in turn is located just upstream of a very large waterfall. The flow in this area was complex with two channels active except during extreme low flows. At high flows it is likely that a waterfall covered the logger and since the logger measures stage using pressure this could lead to erroneous readings when this occurs. The control for the logger site is stable, being a bedrock channel section downstream for low to medium flows, while at higher flows the culvert will become the control. The logger was located about 35 m upstream of a critical section located close to the culvert at low flows.

During September 2014, the logger was moved to a site roughly 80 m downstream of the initial location (Site A1-b) to below the waterfall where a bedrock shelf forms an effective control downstream (Figure 2.1). The bedrock shelf is approximately 30 m wide and is likely to control the level of the upstream pool for all flows. The stage logger is located roughly halfway up this pool which is 70 m long and 20 m and > 4 m deep – far enough away from both the waterfall and the outflow over the control for it not to be affected either by turbulence of the waterfall or by the drawdown curve of the control.

3.3 Design and installation of stilling wells and water level loggers

A key consideration for the installation of the water level loggers was the mounting of the stilling wells that house the loggers (Figure 3.4). The requirement was that these stilling wells should be stable enough to withstand flooding conditions with debris and have a life in excess of ten years.

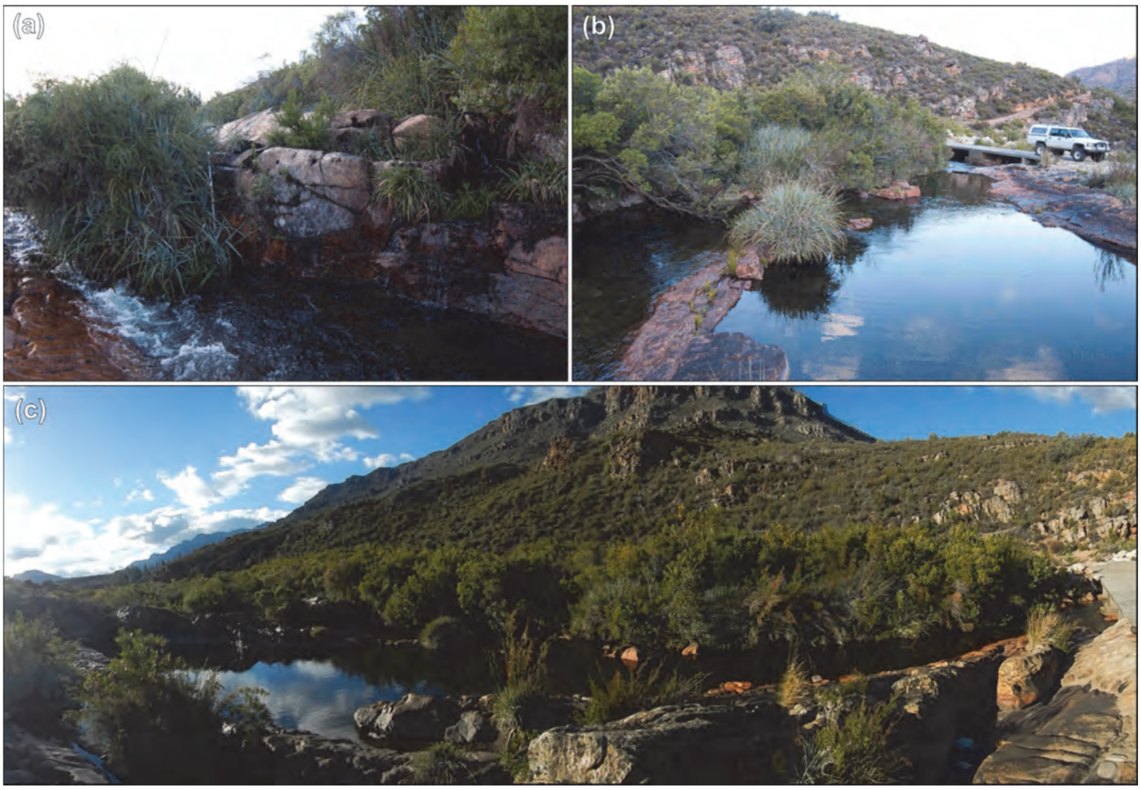

Figure 3.3 (a) Final location of the stilling well and water level logger on the Twee River flow monitoring Site A1, (b) the view of the hydraulic control downstream, (c) view of the site looking upstream.

This required that the mounting had to be structurally strong enough, but also consideration needed to be given to the choice of materials. Galvanised mild steel was not considered feasible due to the highly acidic nature of the water in the Cape Floristic Region. The remaining options considered were either aluminium or stainless steel. Although, weight for weight both have similar strengths, it was felt that stainless steel was not only more resistant to the acidic water conditions, but that aluminium would also susceptible to galvanic corrosion when in contact with other materials.

The stilling wells would be in permanent contact with rock anchors, the nuts and bolts that held them in place therefore also had to be stainless steel. We opted to use stainless steel Gr 304 for the stilling wells. Two alternatives were considered for fixing the stilling wells to the rock: mechanical 'rawlbolt' type bolts and Hilti chemical (epoxy) grout. The former rawlbolt option was chosen as no cure time was necessary, and 'tighten and go' was opted for due to the relative remoteness of the locations. Three different mounting plates were designed that could be used at a variety of angles or distances from the rock surface. Slots in the mounting brackets enabled a fair degree of flexibility given the uneven surfaces and the variety of mounting positions.

Figure 3.4 (a) Rawlbolt insertion into bedrock , (b) Fitting the mounting bracket to the mounting plate, (c) cap on the stilling well held in place with a bolt and clinch pin (d) installed stilling well with mounting brackets, (e) inserting the Solinst water level logger.

A wide range of mounting brackets were designed that could be applied to rock surfaces with a variety of different morphologies which precluded the necessity for designing unique brackets for each site. The water level loggers (Solinst® Edge LT), accurate to a depth of 5 m, were housed in 50 mm diameter, 1.5 mm thick stainless steel tubes fitted to 4.5 mm thick mounting brackets. M8 diameter ‘U’ clamps held the tube to the mounting brackets. M12 rawlbolts were used to attach the mounting brackets to the rock surface. Holes for these rawlbolts were drilled using a rotary hammer drill. Water Level loggers were secured to 1.5 mm stainless steel cable fixed to the cap of the tube (Figure 3.4).

3.4 Methodology for deriving rating curves

A similar methodology to the one that is generally used for EWR studies in South Africa was employed to derive a rating curve for the sites on the Twee and Riet Rivers. Five cross-sections were surveyed relative to local benchmarks on the Riet River (Site R 43) and eleven at the site on the Twee River (Site A1) through the geomorphic units of interest (riffle, pool and run). The water surface slope and macro channel slope were also surveyed at both sites. Discharge was measured which corresponded to the water level measured on the cross-section at the time of the survey. Random spot velocities were also collected in the reach and along each of the cross-sections on five separate occasions on each river. On repeat site visits, water levels on the cross-sections, water surface slopes, the discharge and velocities were collected (Table 3.1). These data were then used to determine a rating curve for each cross-section. The accuracy of the rating curve depends on the number of observed stage and discharge measurements and also on the hydraulic suitability of the site for modelling the higher flows that are not feasible to measure.

Table 3.1 Recorded stages and calculated discharges for the Twee and Riet Rivers.

Twee River (Node A1)				
	Date	**Time**	**Depth**	**Discharge**
	2013/05/16	16:00	0.67	0.661
	2013/07/18	14:00	1.008	1.719
	2014/02/20	11:00	0.573	0.433
	2014/05/21	16:00	0.65	0.540
	2015/02/05	12:00	-	0.163
Riet River (Node R43)				
	2013/05/16	13:00	0.357	0.000
	2013/08/27	15:30	2.242	0.953
	2013/09/10	13:00	2.236	1.355
	2013/09/28	13:00	2.268	1.212
	2014/03/27	11:30	0.551	0.000

The rating curves were determined using the stage at cessation of flow (which can be surveyed on site and is zero for a riffle, and non-zero for a pool) and the observed stage and discharge pairs on the site visits, as well as a number of high flows estimated using the hydraulic models. The rating curve is fitted using the method suggested by Birkhead and James (1998) (Equation 3.1). This equation is widely used and accepted in South Africa and the standard equation recommended by the World Meteorological

Organisation (WMO 2010) for flow gauging stations on river cross-sections, In this instance, stage is the dependent variable. In some cases it may be necessary to fit more than one equation to represent the rating curve – for instance where there are major discontinuities in topographical profile – and this was done for both sites.

$$y = aQ^b + c \qquad \text{Equation 3.1}$$

3.5 Topographical surveys

For the purposes of surveying in the transects for input to the hydraulic models, the Twee and Riet River sites were visited on 21 and 22 May 2014 respectively. The sites were surveyed using a Total Station, benchmarks were set up and the cross-sections and logger positions were surveyed at both sites. The intention of surveying cross-sections was to enable a backwater model to be set up in order to estimate the hydraulics of the sites due to their expected complex hydraulic responses at different flows. Eleven cross-sections were surveyed on the Twee River including the geometry of the culvert, with one of the cross-sections crossing through the logger, and one at the lip of the large waterfall where critical flow was expected to occur, providing a suitable boundary condition for the hydraulic model. On the Riet River, five cross-sections were surveyed including one through the logger and one at the downstream boulder field where a significant change in bed slope occurs and where the control probably lies during floods. A cross-section was also surveyed across the bedrock lip of the pool, which controls pool levels at lower flows.

3.6 Hydraulic modelling and discharge estimation

Models were set up of both sites using the United States Army Corp of Engineers (USGS), Hydrologic Research Centre's software HEC-RAS. The models used the following boundary conditions:

- For the Twee River the downstream boundary condition was set to critical depth as a large waterfall is located there;
- For the Riet River a downstream energy slope (0.02) was used, based on a survey of the channel slope downstream.

On the Twee River the culvert was modelled using the energy method and included as part of the calibration. Cross-sections were interpolated where necessary to improve the accuracy of the models. The models were calibrated based on the discharge and stage data collected during the course of the study. For high flows the parameters were estimated based on various references. The models were calibrated as follows:

- On the Twee River, calibration was achieved through adjustment of the Manning resistance values for open channel flow. One set of water levels and a discharge were available for the day of the survey for all cross-sections, and for various other measured points data were available for the logger cross-section.
- On the Riet River, calibration was achieved through adjustment of Manning resistance values.

3.6.1 Twee River Hydraulic Model

A three dimensional representation of the initial site on the Twee River (Site A1) is shown in (Figure 3.5) where the causeway is visible in the foreground. Table 3.2 lists the measured and modelled values used for the stage-discharge relationship. The parameters for Equation 3.1 for the rating curve are shown in Table 3.3 and the rating curve for the Twee River is given in Figure 3.6. The hydrograph is for the roughly two year period starting 15 April 2013 and ending 27 July 2015 (Figure 3.7).

Table 3.2 Measured and modelled (HEC-RAS) stages and discharges for the Twee River for Site A1-a.

Measured & Modelled		
Stage, y (m)	**Discharge, Q ($m^3.s^{-1}$)**	**Source**
0.58	0.45	Measured
0.65	0.55	Measured
0.67	0.67	Measured
1.01	1.73	Measured
1.15	2.50	HEC-RAS
1.30	5.00	HEC-RAS
1.57	10.00	HEC-RAS
2.00	20.00	HEC-RAS
2.74	50.00	HEC-RAS
3.51	100.00	HEC-RAS
4.12	150.00	HEC-RAS

3.6.2 Riet River hydraulic model

The measured data for the Riet River appeared to be inaccurate (Figure 3.8) and it was not clear which of the measured stages or discharges were correct and which were not. We therefore calibrated the model until stages were within the range of those measured for the given discharges, but on condition that the other parameters were within reasonable bounds. It was possible to model similar stages to those measured while using realistic Manning resistances. A satellite photograph was also available of the site on 1 October 2013, just three days after a measurement was taken on the 28th of September 2013.

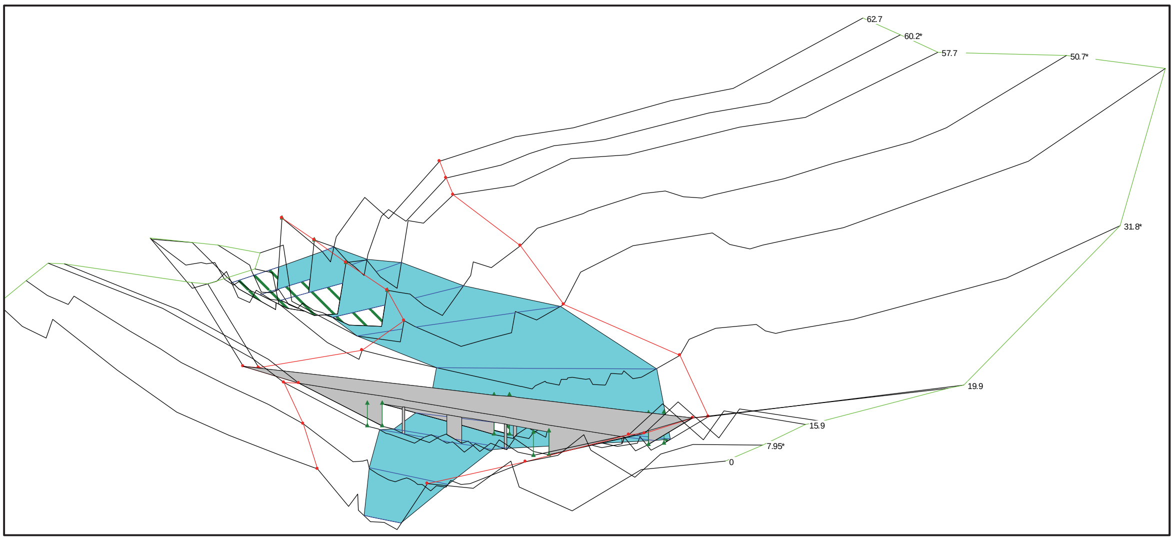

Figure 3.5 Three dimensional representation of the initial Twee River site (Site A1) showing the water stage at 0.65 m (blue shaded areas), the surveyed cross-sections (black lines) and causeway (shaded grey).

Table 3.3 Coefficients for the rating curve derived for the Twee River for stage values ≤ 1.035 m and > 1.035 m river stage.

Coefficients for Equation 3.1	y ≤ 1.035 m	y >1.035 m
a	0.506	0.372
b	0.664	0.451
c	0.283	0.547

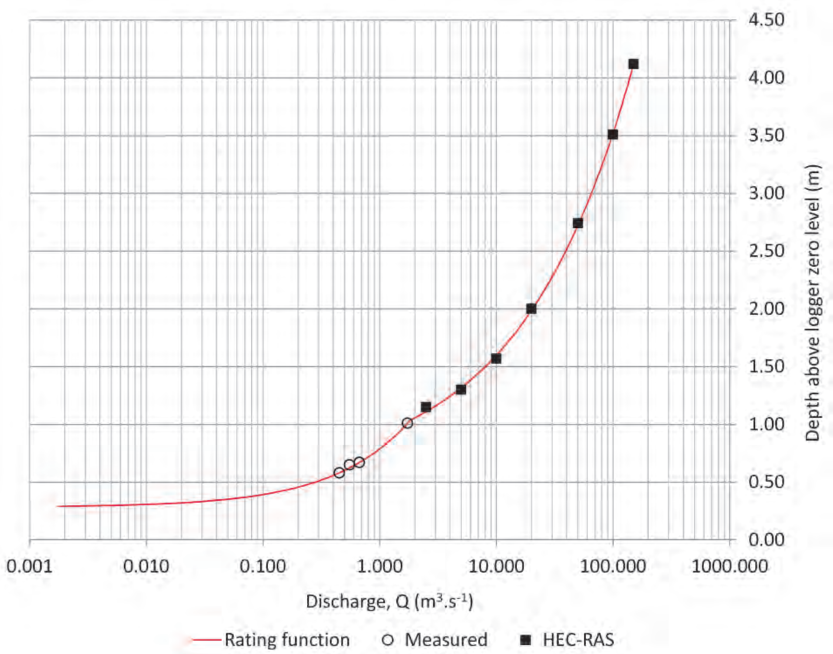

Figure 3.6 Discharge rating curve (black line) for the measured (open circles) and modelled (HEC-RAS: closed circles) data on the Twee River.

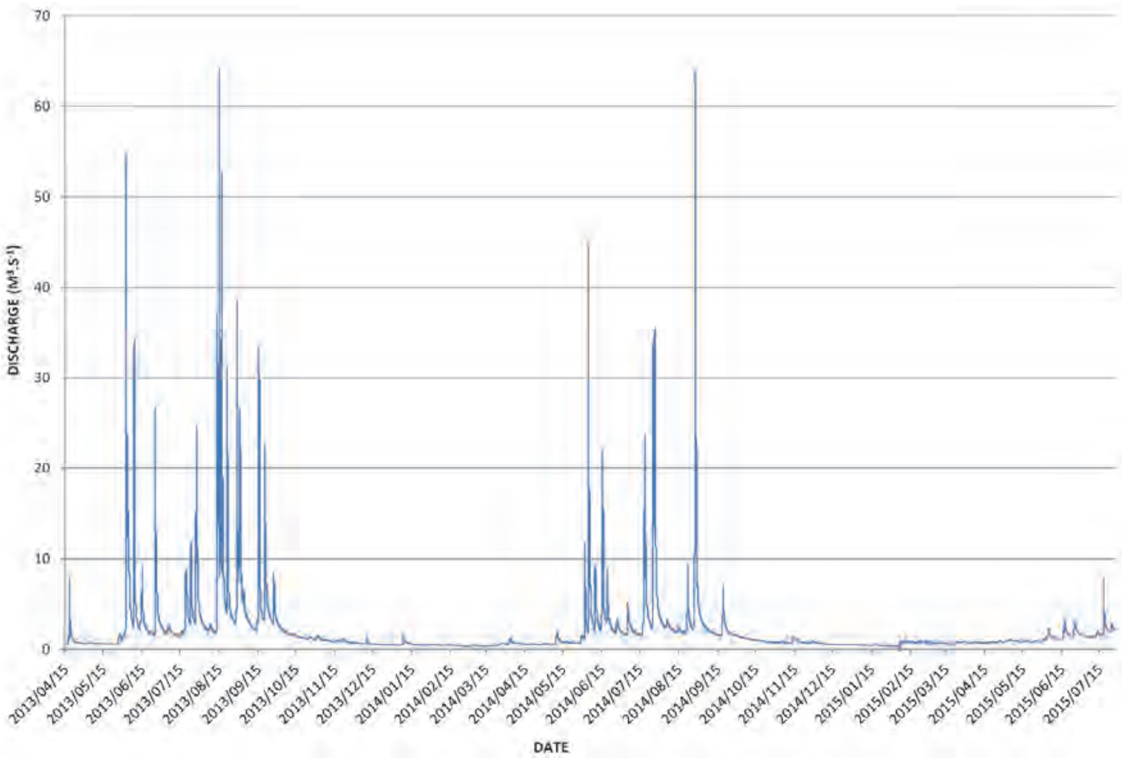

Figure 3.7 Hydrograph of observed flows in the Twee River between 15 April 2013 and 27 July 2015 based on records from the stage logger and the rating curves developed at the site.

Inspection of flows gauged at the Department of Water Affairs gauging station E2H007 on the Leeu River nearby, showed that peak flows occurred around the 28th of September (the day of the measurement in the Riet River) and that flow decreased by approximately 50% by 1 October 2013 in the Leeu catchment. Thus the inundated areas and the areas of white water in the Riet River shown in the satellite photograph are considered reasonably representative of the conditions that occurred on the 28th of September 2013, and these were used to validate the modelled output on this day. Good agreement on inundated areas and widths was obtained with the above calibration, adding some confidence to the outputs from the modelling exercise. A three dimensional representation of the site on the Twee River is shown in (Figure 3.9). Table 3.4 lists the measured and modelled values used for the stage-discharge relationship. The parameters for Equation 2.1 for the rating curve are shown in Table 3.5 and the rating curve for the Riet River is given in Figure 3.10 and the Hydrograph for the period 16 May 2013 and 22 June 2015 is shown in Figure 3.11.

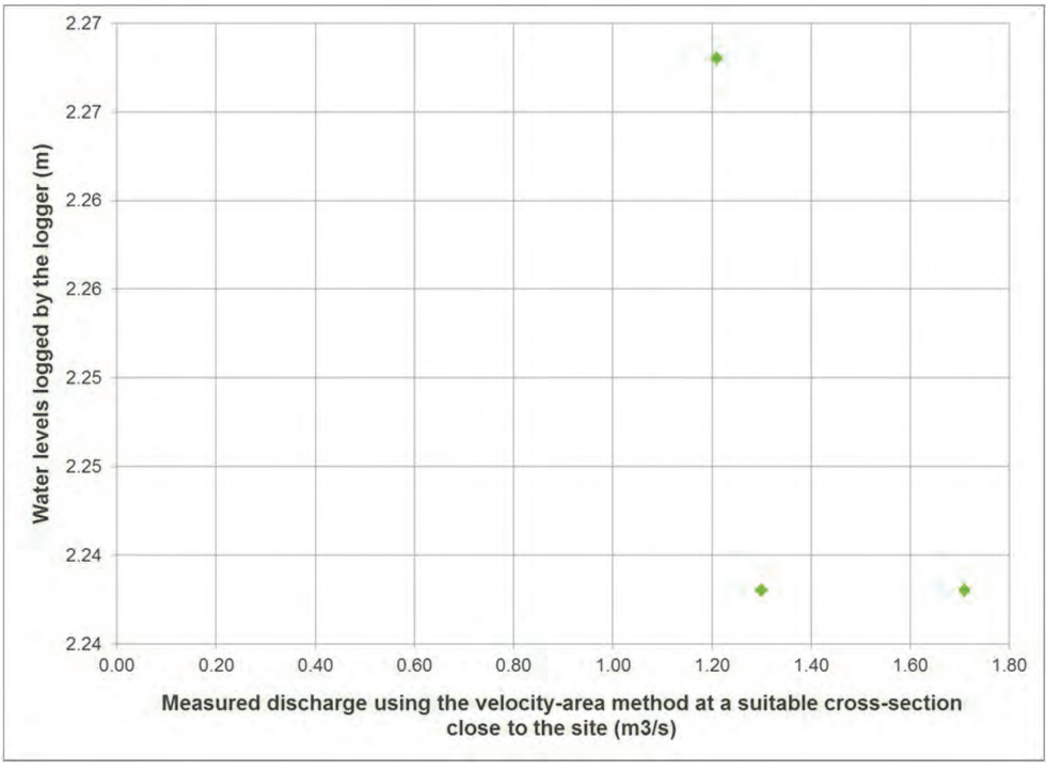

Figure 3.8 Measured discharges and logger recorded water depths at the Riet River site, showing the anomalous behaviour of the data.

Table 3.4 Measured and modelled (HEC-RAS) stages and discharges for the Riet River.

Measured & Modelled Stage, y (m)	Discharge, Q ($m^3.s^{-1}$)	Source
1.43	0.00	HEC-RAS
2.35	1.71	HEC-RAS
2.27	1.30	HEC-RAS
2.24	1.21	HEC-RAS
2.72	5.00	HEC-RAS
3.08	10.00	HEC-RAS
3.52	20.00	HEC-RAS
4.38	50.00	HEC-RAS
5.18	100.00	HEC-RAS
5.78	150.00	HEC-RAS
6.22	200.00	HEC-RAS

Table 3.5 Coefficients for the rating curve derived for the Riet River for values ≤ 2.13 m and > 2.13 m river stage.

Coefficients for Equation 3.1	y ≤ 2.13 m	y >2.13 m
a	0.755	0.681
b	0.359	0.366
c	1.434	1.503

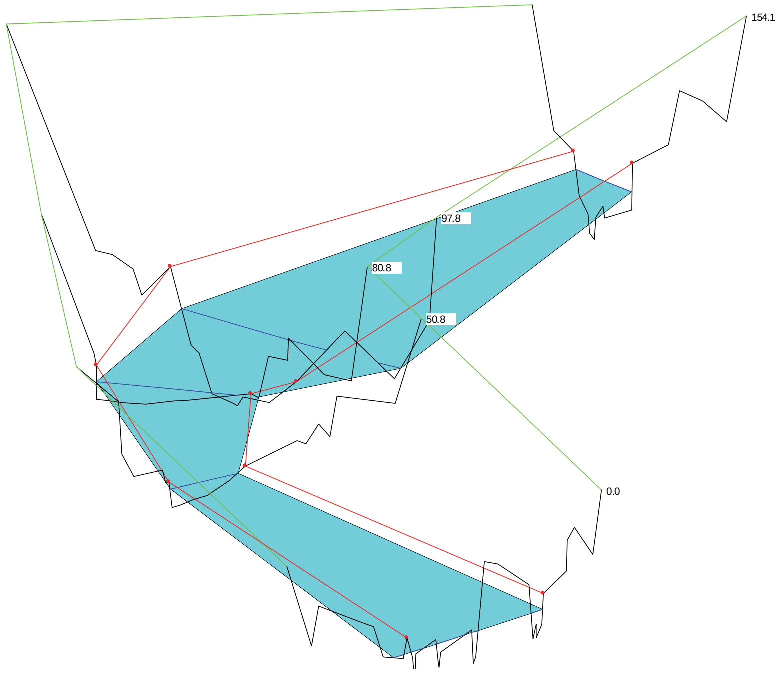

Figure 3.9 Three dimensional representation of the Riet River showing the water stage at 2.268 m (blue shaded areas), the surveyed cross-sections (black lines).

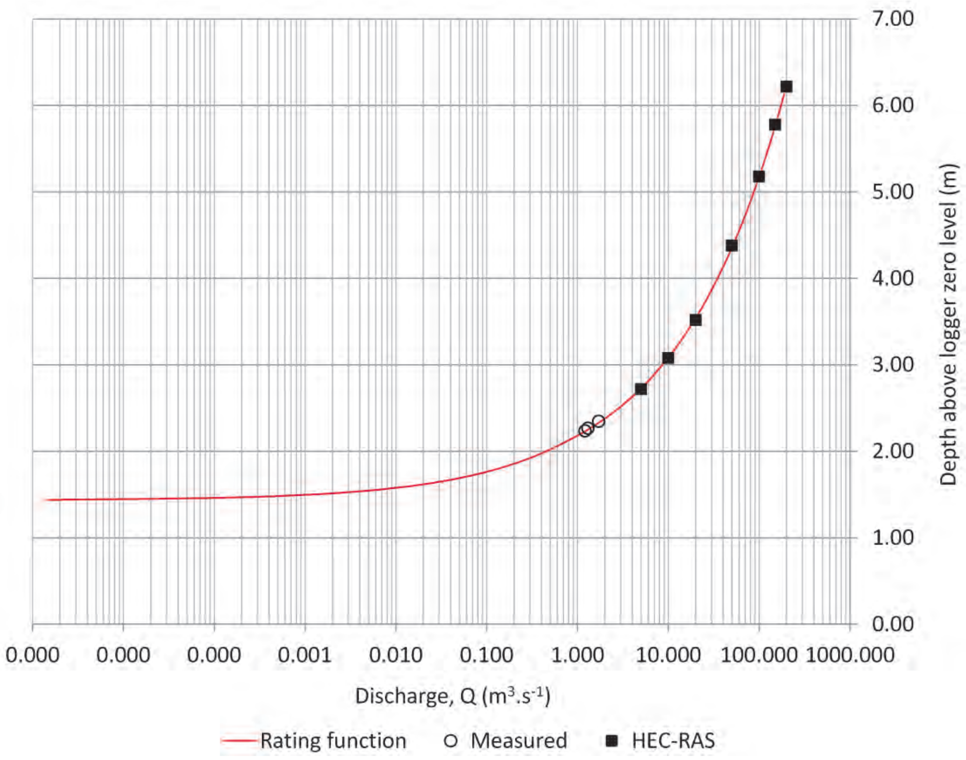

Figure 3.10 Discharge rating curve for the measured (open circles) and modelled (HEC-RAS: shaded squares) data on the Riet River.

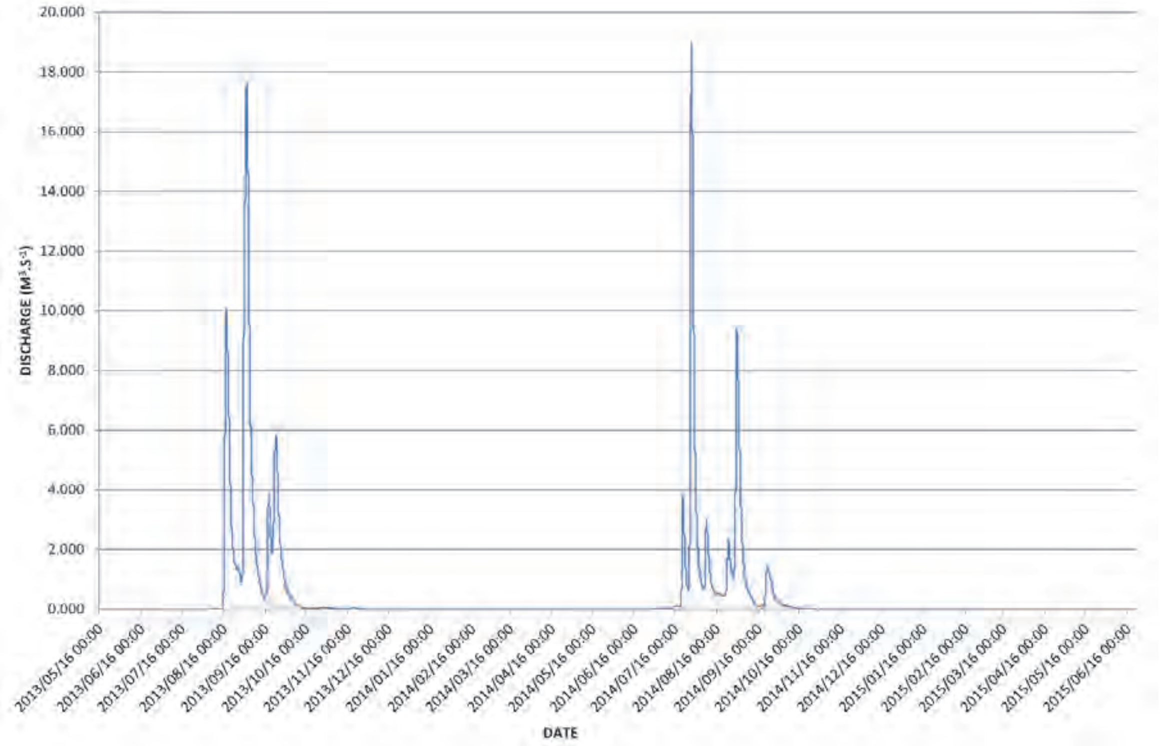

Figure 3.11 Hydrograph of observed flows in the Riet River between 16 May 2013 and 22 June 2015 based on records from the stage logger and the rating curves developed at the site.

4 HYDROLOGY OF THE KOUE BOKKEVELD

4.1 Observed flows

Observed daily average flows from existing DWS gauging weirs on the Leeu and Doring Rivers (E2H007 and E2H002: Nodes R41 and R37 respectively) are available for download from the DWS website via a Google Earth *kml* layer which directs the user to the correct gauging station. Data from gauging weir E2H007 were available from 1980 to present and data from gauging weir E2H002 were available from 1923 to present. Flow data for the Riet River were available between 1935 and 1948, after which the gauging weir became unserviceable. These data were supplemented by data from additional water level gauges located at natural control sites on the Riet and Twee Rivers (Nodes R43 and A1 respectively) as described in Section 3. The monitoring nodes were therefore as follows (refer to Figure 2.3 for their locations):

- Gauging weir E2H007 on the Leeu River (R41),
- Gauging weir E2H002 on the Doring River at Aspoort (R37),
- Groot River immediately upstream of the Riet River confluence (R38),
- at the stage logger site on the Riet River (R43), and
- at the stage logger site on the Twee River (A1).

Daily flows from the two data loggers were processed using the daily levels recorded by the stage loggers and the rating curves developed by Aurecon for this study (Section 3). For the purposes of hydrological modelling, data were available at the Riet River site from 16/5/2013 and at the Twee River site from 15/4/2013. A longer comparative period was available at the Leeu River, Aspoort and Groot River sites.

Note that the Groot River node (R38) has no recorded flows so it was necessary to generate a synthetic record based on the observed flows at Aspoort (E2H002). The observed flows at Aspoort were pro-rated using simulated MAR's from the Agricultural Catchments Research Unit (ACRU) quinary database at the Groot and Aspoort sites. In other words, the ACRU model simulated flow at both the Groot River site (R38) and the Aspoort site (R37) were used to determine the MAR at each site. The factor of the MAR at R38 and R37 (R38/R37) was used to reduce all daily observed flows at R38 to represent the observed flow at R37. This method incorporates both catchment area and rainfall variability (both embedded in the ACRU Model) in the pro-rated process.

4.2 Hydrological modelling

Modelled hydrological data used in the WRCS study for the Olifants-Doring catchment (Belcher et al. 2011b) were derived for the period 1920 to 2004 using the WR2005 database and verified with the most recent calibrated information wherever possible. The most detailed work has been completed in the Upper Olifants and parts of the Doring, while the remaining areas of the Olifants-Doorn WMA has been updated from WR90 (Midgley et al. 1994) in the recent WR2005 study (Middleton and Bailey 2008). The use of the ACRU quinary catchment configuration (Schulze and Horan (2011) was investigated in this study since this would ensure that the scale of the hydrology would better correspond to the scale of FEPA catchments and that the methodology could be repeatable at any location within the country. Natural daily flows are available from the ACRU quinary database for the period 1950 to 1999. The WR2005 data is monthly whereas ACRU flow sequences are modelled at the daily level. The initial aim was to use the daily ACRU modelled flows to disaggregate the modelled monthly hydrology from the WRCS and to scale from quaternary catchment level to sub-catchment (quinary) level for selected nodes.

However, several problems deriving natural daily flows using the quinary configuration became apparent:

- The quinary database only includes rainfall for the period January 1950 to December 1999;
- The parameters describing the hydrological characteristics of the soil are regionalised and did not reflect the local characteristics of the smaller catchments in the Koue Bokkeveld that exhibited high rainfall variability;
- Many of the rainfall stations used in the quinary database have since been closed, which means that the simulated flows can't always be extended to a later date without using different rainfall stations. This necessitated replacing rainfall stations that were used in the original configuration with rainfall stations that are still open.

In the case of the quinary configuration for tertiary catchment E21 the three driver rainfall stations originally used were 42669, 63538 and 63452. Of these, only 63452 (Krom River) is still open. This rainfall station is located to the north-east of the catchment and does not represent the wetter western and southern parts of the catchment. For example the inactive rainfall station 63538 has a MAP of 627 mm/annum compared to the available rainfall station (64342) which has a Mean Annual Precipitation (MAP) of 355 mm/annum. In addition, a comparison of rain-days shows that the available rainfall station (64342) has 2040 rain days from 1950-2000 and the closed rainfall station (63538) has 3167 rain-days from 1950-2000.

The validity of the quinary catchment ACRU Model configuration was checked using an earlier period of record (1990 to 1999) on the Leeu River when all the original rainfall station data were available. Results are presented in Figure 4.1 which compares simulated flows with observed flows at the Leeu River flow gauge (E2H007). An initial comparison between the ACRU daily flows and measured flows was therefore unsatisfactory. Clearly the ACRU regional parameters do not represent the hydrological characteristics of the catchment and require adjustment.

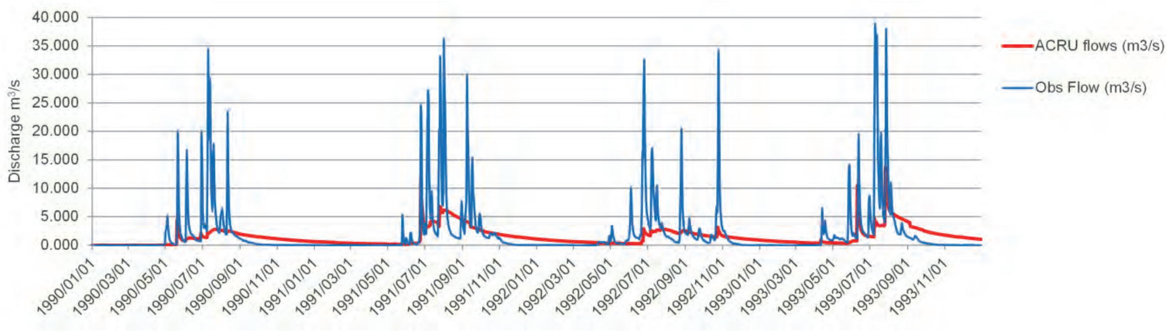

Figure 4.1 Comparison of simulated (red) and observed (blue) flows from the Leeu River flow gauge (E2H007) between 1990 and 1993.

Calibrated ACRU Model parameters from a previous hydrological study in the Koue Bokkeveld (Howard 2010) were therefore used as a basis to adjust the parameters of quaternary catchment E21. These included:

- re-calculating PPTCOR (scales daily rain-gauge using the relationship between rain-gauge MAP and catchment MAP)
- assigning each sub-catchment into either a mountain, part mountain/part valley or valley category
- using new parameter values for each topographical class (Table 4.1).

Table 4.1 Parameter values used in for each topographical class.

Topographic Class	Adjimp	Qfresp	Cofru	Smddep
Mountain	0.5	0.7	0.2	0.1
Mountain/Valley	0.3	0.5	0.2	0.15
Valley	0.0	0.3	0.2	0.2

In order to generate natural flows that can be used to compare against the recorded flows, it was necessary to determine the availability of daily rainfall data that would be representative of rainfall in the catchment. Since two out of three original stations that were used in the ACRU quinary database are now closed, a search of rainfall stations in the surrounding area was undertaken. This revealed the availability of two additional rainfall stations: the Bokveldskloof (42582) rainfall gauge with a MAP of 648 mm.a^{-1} to represent the wetter western portion of the catchment and the Excelsior Ceres (63807) rainfall station used in the drier eastern portion of the catchment. The original Krom River gauge (63452) was used in the driest parts of the catchment to the north.

Figure 4.2 compares the ACRU generated natural flows with revised parameters and rainfall stations, and the recorded flows at the Leeu River gauge E2H007 from January 2013 to December 2013. As expected, natural flows are higher than observed flows, particularly with regards to the first floods of the season. The natural flow peaks during the dry season and start of the wet season do not appear in the observed record as these flows fill farm dams in the Leeu catchment. Generally, the model simulation of the hydrological signal is considered acceptable.

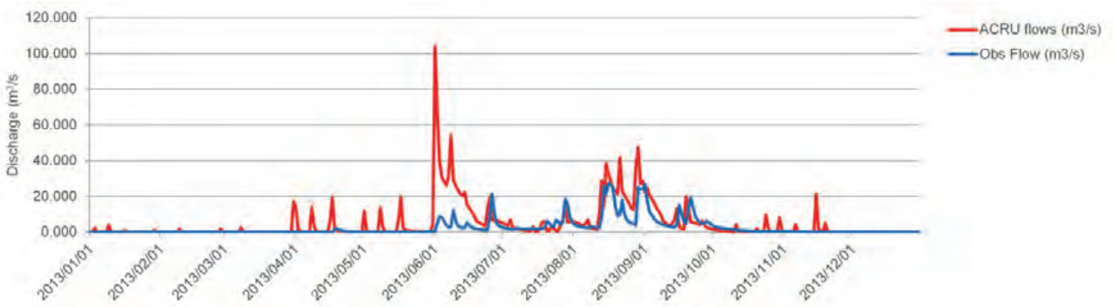

Figure 4.2 Comparisons between ACRU generated natural flow and recorded flows at the Leeu River gauge (E2H007).

4.3 Hydrological summary by quaternary catchment

4.3.1 Twee River (Node A1)

The Twee River Node A1 is located just downstream of the confluence of the Suurvlei and Middeldeur Rivers within the upper reaches of quaternary catchment E21H. It has an estimated catchment area of 195 km^2, an estimated incremental aerial extent of *c*. 404 km^2 and a MAP of 429 mm.a^{-1} (Database of Quaternary Catchment Information – WMA17, WR2005) – although observed rainfall ranges between 1200 mm in the mountains and 350 mm in the lower reaches of the catchment. The cumulative upstream area of E21H, i.e. including catchment E21G is 670 km^2. The Suurvlei and Middeldeur Rivers confluence 3 km upstream of Node A1 on the Twee River where flows were recorded by means of a water stage logger located at a natural control site (Figure 2.1). The maximum discharge recorded between the 15 April 2015 and 13 July 2015 was 34.7 m^3.s^{-1} and the minimum was 1.1 m^3.s^{-1}. The total runoff for the 2014 hydrological year estimated at the natural control site was 30.68 Mm^3. Estimates of natural MAR (nMAR) at Node A1 using the scaled WR2012 hydrology (1920-2009) was 18.6 Mm^3.a^{-1} and the scaled quinary hydrology was 38.83 Mm^3.a^{-1} (1950-1998). Howard (2010) estimated the irrigation demand upstream of A1 to be 4.1 Mm^3.a^{-1}.

4.3.2 Leeu River (Node R41)

The combined Leeu and Lang River catchments are both contained within Quaternary catchment E21G. E21G has an estimated area of *c*. 266 km^2 and a MAP of 475 mm.a^{-1}. Node R41 – together with DWS gauging weir E2H007 – is located on the Leeu River approximately 2.5 km downstream of the confluence of the Lang River and *c*. 10 km upstream of the confluence with the Twee River (Figure 2.1). The recorded MAR at this node for the years 1980 to 2014 using recorded values from the gauging weir E2H007 was 48.2 Mm^3.a^{-1} (min = 9.1, max = 95 Mm^3.a^{-1}). Estimates of the natural MAR (nMAR) at Node R41 vary between 31.2 Mm^3.a^{-1} (WR2005: 1920 to 2009) and 41.8 Mm^3.a^{-1} (Quinary: 1952 to 1999). The storage capacity of farm dams in the E21G Leeu catchment is estimated at 22.6 Mm^3.a^{-1} and the irrigation demand is at 25.3 Mm^3.a^{-1} (Howard 2010). Estimating natural flows in this catchment was complicated by the existence of extensive wetland storage areas.

4.3.3 Riet River (Node R43)

The Riet River spans six quaternary catchments (E2A-F) and is located in the most arid region of the Koue Bokkeveld. These combined catchments have an estimated aerial extent of *c*. 1560 km^2 and a MAP of 476 mm.a^{-1} in the upper catchment (Database of Quaternary Catchment Information – WMA17, WR2005). Node R43 is located in quaternary E21F, just downstream of the boundary of quaternary catchment E21E with an estimated area of 1181 km^2. There are no observed flow records for Node R43 subsequent to 1948. Our own estimates of flows in the river from the natural control site indicate zero flow days for 30% of the year (133 days) during the 2014 hydrological year and maximum discharge was estimated at 19 m^3.s^{-1}. The annual estimated runoff at the control site for 2014 was 12.7 Mm^3.a^{-1}. The estimated nMAR for the Riet at R43 is 150 Mm^3.a^{-1} (WR2005) The estimated volume of farm dams in these quaternary catchments is 113 $Mm^3.a^{-1}$ (WR2005) which accounts for some of the large discrepancies between observed and natural flows (only 8% of the nMAR is being recorded at the control site).

4.3.4 Doring River at Aspoort (Node R37)

The Doring River flows at Aspoort (R37) account for all the quaternary catchments in this study, i.e. the catchments contained within tertiary catchment E21. The total area of E21 is 3072 km^2 and MAP is ranges from 216 to 620 mm through the catchment (Database of Quaternary Catchment Information – WMA17, WR2005). The observed MAR at this node for the years 1923 to 2015 at gauging weir E2H002 was 254.2 $Mm^3.a^{-1}$ (min = 15.5, max = 840.8 $Mm^3.a^{-1}$) and discharge varied between zero and 233 $m^3.s^{-1}$ The WR2005 nMAR is estimated at 281.6 $Mm^3.a^{-1}$. The total volume of the farm dams in catchment E21 is estimated at 162 $Mm^3.a^{-1}$.

4.4 Conclusion

The above assessment of the available hydrology indicates that although there are several databases available for use, an important step in the methodology is a verification of modelled flows to the sites of interest. This would, in most cases, necessitate fine tuning and possible further calibration of hydrology by a specialist.

The project team initially intended to use the ACRU quinary database to generate natural daily flows at the sites of interest. However, following the validation exercise described above, it became apparent that more detailed analysis would be necessary to obtain representative flows and this was beyond the scope of the study.

The objective of the approach was to be able to use readily available hydrology data without necessitating extensive specialist input. It was with this in mind that the team reverted back to using the monthly data from the WR2012 database (waterresourceswr2012.co.za), a national study which has recently been completed as an update to both the WR90 and WR2005 databases and contains simulated monthly runoff and rainfall data for the period October 1920 to September 2010.

5 DEVELOPING A TOOL FOR ECOLOGICAL RESERVE MONITORING

5.1 Introduction

In this section we introduce an elementary method for monitoring the Reserve in catchments characterised by run-of-river abstractions, limited flow monitoring infrastructure and decentralised water resource infrastructure (i.e. rural catchments without large dams that have release mechanisms and extensive reticulation systems). The proposed method assesses deviations from the EWR at coarse spatial and temporal resolutions and does so retrospectively. It is not intended for monitoring real-time compliance in complex catchments with major water resource infrastructure, or for developing operating rules for dams. It has been developed with the budget and skills limitations in mind of managers in smaller catchments with high conservation value and where adherence to the Reserve is a priority.

The methodology has as its starting point, the outputs of the EWR studies as they are gazetted (i.e. Flow Exceedance tables or FDCs), the results of the WRCS and the hydrological RQOs that were derived for the catchment. It requires access to simulated natural hydrology, which can be modelled on a case-by-case basis or, if budget is not available, obtained from national databases (e.g. WR2005, WR2012). Setting up the model requires a moderate level of expertise in the basic principles outlined in this document, but once in operation, it is intended to be run by water managers or conservation authorities with no hydrological training.

During the course of consultations with the DWS, it was decided that the most feasible unit of assessment would be monthly volumes (Mm^3) rather than discharge ($m^3.s^{-1}$). Although it was felt that assessing the Reserve using monthly values would hide daily variability – which is ecologically significant – the simulated hydrology for the Koue Bokkeveld region – and quite realistically many other regions of the country – is simply not capable of simulating daily flows with the requisite degree accuracy. Furthermore, DWS management and allocation systems are reliant on monthly volumes and these measurement units would therefore link well with their planning frameworks. To overcome the coarse resolution of such an assessment, a suite of additional measured flow indicators – such as the duration of minimum observed flows – are included in the model that don't rely heavily on daily discharge estimates from simulated data.

This chapters begins with a discussion of the WRCS of the Koue Bokkeveld (Section 5.2), before moving on to describe the model itself. The procedure for setting up and running the model involves grouping the catchment into Reserve management areas (Section

5.4.1), obtaining and processing rainfall data (Section 5.4.2), developing rainfall-runoff regression relationships to estimate natural flows (Section 5.4.3), transforming natural flows into EWR flows (Section 5.4.4), methods for assessing the degree to which the Reserve is being met (Section 5.4.5) and finally producing a set of measured flow indicators (Section 5.4.6). The challenges associated with each step of the process are discussed.

5.2 The WRCS, Ecological Reserve and RQOs for the Koue Bokkeveld

At the outset, it should be noted that operationalising the Reserve does not depend solely on compliance with a limited set of hydrological parameters, but rather on maintaining a broad suite of biophysical indicators including water quality, geomorphology, riparian and aquatic vegetation, invertebrates and fish in a predetermined condition agreed upon by a broad group of stakeholders. The level of protection accorded each of these ecosystem components is determined during a consultative classification process – the Water Resource Classification System (WRCS) – where the Management Class (MC) of the resource is determined in terms of Section 13.1 (A) of the National Water Act (1998). The catchment is divided into Integrated Unit of Analysis (IUA) – i.e. areas that display congruent biophysical and socio-economic attributes – and each IUA is classified in terms of permissible levels utilisation and protection. There are three management classes:

> **Class I:** The configuration of Ecological Categories (ECs) of the water resource within a catchment results in an overall water resource condition that is **minimally** altered from its predevelopment condition, i.e. High environmental protection and minimal utilization.
>
> **Class II:** The configuration of Ecological Categories (ECs) of the water resource within a catchment results in an overall water resource condition that is **moderately** altered from its predevelopment condition, i.e. Moderate protection and moderate utilization.
>
> **Class III:** The configuration of Ecological Categories (ECs) of the water resource within a catchment results in an overall water resource condition that is **significantly** altered from its predevelopment condition, i.e. Sustainable minimal protection and high utilization.

The Koue Bokkeveld IUA has been accorded a Management Class of II, i.e. moderate protection and moderate utilization (Table 5.1) (Department of Water and Sanitation 2015). Once the Management Class has been allocated, the significant water resources within the IUA are assigned an Ecological Category (EC). The ECs are indices that provide an estimate of deviations from natural conditions with A being natural/unmodified and F being critically modified. The ECs for the Koue Bokkeveld range from B (e.g. E21E, E21H and E21J) to a D (e.g. E21B, E21Ds and E21G) (Table 5.1). In order to meet the recommended ECs, Resource Quality Objectives (RQOs) are set which are hydrological (Table 5.2) and biophysical (Table 5.3) targets which, if met, will maintain the water resources in the stipulated EC.

Thus for catchment E21K, the hydrological RQOs can be said to have been met if there are visible summer flows, the discharge for December/January is >0.005 $m^3.s^{-1}$ and >80% of the floods occur at the right time of year (Table 5.2). Monitoring the RQOs is central to the operationalisation of the Reserve and therefore for ensuring the sustainable utilisation of the South Africa's water resources. Maintaining the condition of the biophysical components of catchment E21L will require complying with the conditions specified in each of the water quality, geomorphology, riparian vegetation, aquatic macro-invertebrates and fish components (Table 5.3).

The methodology proposed in this report is not meant to replace the RQOs, but rather to reinforce and complement them by providing quantitative hydrological measures of compliance, as well as supporting water allocations.

Table 5.1 Summary of the water resource Management Classes (MC) for Integrated Units of Analysis (IUAs) and Ecological Categories (ECs). The Mainstem Cumulative Category refers to flows and impacts together with all upstream flows and impacts. The Average Tributary Incremental Category refers to the river segment only (Department of Water and Sanitation 2015).

IUA	MC for IUA	Quaternary catchment	River Name	Mainstem / Cumulative EC	Average Tributary / Incremental EC	Wetland area (% of quaternary) and [Ecological Category]
Koue Bokkeveld	II	E21A	Kruis	C	C	-
		E21B	Welgemoed	D	D	-
		E21C	Winkelhaak	C	B	0.5% [98% in AB]
		E21D	Houdenbeks	D	D	-
		E21E	Riet	B	B	-
		E21F	Riet	B	B	0.001% [91% in AB]
		E21G	Leeu	D	D	-
		E21H-Twee	Twee	B	B	-
		E21H	Leeu	B	B	-
		E21J	Groot	B	B	-
		E21K	Maatjies	B	B	1.7% [99% in AB]
		E21L	Groot	B	B	-

Table 5.2 Summary of hydrological RQOs for the Koue Bokkeveld rivers (Department of Water and Sanitation 2015).

IUA	Quaternary	Node	River	Location for monitoring	Ecological Category		RQO hydrology						
					2013	RQO	Visual (lowflows)	Month with lowest flow	Mean of month with lowest flow ($m^3.s^{-1}$)	Instantaneous drought absolute minimum ($m^3.s^{-1}$)	%nMAR (DWS 2013)	Floods in addition to Desktop Model (DWS 2013)	Implications of flood RQOs
Koue Bokkeveld	E21K	R 37	Matjies	Matjies	B	B	Visible summer flow	December/ January	0.005	-	60.4	>80% of natural floods for July, August and September	No in-channel dams
	E21L		Groot	E2H002	B	C/B	Visible summer flow	February	0.017	0.001	48.1	>80% of natural floods for July, August and September	No in-channel dams
	E21J	R38	Groot	EWR Site 6	B	B	Visible summer flow	February	0.010	0.001	48.1	>80% of natural floods for July, August and September	No in-channel dams
		-		Brandkraals	B	B	Visible summer flow	February	-	0.001	48.1	>80% of natural floods for July, August and September	No in-channel dams
	Tributary of Leeu in E21H	A1	Twee	Twee	B	B	Visible summer flow	February	0.125	0.001	60.4	>80% of natural floods for July, August and September	No in-channel dams
	E21G	R 41	Leeu	E2H007	D	D	Visible summer flow	February	0.010	0.001	13.2	>60% of natural floods for July, August and September	Limited in-channel dams

Table 5.3 Biophysical RQOs for the Koue Bokkeveld. TWQR = Target Water Quality Range (Department of Water and Sanitation 2015).

IUA	Quat	River	Location for monitoring	WQ	Geomorphology	Riparian vegetation	Macro-invertebrates	Fish
Koue Bokkeveld	E21K	Matjies	Matjies	Should comply with the TWQRs for aquatic ecosystems (DWAF 1996a) and the Fitness for use -Class I for agricultural use (DWAF 1996b).	-	-	-	At least one of *Labeobarbus capensis*, *Barbus calidus*, *Pseudobarbus phlegethon*, *Barbus serra*, *Labeo seeberi* should be present.
	E21L	Groot	E2H002	Should comply with the TWQRs for aquatic ecosystems (DWAF 1996a) and the Fitness for use -Class I for agricultural use (DWAF 1996b).	A riffle/run-pool sequence should be present at all flows.	Riparian vegetation should be intact and dominated by indigenous species. The presence of *Nerium oleander* should be strictly controlled. There should be no other alien species present.	Community should be dominated by Ephemeroptera, Trichoptera	*Labeobarbus capensis*, *Barbus serra* and *Labeo seeberi* should be present.
	Tributary of Leeu in E21H	Twee	Twee	Should comply with the TWQRs for aquatic ecosystems (DWAF 1996a) and the Fitness for use -Class I for agricultural use (DWAF 1996b).	-	-	-	*Labeobarbus capensis*, *Barbus serra* and *Labeo seeberi* should be present.
	E21J	Groot	EWR Site 6	Oligotrophic and should comply with the TWQRs for aquatic ecosystems (DWAF 1996a) and the Fitness for use -Class I for agricultural use (DWAF 1996b).	A riffle/run-pool sequence should be present at all flows.	Riparian vegetation should be intact and dominated by indigenous species. The presence of *Nerium oleander* should be strictly controlled. There should be no other alien species present.	Community should be dominated by Ephemeroptera, Trichoptera	*Labeobarbus capensis*, *Barbus serra* and *Labeo seeberi* should be present.
			Brandkraals	Oligotrophic and should comply with the TWQRs for aquatic ecosystems (DWAF 1996a) and the Fitness for use -Class I for agricultural use (DWAF 1996b).	-	-	-	At least one of *Labeobarbus capensis*, *Barbus calidus*, *Pseudobarbus phlegethon*, *Barbus serra*, *Labeo seeberi* should be present.
	E21G	Leeu	E2H007	Should comply with the TWQRs for aquatic ecosystems (DWAF 1996a) and the Fitness for use -Class I for agricultural use (DWAF 1996b).	-	-	-	*Labeobarbus capensis* and *Galaxias zebratus* should be present.

5.3 The STandardised REserve Analysis and Monitoring tool (STREAM)

The hydrological and biophysical targets outlined in the previous section are central to the operationalisation of the Reserve. However, sustainably managing water in a catchment and allocating water use licences requires a knowledge of water balances and the degree to which those balances are falling short of, or exceeding, the volumes required by the Reserve.

We propose in the ensuing sections, a simple spreadsheet-based model – the STandardised REserve Analysis and Monitoring tool (STREAM) – that will, within acceptable margins of accuracy, quantify the extent to which *hydrological* targets are being met in any catchment. The question of whether the biophysical RQOs are being met should be part of a separate monitoring programme using the tools recommended by the DWS for this purpose (Kleynhans and Louw 2007). STREAM can then be used to troubleshoot hydrological drivers and adjust water seasonal water distribution or individual allocations where these RQOs are not being met. It is believed that over time, understanding the relationships between STREAM outputs and RQO indictors will provide key insights into hydrological drivers of ecosystem change in the system and promote the sustainable use of water in priority catchments in an adaptive management context. STREAM is intended to provide a very basic level of monitoring – a step up from simply prescribing 'visible summer' or 'minimum' flows.

5.4 STREAM: structure and function

STREAM methodology is described in greater detail from Section 5.4.1 onwards, here we provide a brief step-by-step overview. As it currently stands, STREAM comprises a series of Excel spreadsheets incorporating a combination of data entry templates, mathematical and logical functions, together with pivot tables and graphic outputs that require basic Excel skills to generate. The steps are as follows:

***Preparatory steps**:*

a) *Ecological Reserve Management Areas*: secondary or quaternary catchment management areas within IUAs are identified based on biophysical, socio-economic or infrastructural congruency, as well as on the location of gauging stations (Section 5.4.1).
b) *Assimilating and preparing rainfall records*: for each management area, a set of indicator rainfall stations is identified and records are assimilated for the period under review (Section 5.4.2).

c) *Rainfall-runoff relationships*: historical rainfall records for each Reserve management area are assimilated from the WR2012 database and linear and non-linear regressions are used to estimate relationships between total monthly observed rainfall and simulated runoff over the historical period (from previously simulated data e.g. WR2012, or from the latest hydrology). This initial step is necessary to set the model up and requires a familiarity with regression analysis. However, once it the model is set up, STREAM can be run with limited expert input aside from periodic reviews (Section 5.4.3).

Analysis:

d) *Calculate aggregated catchment rainfall on a monthly basis*: the monthly rainfall data for the period under review which is assimilated in (b) above is entered into STREAM and catchment rainfall is aggregated for each Reserve management area (Section 5.4.2).

e) *Estimating natural flows*: The regression equations developed in (c) above are used to estimate natural flows in monthly volumes for the evaluation period – either monthly, biannually or annually depending on agreed upon assessment intervals.

f) *Convert natural flows to EWR equivalents*: the Reserve rule curves obtained from the gazetted flows, are then used to convert the natural flow volumes into EWR volumes and these are then compared to the observed flows.

g) *Calculate monthly time-series observed flows*: observed flow data from monitoring stations – DWS gauging stations or natural control sites – are assimilated and monthly flow volumes are calculated from these (Section 5.4.5).

h) *Plot the deficit/excess of observed flows vs EWR flows on monthly and annual basis*: The model then outputs simple bar charts indicating whether the observed flow volumes are above, below or equal to the EWR flows for the evaluation period on an annual and month-by-month basis (Section 5.4.5).

The sections that follow outline the above steps in greater detail.

5.4.1 Identifying Ecological Reserve Management Areas

Selecting appropriate Reserve management areas for this study was constrained by factors common to many of South Africa's catchments, i.e. limited rainfall stations and flow monitoring gauges, as well as the number, suitability and accessibility of natural hydraulic control sites. Ideally, for Reserve monitoring purposes, nodes should be located at the downstream outlet of quaternary or quinary catchments, since these are the units that correspond to simulated flows in national hydrological databases. If this is not possible, natural flows will need to be scaled to match the upstream catchment (Hughes 2004). In this study, monitoring nodes for each management area were selected at the downstream outlet of quaternary catchments E21G on the Leeu River (Node R41), E21L on the Doring River (Node R37) and E21E on the Riet River (Node R43) (Figure 5.1).

On the Twee River (E21H), however, the monitoring location was located at Node A1, some distance upstream of the Twee and the Leeu quaternary outlet (Figure 5.1) and downstream of the last abstraction point. This site was selected because of the presence in the river of the critically endangered Twee River redfin. It was therefore considered necessary to monitor the Twee separately from the Leeu. The hydrology at A1 was scaled to match the location of this monitoring site. Management areas were named in accordance with the monitoring nodes at their outlet as shown in Figure 5.1.

5.4.2 Assimilating and preparing rainfall records

STREAM uses rainfall data for three different computations. The first computation entails deriving rainfall-runoff relationships using monthly linear and non-linear regressions between observed monthly rainfall and simulated hydrology (Section 5.4.3). For this computation, historical WR2012 rainfall data is required and it is essential that the rainfall stations used in the original simulation are selected for the regressions. The second computation involves deriving aggregated catchment rainfall for the quaternaries in question and historical records (1920 to 2009) for each individual rainfall station must be entered separately into the model when it is first set up. In the third computation, rainfall records are used for assessing current flows in relation to EWR flows. For this last computation, the most up-to-date records will be obtained from local rainfall stations and from the SAWS.

For calculating aggregated catchment rainfall (the second computation), rainfall is aggregated for the years 1920-2009 using the Pitman model approach which derives catchment representative rainfall by averaging records from a number of stations within the catchment, or from those in close proximity to it. The method was developed to avoid bias in mountainous catchments with steep isohyetal gradients. The method gives equal weighting to all stations, but allows individual stations to vary even if there is only one station record available as shown in Equation 5.1:

$$PC = 100 \times [\sum(Pn/Mn)]/N \qquad \text{Equation 5.1}$$

where: Pn = monthly precipitation for rain gauge ‘n’; Mn = Mean Annual Precipitation for rain gauge ‘n’, N = Total number of rain gauges used in the averaging process and PC = catchment rainfall expressed as a percentage of its MAP. These equations are built into the spreadsheet which automates the calculation of aggregated catchment rainfall in the catchment of interest.

Hughes et al. (2008) recommends that rainfall stations be selected for the historical length of their records (>20 years), on the assumption that they will remain active for the foreseeable future and that they represent rainfall variation across the catchment. In the Koue Bokkeveld, most of the rainfall stations, with the exception of Excelsior (63807) contain records exceeding this period of time. The longest rainfall records are available from the forest station at Algeria (85112) that contains records for 104 years.

For the last computation (EWR flow assessment), monthly rainfall records ($mm.mon^{-1}$) for the Koue Bokkeveld were obtained for ten stations from the SAWS, Regional Office, Western Cape (Table 5.4 and Figure 5.1). All but two of these (63005, Citrusdal and 85112, Algeria) fall within the boundaries of the Koue Bokkeveld IUA. Mean Annual Precipitation (MAP) at these stations varied between a minimum of 263.2 $mm.a^{-1}$ at Odessa (42789) and a maximum of 680.7 $mm.a^{-1}$ recorded at Algeria (85112).

Selecting the correct rainfall stations is critical if the model is to produce accurate outputs. The WR2012 quaternary information datasheet should be used for this purpose to link quaternaries to corresponding rainfall zones. The correct rainfall station data for each quaternary can then be obtained from the aggregated rainfall sheets coded by rainfall zone.

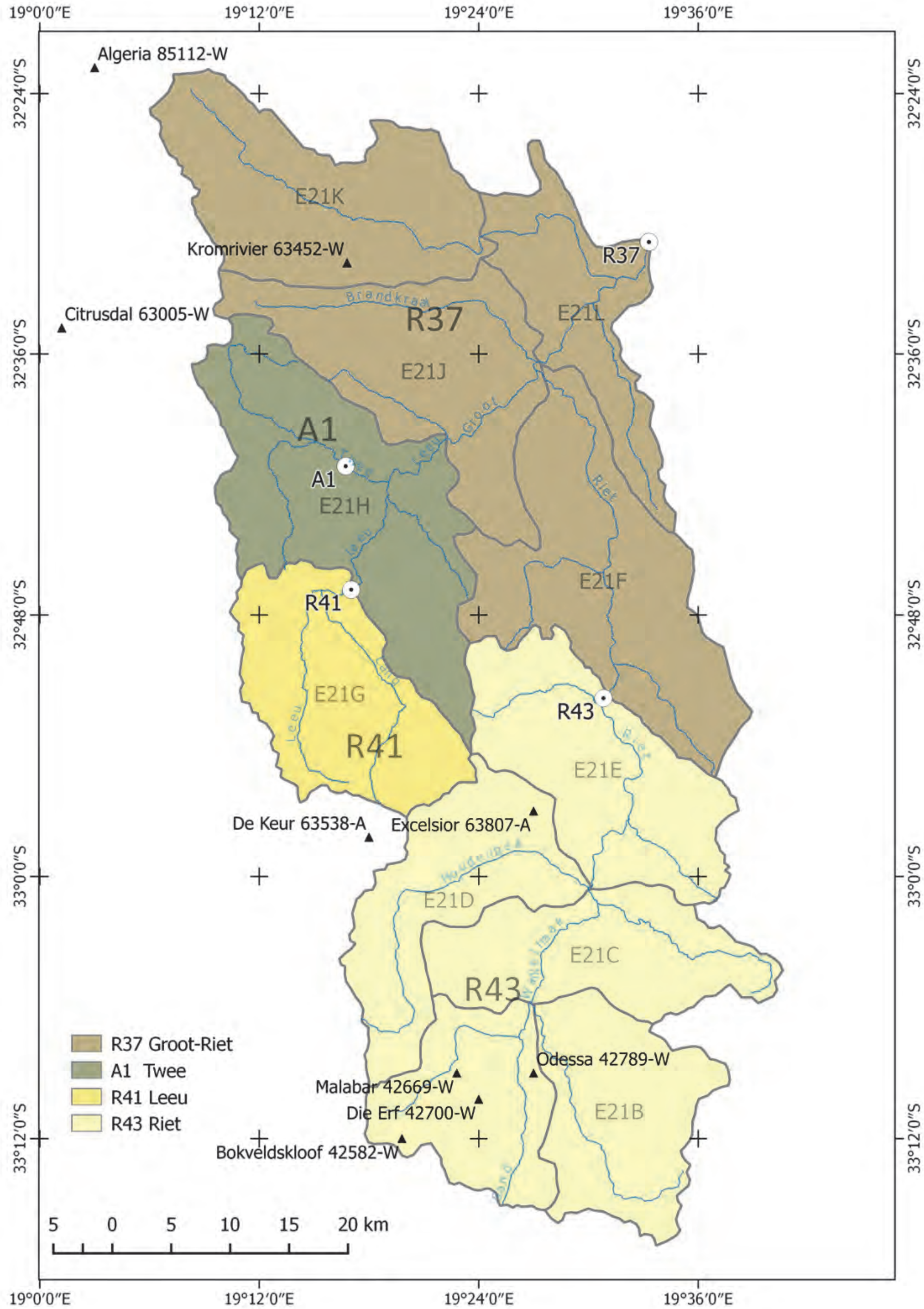

Figure 5.1 Koue Bokkeveld Reserve Monitoring Areas and Nodes: R37 Groot-Riet, A1 Twee, R41 Leeu, R43 Riet. Black triangles indicate rainfall gauges. Open circles indicate the location of gauging weirs or natural control sites for monitoring flows in each management area

Table 5.4 Rainfall gauges selected for the Koue Bokkeveld showing their coordinates, period of operation, MAP (mm), Standard Deviation (SD mm), Coefficient of variation and percentage of missing months.

Number	Name	Latitude	Longitude	Start	End	MAP(mm)	SD (mm)	CV %	%Missing months	Duration (years)
0042582-W	BOKVELDSKLOOF	-33.201	19.333	1932	2011	648.2	249	38.4	3.0	79
0042669-W	MALABAR FARM	-33.153	19.384	1943	2009	372	165.3	44.4	5.2	66
0042700-W	DIE ERF	-33.167	19.401	1993	2011	321.2	169.3	52.7	6.6	18
0042789-W	ODESSA	-33.153	19.452	1981	2011	263.2	90.6	34.4	6.7	30
0063452-W	KROMRIVIER	-32.534	19.285	1959	2011	315.1	174.4	55.3	10.4	52
0063538-A	DE KEUR	-32.969	19.302	1941	1988	624.1	186.2	29.8	22.9	47
0063005-W	CITRUSDAL	-32.579	19.019	1964	2007	310.1	157.8	50.9	7	43
0085112-W	ALGERIA	-32.380	19.049	1907	2011	680.7	210.6	30.9	0	104
0063807-A	EXCELSIOR	-32.952	19.452	1975	1988	492.6	181.4	36.8	21.4	13
0063807-W	EXCELSIOR E	-32.952	19.452	1992	2011	378.1	105.3	27.8	6.3	19

5.4.3 Estimating natural flows

STREAM estimates natural flow using month-by-month regression relationships between aggregated catchment rainfall ($mm.month^{-1}$) and simulated WR2012 runoff ($Mm^3.month^{-1}$). Both of these data can be obtained from the WR2012 database and are available for the years 1920 to 2009 for all quaternary catchments in the country. It is essential that the same stations used in the WR2012 simulation are used for the regression. Initially, an attempt was made to develop a single relationship for one year and all months combined, but it was found that the relationships during the drier months were linear, whereas during the wetter months they were exponential. Regressions were computed using the statistics package '*R*'. Figure 5.2 shows the relationships for catchment E21E. Linear equations were of the form:

$$MCMn = aPn + b \qquad \text{Equation 5.2}$$

Where MCMn is flow volume in month '*n*' and Pn is rainfall in month 'n'. Non-linear equations were of the form:

$$MCMn = a^{(bPn)} \qquad \text{Equation 5.3}$$

The regression relationship is derived from the modelled data only (October 1920-September 2009) and then applied to the observed rainfall from October 2010 onwards. Regression statistics and coefficients for the rainfall-runoff relationships for each month and of the catchments and months are reported in APPENDIX A.

5.4.4 Converting estimated natural flows to EWR flows

Once the rainfall-runoff relationships have been determined, it is necessary to translate natural flows into their Reserve equivalents. Reserve flows are typically represented as a set of Flow Duration Curves (FDCs) and converting from natural flows is undertaken by identifying the percentile into which the natural flows fall and then finding their corresponding Reserve percentile. This is illustrated in Figure 5.3 which shows a Reserve and Natural FDC in monthly volumes (Mm^3) during October for a hypothetical river. In this diagram, a flow volume of (a) 4.01 Mm^3/month is exceeded 60% of the time in this river under natural conditions. This natural flow volume corresponds to a Reserve volume of (b) 2.99 $Mm^3.month^{-1}$. The diagram shows two possible scenarios: a gauged (observed) flow higher than requested by the Reserve is indicated by (c) (3.5 $Mm^3.month^{-1}$) and a lower than requested flow is indicated by (d) (1.85 $Mm^3.month^{-1}$). Table 5.7 shows the same figure represented as an EWR 'Rule Curve' or table, with Natural and corresponding Reserve flows as they appear in the gazette. Thus for each month and 10 percentile interval there is a ratio of Natural to Reserve flows. It is this ratio which is used as a conversion factor in STREAM as shown in Equation 5.4:

$$EWR\ (m) = \frac{TRVmp}{NFVmp} \times nMEV \qquad \text{Equation 5.4}$$

Where: EWR (*m*) = Ecological Water Requirements for month *m*, TRV*mp* = Total Reserve Volume for a month *m* and percentile *p*, NFV*mp* = Natural Flows Volumes for corresponding month *m* and percentile *p* and nMEV = Monthly Estimated Natural Volume (all units are Mm^3).

5.4.5 Ecological Reserve Evaluation

Once EWR flow data have been calculated, observed flows can be downloaded from the gauging stations in the catchment for the period under investigation. For the Koue Bokkeveld, flow data from DWS gauges were supplemented by two additional natural control sites on the Twee and Riet Rivers as outlined in Section 3 and shown in Figure 5.1. Monthly volumes (Mm^3) can then be computed from the observed flow data in STREAM spreadsheet – either from daily average, or instantaneous flow – depending on how the data has been collected and reported.

Traditionally, FDCs as described in Section 5.4.4, are used to evaluate compliance with the Reserve. However, although these are familiar to hydrologists and ecologists, they are not easily interpreted by a wider audience.

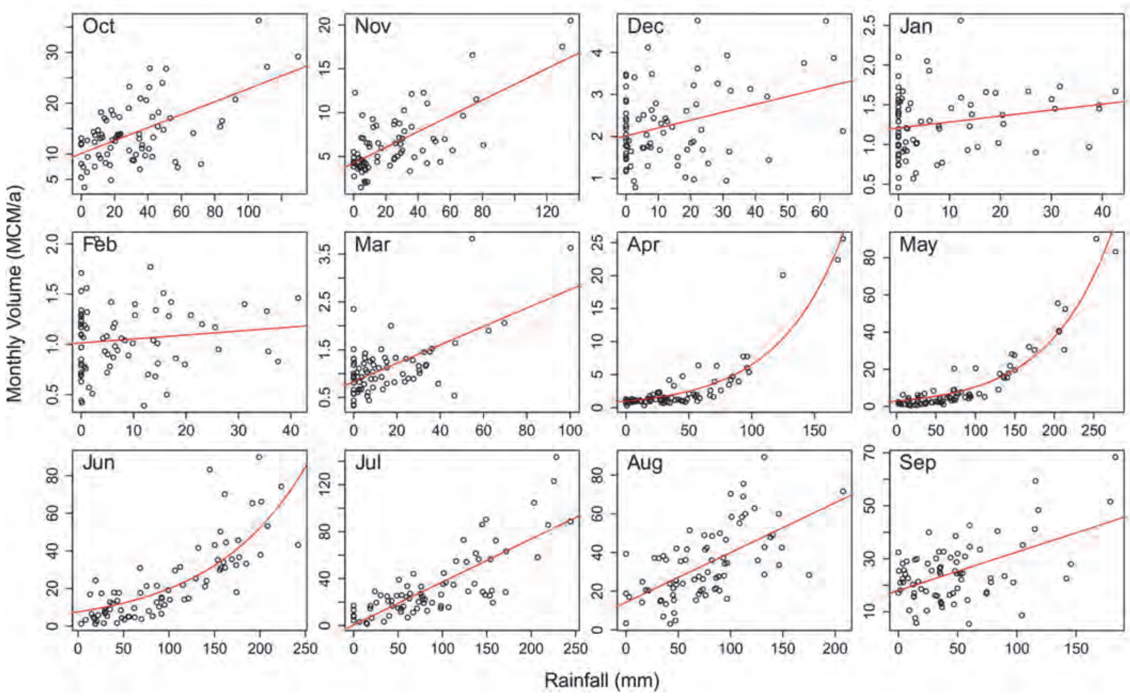

Figure 5.2 Monthly regressions between rainfall (mm) and WR2012 monthly volumes predicted by the WR2012 data ($Mm^3.month^{-1}$) for quaternary catchment E21E Node R43, Riet River (regression statistics and coefficients are reported in APPENDIX A).

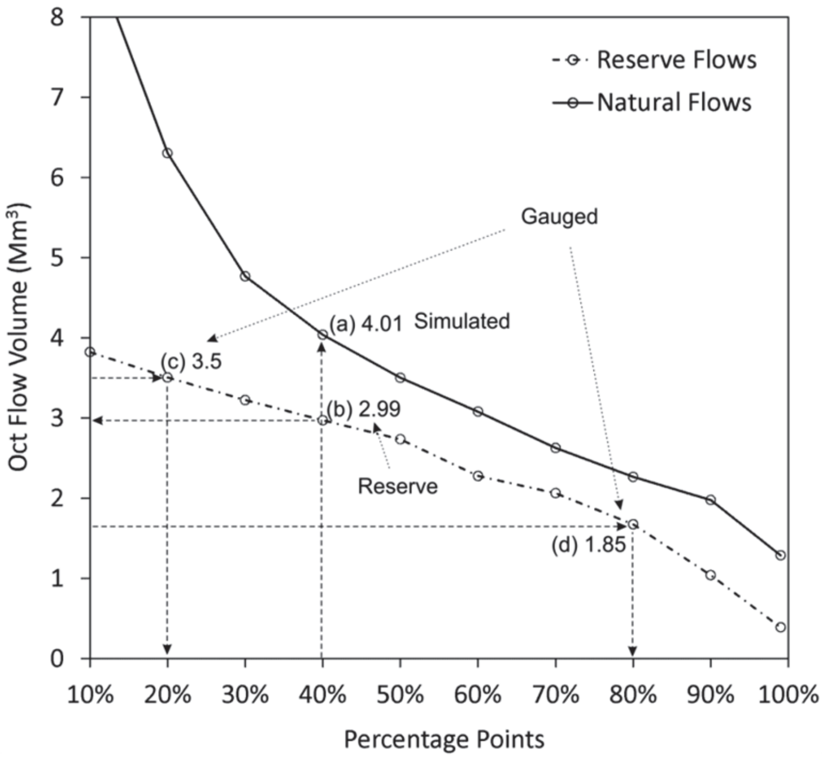

Figure 5.3 Natural and Reserve Flow Duration Curves (FDCs) in monthly volume (Mm^3) for the month of October for a hypothetical river: (a) Natural simulated flows, (b) corresponding Reserve flows at the 60th Percentile, (c) a gauged flow (high), (d) a gauged flow (low).

In STREAM, therefore, differences between EWR and observed flows are represented on bar charts with negative values indicating volumes less than the EWR, zero equal to the EWR, and positive values indicating volumes recorded in the river which were greater than the EWR. The bar charts make for a more immediate and visual interpretation of the data (refer to Section 1 for examples from the Koue Bokkeveld).

5.4.6 Measured Flow Indicators

Because of the acknowledged difficulties of monitoring Reserve flows and the uncertainties inherent in modelled hydrology, the hydrological RQOs list several indicators which would be relatively simple to derive from observed flows in each quaternary catchment. The most basic of these is visual low flows (Table 5.2) which simply require that an observer is able to discern flowing water in the river during summer. Other indicators which are relatively simple to derive from measured flows include month with the lowest flow, mean of the month with the lowest flow, instantaneous drought absolute minimum and % nMAR (which will depend on estimating natural flows).

Richter et al. (1996) developed the Indicators of Hydrological Alteration (IHA) statistical package for deriving biologically relevant hydrological statistics from time series of data. The IHA calculates 64 inter-annual statistics based on five fundamental characteristics of hydrological regimes, i.e. the magnitude, timing, frequency, duration and rate of change of flow. Similarly the Downstream Response to Instream Flow Transformations (DRIFT: King et al. 2004) enables the user to calculate any number of flow statistics from hydrological data.

Currently, in addition to providing monthly and annual flow volumes, STREAM reports some of the most important of these including mean monthly, as well as the value and the duration of the monthly 90th percentile flow (i.e. the lowest flows in the month). These figures are determined and evaluated in conjunction with the monthly volumes. Any number of additional indicators could be included in the future. However, the essence of STREAM remains its simplicity and it was felt that users should not be overwhelmed by large numbers of indicators which may be difficult to interpret for the non-specialist.

5.5 STREAM: operational description

Most of the calculations described above are undertaken only once when the model is initially set up. Once this is complete, the user will simply obtain the latest flow data downloaded from stage loggers or from the DWS website, the latest rainfall records from the local weather stations and enter these into the appropriate locations indicated in the spreadsheet. All calculations and outputs are then automated using a macro function.

The first step in setting up STREAM prior to running the model, is to identify the appropriate rainfall stations and analyse relationships between these stations and the simulated natural flows. The WR2012 Quaternary summary datasheets are consulted for identifying the rainfall driver stations (Table 5.5). For example, from Table 5.5, it is evident that catchment E21G – the Leeu River – falls within rainfall zone E2D. The rainfall stations for E2D, with their date intervals and coordinates are listed in Table 5.6. Monthly regressions can then be run against the naturalised flow data for the years 1920 to 2009. The flow data should be obtained from the WR2012 flow database and cumulative flows should be calculated if there are several quaternary catchment upstream. The data is then ready to enter into the Excel spreadsheets.

5.5.1 Worksheet structure

I1 INPUTS – Day to day: Flow from DWS or natural control sites and rainfall data from SAWS is entered into this spreadsheet by general users. The appropriate rainfall stations are automatically inserted in this spreadsheet as they are entered in the adjacent worksheets when they are set up for new sites. Detailed instructions for obtaining and entering the data are provided in the spreadsheet itself. The user will then navigate to "*O1 OUTPUT – Summary*" Tables and select the "*Update results*" button. The macro will automatically run the analysis and the results will be output as a set of table and graphs.

I2 INPUTS – Setup for new site: Entries into this spreadsheet should only be undertaken initially by a specialist in order to set the site up. Once the monthly rainfall-runoff regressions have been undertaken, the EWR Rule curves are obtained from the gazetted Reserve tables and entered this spreadsheet. Rule curves reported in discharges ($m^3.s^{-1}$) should be converted to volumes ($Mm^3.month^{-1}$) before doing so. The calculated regression parameters are entered into *Rainfall-natural streamflows* table. Rainfall data from the same stations identified in Table 5.6 can then be entered into the subsequent tables. STREAM is now ready to analyse any additional data entered into *I1 INPUTS – Day to day* unless new data become available, or any of the above relationships should change for some reason, no further intervention by a specialist is necessary.

O1 OUTPUT – Summary: This worksheet reports detailed summaries of the natural, measured and EWR flows on a monthly, quarterly and annual basis. This graph will mostly be consulted by general non-specialist operators.

O2 OUTPUT – Detailed Tables: This worksheet reports detailed summaries of the natural, measured and EWR flows on a monthly, quarterly and annual basis. It also reports a selected group of indicators derived from the measured flows including: maximum and average daily average discharge in each month, daily average discharges exceeding the 90^{th} percentile and their duration. These indicators will require specialist interpretation. A score is also calculated which is the percentage by which the EWR flows were exceeded (positive) or not met (negative). A zero indicates that the measured flows equalled the EWR flows. These scores will facilitate the setting of year on year targets.

G1 GRAPH – Time series: This graph plots the monthly volume ($Mm^3.s^1$) time series of natural, EWR and measured flows.

G2 GRAPH – Monthly: This graph will most often be consulted by non-specialist users on a quarterly or bi-annual basis to review the current conditions in the River. The monthly volume surpluses or deficits are plotted on a bar chart where negative bars (red) indicate volumes below the required EWR and positive bars (blue) indicated volumes above the EWR. If the bars fall on the centre axis, it indicates that the measured flows are equivalent to the EWR flows.

G3 GRAPH – Annual: This graph is essentially the same as the monthly graph, but here, annual as opposed to monthly volumes are reported. The bar chart will only updated once the data for one entire hydrological year is available and have been entered into the input tables.

Table 5.5 Hydrological summary from the WR2012 database of the Koue Bokkeveld: Tertiary catchment E21. Quaternary catchment E21G – the Leeu River is highlighted

	BASIC INFORMATION							NATURALISED FLOW (1920-2004) COMPARISON OF MAR AGAINST WR90				
	Catchment area		S-pan evaporation			Rainfall		MAR (WR90)	MAR (WR2005)		WR2005 to WR2012	Change
Quaternary catchment	Gross (km^2)	Net (km^2)	evap zone	MAE WR2005 (mm)	MAE WR90 (mm)	Rainfall zone	MAP (mm)	Net (mcm)	Net (mcm)	split	Net (mcm)	in MAR (percent)
E21A	190	190	23B	1660	1660	E2C	620	34.90	35.36		35.91	1.6
E21B	223	223	23B	1670	1670	E2C	497	26.90	27.07		27.74	2.5
E21C	233	233	23B	1675	1675	E2C	467	25.00	25.12		25.80	2.7
E21D	242	242	23B	1665	1665	E2C	627	45.40	46.03		46.71	1.5
E21E	293	293	23B	1680	1680	E2D	360	19.60	36.40	16.00	36.93	1.5
E21F	379	379	23B	1690	1690	E2D	289	16.50		20.40		
E21G	266	266	23B	1655	1655	E2D	475	30.60	31.23		31.08	-0.5
E21H	404	404	23B	1670	1670	E2D	429	38.10	39.07		38.84	-0.6
E21J	317	317	23B	1680	1680	E2D	338	18.80	19.12		19.20	0.4
E21K	330	330	23B	1680	1680	E2E	352	21.50	21.74		20.51	-5.7
E21L	195	195	23B	1700	1700	E2B	216	1.30	0.50		0.90	80.0
TERTIARY E21	***3072***	***3072***		***1675***	***1675***		***413***	***278.60***	***281.64***		***283.62***	**0.7**

Table 5.6 Rainfall stations in Rainfall Zone E2D used for deriving WR2012 naturalised flow data.

Stn. No.	MAP (mm)	PERIOD	LATITUDE	LONGITUDE
42669	379	1907-2008	33.09	19.23
63005	287	1907-1965	32.35	19.01
63005	375	1971-2007	32.35	19.01
63452	281	1907-1958	32.32	19.16
63452	373	1971-2009	32.32	19.16
85112	704	1907-2009	32.22	19.04

Table 5.7 EWR Rule curves for (a) Reserve flows and (b) Natural Flows. Units are M.m^3.

(a) Reserve Flows (Total Reserve Volume)

	0-10	*10-20*	*20-30*	*30-40*	*40-50*	*50-60*	*60-70*	*70-80*	*80-90*	*90-99*
Oct	1.207	1.194	1.162	1.092	0.964	0.772	0.542	0.337	0.212	0.183
Nov	0.773	0.762	0.734	0.672	0.565	0.422	0.28	0.18	0.134	0.128
Dec	0.297	0.293	0.282	0.258	0.216	0.162	0.109	0.072	0.056	0.055
Jan	0.133	0.131	0.124	0.108	0.081	0.055	0.033	0.021	0.016	0.016
Feb	0.094	0.093	0.089	0.068	0.047	0.03	0.021	0.007	0.001	0
Mar	0.073	0.072	0.069	0.062	0.05	0.033	0.018	0.006	0.001	0
Apr	0.167	0.165	0.159	0.148	0.127	0.096	0.059	0.026	0.006	0
May	1.198	1.187	1.162	1.11	1.014	0.854	0.631	0.369	0.168	0.019
Jun	2.427	2.406	2.357	2.257	2.07	1.762	1.328	0.827	0.4	0.103
Jul	4.387	3.941	3.554	3.206	2.862	2.287	1.919	1.401	0.798	0.342
Aug	1.767	1.656	1.552	1.438	1.234	1.069	0.836	0.569	0.339	0.233
Sep	2.349	2.129	1.936	1.748	1.412	1.213	0.933	0.616	0.354	0.248

(b) Natural Flows (Natural Flow Volume)

	0-10	*10-20*	*20-30*	*30-40*	*40-50*	*50-60*	*60-70*	*70-80*	*80-90*	*90-99*
Oct	5.388	3.819	2.922	2.5	2.127	1.907	1.604	1.373	1.2	0.781
Nov	2.993	2.098	1.403	1.065	0.938	0.803	0.739	0.64	0.509	0.334
Dec	1.427	0.635	0.473	0.36	0.28	0.239	0.208	0.177	0.142	0.088
Jan	0.572	0.196	0.142	0.108	0.081	0.062	0.05	0.035	0.027	0.019
Feb	0.546	0.251	0.115	0.068	0.047	0.03	0.021	0.017	0.008	0
Mar	1.156	0.34	0.165	0.092	0.062	0.045	0.027	0.016	0.007	0
Apr	2.841	1.684	0.846	0.493	0.357	0.227	0.127	0.064	0.035	0
May	10.903	6.178	3.549	2.262	1.923	1.2	0.701	0.369	0.2	0.019
Jun	16.515	10.227	9.039	6.767	5.29	3.719	3.036	1.828	1.037	0.103
Jul	13.429	10.333	9.479	8.23	6.618	4.732	3.334	2.515	1.358	0.342
Aug	11.912	9.506	8.156	6.425	5.772	4.457	3.619	3.188	2.046	0.839
Sep	8.231	6.369	5.619	4.736	4.053	3.42	2.853	2.471	1.943	1.2

6 KOUE BOKKEVELD CASE STUDY

6.1.1 E21H – A1 – Twee River

Twee River flow records at Node A1 in quaternary catchment E21H were analysed using STREAM between May 2013, when the stage logger was first introduced into the system by the study team, and June 2015 – although Figure 6.1 plots the simulated hydrology and EWR flows back to October 2009 (observed flow records are shown in red). The WR2012 hydrology estimated the nMAR at the outlet of E21H at 38.08 $Mm^3.a^{-1}$ (min = 12.4; max = 129.9). Node A1, however, is a sub-catchment within E21H and the nMAR therefore needed to be scaled by area to 18.6 $Mm^3.a^{-1}$ (min = 5.9, max = 62.3). STREAM estimated the nMAR at A1 between 2009 and 2014 at 19.5 $Mm^3.a^{-1}$ (min = 14.4, max = 28.46) which is well within range of the WR2012 estimates for the sub-catchment. However, the EWR appears to have overestimated the nMAR for Node A1 which is reported at 55.0 $Mm^3.a^{-1}$ – significantly higher than the WR2012 value. This explains why the EWR is requiring between 90 and 100% of the monthly volume at this site (Figure 6.1) and flows are failing to meet the EWR by a significant margin – particularly over the winter months which is unusual for the Western Cape (Figure 6.2). The EWR rules will need to be reviewed in this instance before conclusions can be reached with regards to the state of the river. Because of the exceptional biodiversity importance of the rivers in this catchment, the Reserve was set at 60.37% of the nMAR. If this figure is applied to the 2013 hydrological year, measured flows were only reaching 27% of the nMAR – considerably less than required, but not as much as what is suggested in Figure 6.1 and Figure 6.2.

Measured flow statistics for the Twee River at A1 show that maximum average daily flows for the period on record do not exceed 2.5 $m^3.s^{-1}$, mean average daily flows were 0.17 $m^3.s^{-1}$ and minimum average daily flows were 0.09-2.5 $m^3.s^{-1}$ (APPENDIX B, Table B.1). This appears to suggest that overall, the system has lost a considerable component of its natural variability which would support claims by landowners that the river is gradually being terrestrialised, with a significant loss of open water areas and invasion by the indigenous palmiet (*Prionium serratum*).

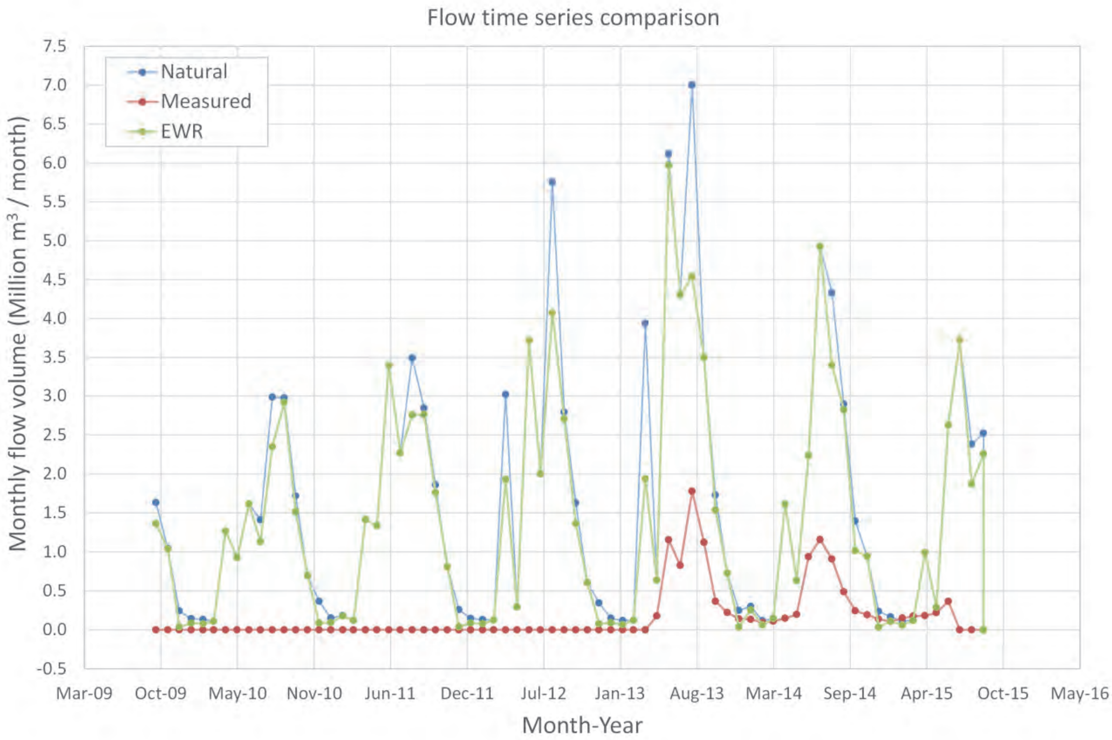

Figure 6.1 Flow time series comparison of natural, measured and EWR flows in monthly volumes ($Mm^3.month^{-1}$) for monitoring node A1 in quaternarry catchment E21H on the Twee River between May 2013 and Jul 2015.

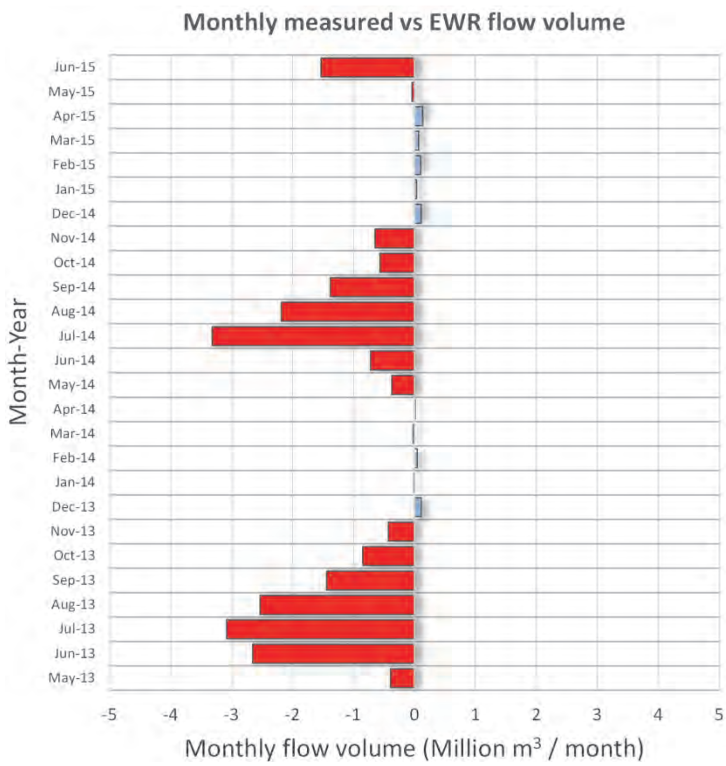

Figure 6.2 Monthly volumes ($Mm^3.month^{-1}$) greater (blue), or less than (red) the EWR flows for monitoring node A1 in quaternarry catchment E21H on the Twee River between May 2013 and Jun 2015.

6.1.2 E21G – R41 – Leeu River

Leeu River records at the downstream outlet of quaternary catchment E21G were analysed between October 2009 and July 2009. The WR2012 hydrology estimates the nMAR for E21G at 31.08 $Mm^3.a^{-1}$ (min = 9.9; max = 101.9). STREAM estimates the nMAR between 2009 and 2014 at 27.7 $Mm^3.a^{-1}$ which is within range of the WR2012, but considerably lower than the average recorded flows at gauging weir E2H007 (48. 8 $Mm^3.a^{-1}$) over the same period. This discrepancy is evident in Figure 6.3 which shows the measured flows as being higher than the natural. The model has therefore either underestimated natural flows, or the natural hydrology has not been calibrated with the weir. The consequence of this is that the EWR flows are likely to be underestimated in Figure 6.4 which shows that, for the most part during the winter months, flows in the river exceed the EWR by between around 5 and 25 $Mm^3.month^{-1}$. During the summer, the EWR is mostly being met, but occasionally falling below the EWR by around 2 $Mm^3.month^{-1}$. If natural flow estimates are indeed reliable, this would indicate that there is between 20 and 50 $Mm^3.a^{-1}$ available in the catchment over and above the EWR, but that its distribution through the year is unfavourable – i.e. that more of it should be made available through the summer months when the river is most stressed – particularly October, November and December when many organisms are undergoing critical phases of their life histories.

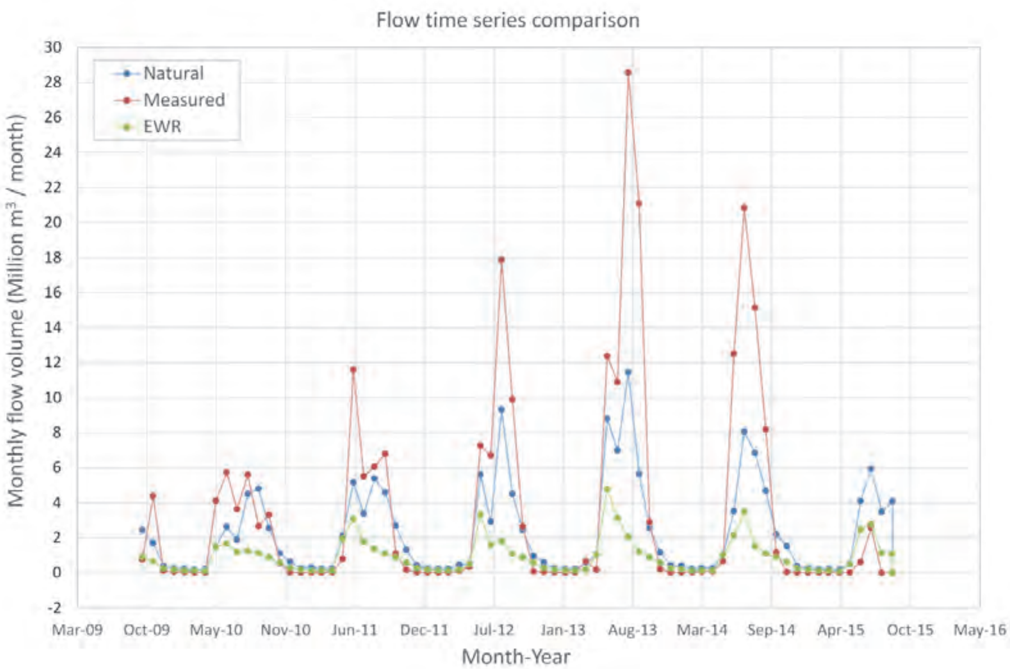

Figure 6.3 Flow time series comparison of natural, measured and EWR flows in monthly volumes ($Mm^3.month^{-1}$) for monitoring node R41 in quaternarry catchment E21G on the Leeu River between Oct 2009 and Jul 2015.

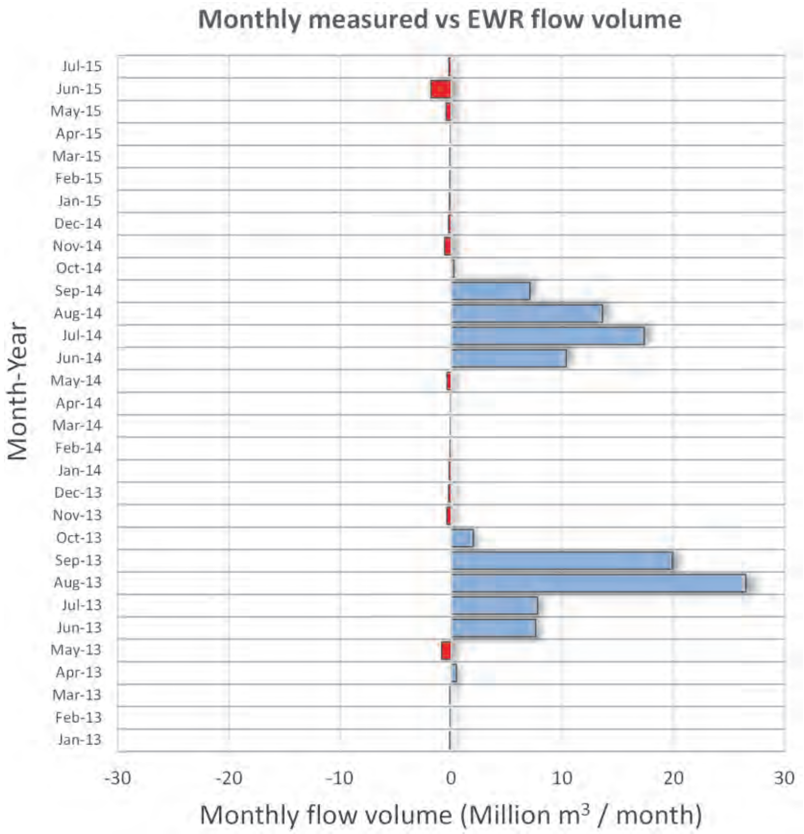

Figure 6.4 Monthly volumes ($Mm^3.month^{-1}$) greater (blue), or less than (red) the EWR flows for monitoring node R41 in quaternarry catchment E21G on the Leeu River between Jan 2013 and July 2015.

Examination of the measured flow statistics produced by STREAM (APPENDIX B, Table B.2) suggests that the river is particularly stressed during March and April when very low flows (<0.005 $m^3.s^{-1}$) may persist for more than half the month.

6.1.3 E21E – R43 – Riet River

The period of the Riet River assessment is much shorter than the Leeu and the Doring since stage loggers were only installed in 2013. These then are the first records available since 1948 when the DWS gauging weir on the Riet became unserviceable. This is the most arid and variable system in the catchment and the nMAR varies here between a minimum of 41.9 and a maximum of 560.2 $Mm^3.a^{-1}$. The WR2012 hydrology estimated the nMAR at 152.16 $Mm^3.a^{-1}$. Riet River flow records at the downstream outlet of quaternary catchment E21E were analysed between October 2009 and July 2009 with STREAM which estimated the mean 2009-2014 nMAR at 222.5 $Mm^3.a^{-1}$ (min = 158.2, max = 352.5) – these are in range of the WR2012 estimates (Figure 6.5). For the year 2013, which is the only complete hydrological year available to date, the annual runoff was measured at Node R43 as 12.3 $Mm^3.a^{-1}$ – a fraction of the driest simulated hydrological year – as well as of the annual EWR requirements for that year (41.3 $Mm^3.a^{-1}$). Figure 6.6 shows that flows in the Riet River are failing to meet the EWR in every month, but especially during the winter months, by as much as 13 $Mm^3.month^{-1}$. This is contrary to the pattern elsewhere in the catchment where the summer months are most affected by abstraction. The reason for this is that the Riet is a naturally seasonal system with long periods of no-flow conditions expected during the summer – a condition that remains unchanged under the present circumstances where extensive agricultural abstraction upstream keeps these summer months low, but extends them into the wet season. The only period where the recorded flows are above the EWR in September and August of 2013. Examination of the measured flow statistics produced by STREAM show that zero flow conditions prevail in the river all year, save for the months August to November, and that even during these months, flows may cease for three or four days at a time (APPENDIX B, Table B.3). Daily average flows did not exceed 18 $m^3.s^{-1}$.

6.1.4 E21L – R37 – Doring River at Aspoort

The Doring River records from the Aspoort weir at the downstream outlet of quaternary catchment E21L were analysed between October 2009 and July 2009. The WR2012 estimated the nMAR at 283.62 $Mm^3.a^{-1}$ (min = 88.2; max = 929.9). STREAM estimated the nMAR between 2009 and 2014 at 405.11 $Mm^3.a^{-1}$ (min = 288.6, max = 634.62) which is slightly elevated, but within range of long term WR2012 estimations. Figure 6.7 shows the time series comparison between natural, measured and EWR flows with the wettest year being 2013. For the most part, measured winter flows exceed EWRs, whereas during February, March and April, river flows are equivalent to the EWR flows (Figure 6.8). During July of 2013 and 2015, EWR flows were not being met by a comparatively wide margin in relation to the remainder of the months on record. The reason for this is not clear. The pattern may be related to water management practices in the catchment, but it also may be related to inconsistencies in the EWR rule curves, or natural hydrology.

Figure 6.8 provides an example of an annual output, showing the annual EWR was met in all years except for 2009 when there was a shortfall of 24.7 Mm^3. Examination of the measured flow statistics produced by STREAM for Aspoort from weir E2H002 show that zero or very low flow conditions (<0.1 $m^3.s^{-1}$) prevail in the river for a significant proportion of the time in February, March and April (APPENDIX B, Table B.3). Maximum daily average flows between 2009 and 2014 reached as high as 190 $m^3.s^{-1}$.

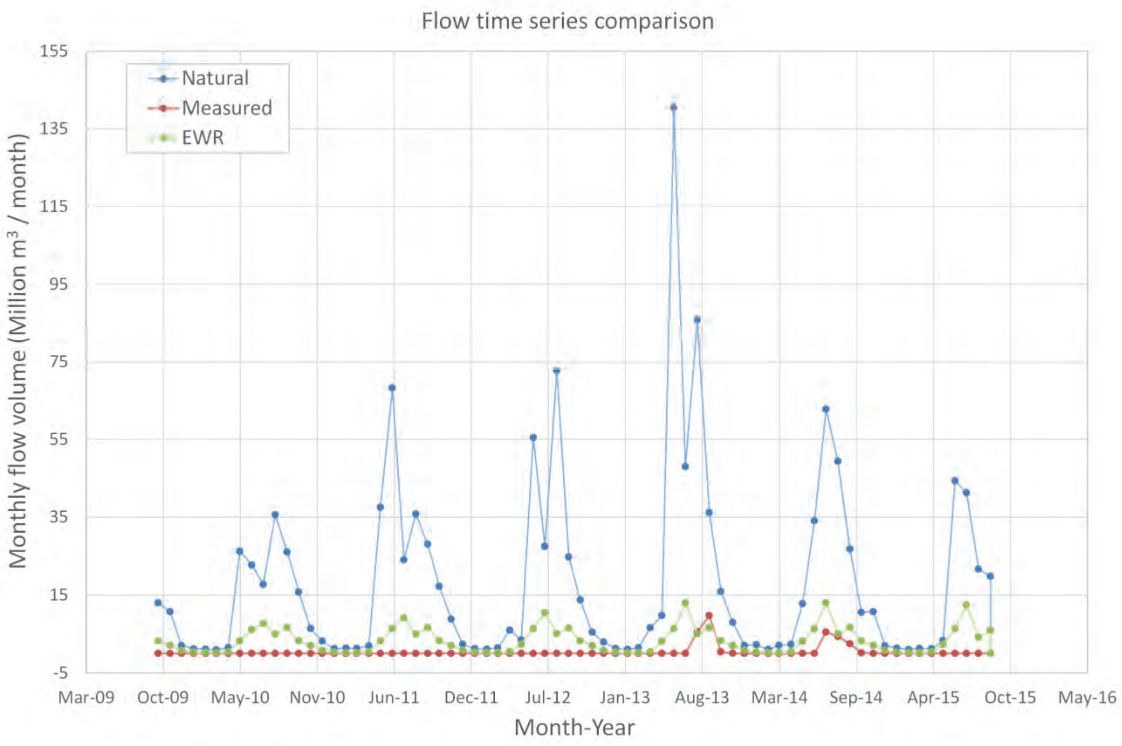

Figure 6.5 Flow time series comparison of natural, measured and EWR flows in monthly volumes ($Mm^3.month^{-1}$) for monitoring node R43 in quaternarry catchment E21A to E21E on the Riet River between Oct 2009 and Jun 2015.

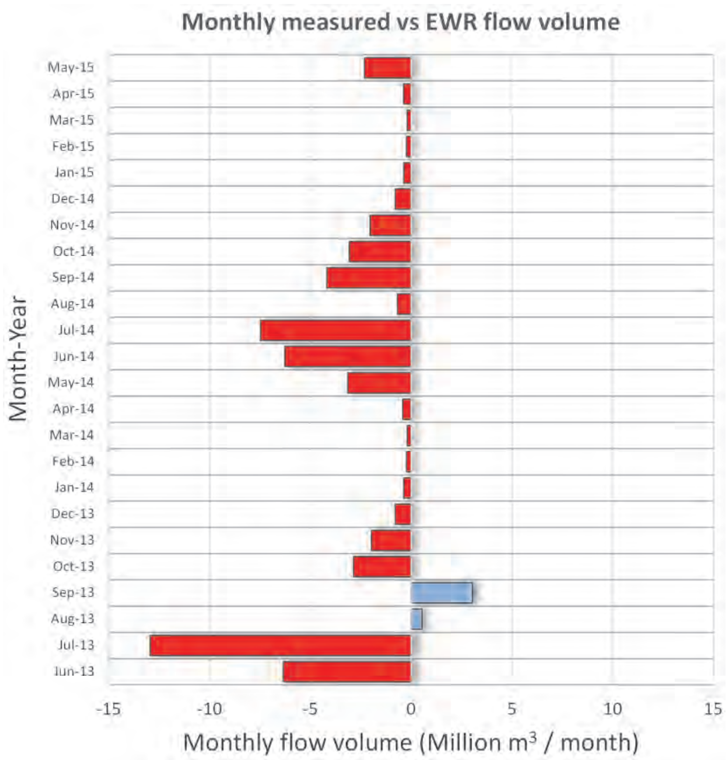

Figure 6.6 Monthly volumes ($Mm^3.month^{-1}$) greater (blue), or less than (red) the EWR flows for monitoring node R43 in quaternarry catchment E21A-E on the Riet River between Jun 2013 and May 2015.

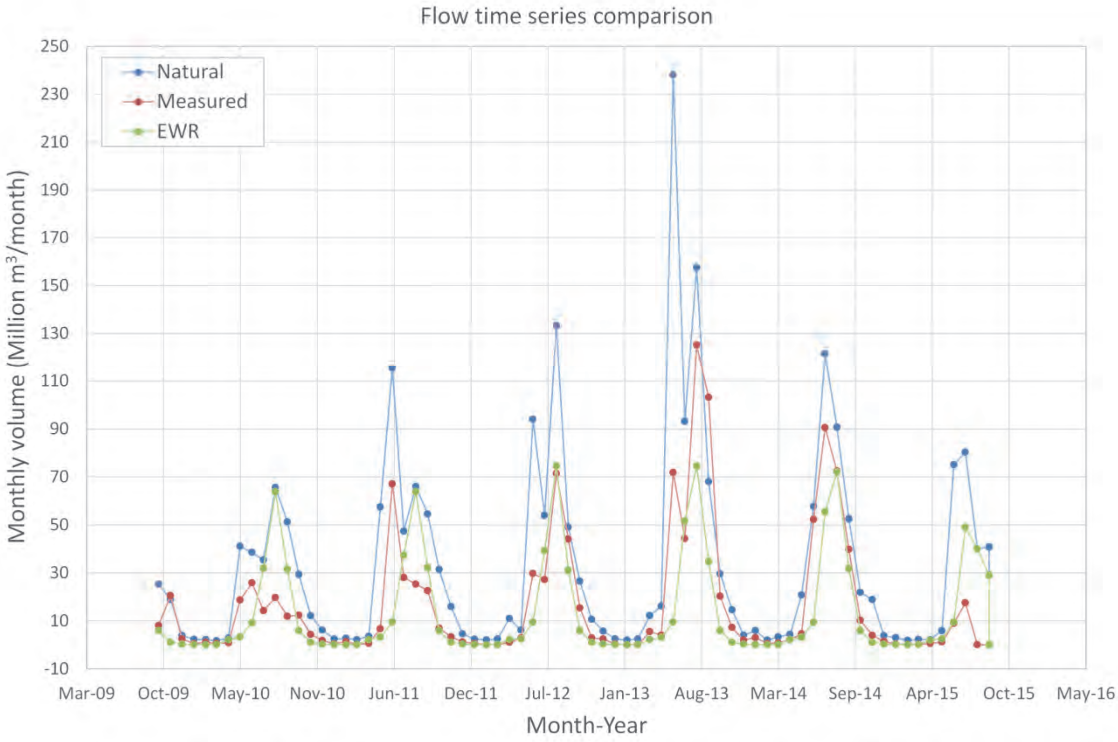

Figure 6.7 Flow time series comparison of natural, measured and EWR flows in monthly volumes ($Mm^3.month^{-1}$) for monitoring node R37 in quaternarry catchment E21A to E21L on the Doring River at Aspoort between October 2009 and July 2015.

6.2 Lessons from the Koue Bokkeveld

Based on our analysis of EWR flows in the Koue Bokkeveld, we are of the opinion that STREAM is reliable and appropriate for its purpose provided the input data is of an acceptable standard. It may become especially valuable in smaller catchments of high conservation worthiness, where faithful adherence to the Reserve needs to be balanced against socio-economic realities. It is able to produce a range of ecologically meaningful flow metrics and provides a valuable way of interrogating natural, as well as the Reserve hydrology. It has a simple user interface and its outputs will be readily understood by a wide audience. Water balances in the catchment and possible management solutions can be readily assessed and mitigations planned.

However, it is necessary to qualify our endorsement of STREAM with several provisos. Firstly, estimating the natural hydrology of sites in upper tributary reaches is much less reliable than those further downstream (Kleynhans et al. 2008a). This is demonstrated by the uncertainty of EWR and natural flow estimations on the Twee and Leeu Rivers which are less reliable than those at Aspoort – the most downstream site in the study area.

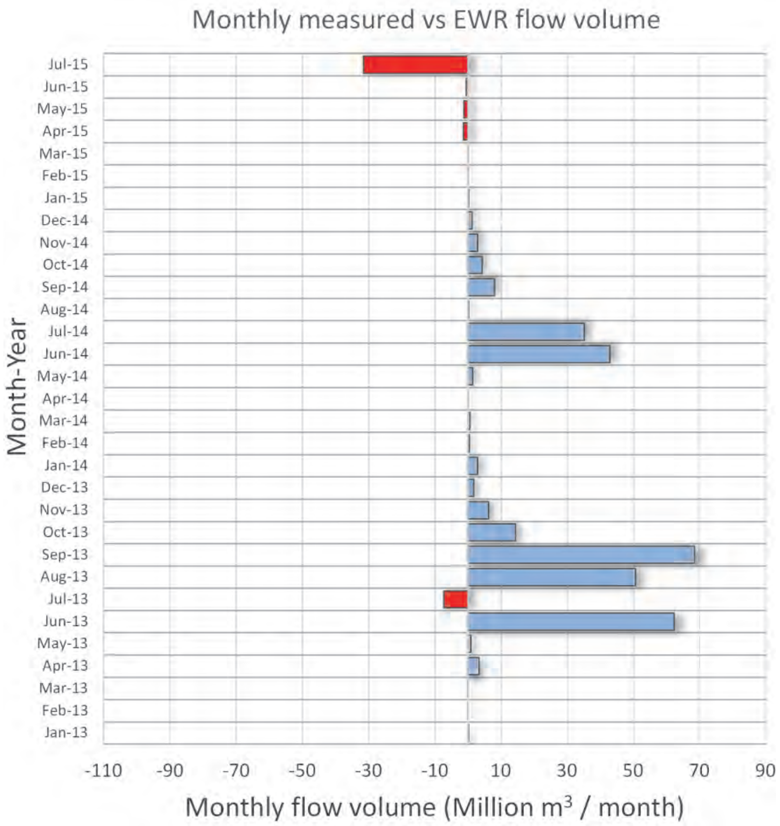

Figure 6.8 Monthly volumes ($Mm^3.month^{-1}$) greater (blue), or less than (red) the EWR flows for monitoring node R37 in quaternarry catchment E21A to E21L on the Doring River at Aspoort between Jan 2013 and July 2015.

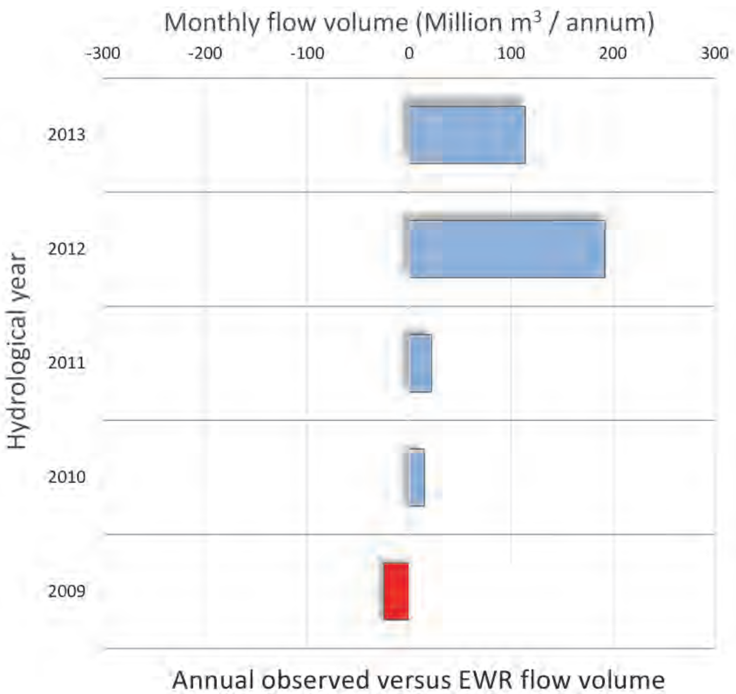

Figure 6.9 Annual volumes ($Mm^3.month^{-1}$) greater (blue), or less than (red) the EWR flows for monitoring node R37 in quaternarry catchment E21A to E21L on the Doring River at Aspoort between 2009 and 2013.

In this regard, it is of the utmost importance for specialists to rigorously review STREAM input data when a new catchment is set up. Checks and balances need to be built into future versions to ensure that errors are not perpetuated. Furthermore, it is essential during the Reserve determination process that practitioners record and report on all their deliberations. Often important information relating to hydrological estimations are not provided in EWR documentation. In some instances, details on what decisions were made, and which parameters were used in particular catchments are only available from the practitioners themselves who undertook the study. Once this information is documented, it is then up to the relevant authorities to manage its dissemination in such a way as to ensure that it is current and widely available for both Reserve monitoring and review purposes.

It should be noted that the routing of flows in a catchment to obtain EWRs for tributary sites is prone to error, especially if this is undertaken at a sub-quaternary scale. The very high nMAR estimated for the EWR flows at the Twee site testifies to this. It also highlights the importance of carefully interrogating and reviewing EWR outputs before they are gazetted.

What STREAM makes abundantly clear in its estimations is that summer low flows are especially vulnerable to alterations in rural Western Cape catchments – particularly during October, November and December when many organisms are undergoing important phases of their life histories including emergence, flowering, migration and reproduction. Increasing storage infrastructure and re-allocating winter flows to the summer months has been suggested as a means to mitigate this. In some catchments, like the Riet, this would well-near be impossible since there is simply no more water to be had. The Riet is essentially a ‘closed’ catchment and any further interventions would require stricter adherence to water conservation and demand management measures, or reducing the number of hectares under irrigation. However in other catchments like the Leeu, shortfalls over the summer months could be augmented relatively easily with winter flows. Caution should, however, be exercised that firstly; additional dam infrastructure does not further impact low flows, i.e. that dams are located along ‘off-channel’ or seasonal drainage lines and that secondly, that any new dams don’t compromise high flows – particularly 1-in-2 year flood events and higher which are responsible for structuring channel morphology and riparian zonation. Care should also be exercised that a reduction in high flows from the Koue Bokkeveld will not compromise flows to the estuary which relies on winter flows to keep it open.

In addition to its value in monitoring the EWRs, the potential for STREAM to contribute to understanding ecosystem dynamics is substantial if linked with regular biological monitoring programmes. Of particular interest in this regard is the response of the endemic fish populations to inter-annual flow variations. Further research into these responses will refine the selection of significant ecological indicators and enhance our understanding of biotic-abiotic links in the system.

7 SUPPORTING AND PROMOTING ECOLOGICAL RESERVE MONITORING IN PRIORITY CATCHMENTS IN SOUTH AFRICA

7.1 Ecological Reserve compliance and STREAM

STREAM is not intended to assess whether the Reserve is being legally complied with in terms of the National Water Act. As Pollard et al. (2012) has suggested, the issue of compliance needs to be interrogated beyond the simple fact of whether a certain hydrological value has exceeded a threshold or not, i.e. whether non-compliance equates to 'anything below the Reserve'. Pollard et al. (2012) provide an extensive review of the subject, but it is worth reiterating and reinforcing some of their points here.

In terms of the National Water Act, the Reserve comprises both the quantity (magnitude, duration and timing), was well as the quality of the water resource. Reserve 'quality' is reflected in the set of RQOs as discussed in Section 5.2. Any discussion on compliance should provide clear differentiations between Reserve implementation, determination and operationalisation. Pollard et al.'s (2012) definitions of these words in the context of the Reserve are listed here and expanded on as follows:

- *Implementation*: strategic actions that ensure the Reserve is incorporated into policy, that it is provided institutional support and that the appropriate determination methodologies are developed, reviewed and available. Implementation includes both determination and operationalisation.
- *Determination*: includes the set of macro-planning processes and methodologies required to estimate the quantity and quality of water required by human communities and aquatic ecosystems in order that the negotiated desired state of these systems be met.
- *Operationalisation*: includes projecting Reserve requirements for a predefined management period, monitoring, regulation, enforcement, reflection (review) and learning.

This study, therefore addresses an aspect of operationalisation, and in particular, the quantity component of the Reserve. Pollard et al. (2012) suggest that it would be inadvisable to consider failure to meet a certain threshold of flow as non-compliance and a legal transgression for a number of reasons, chief among these being the level of uncertainty inherent in the determination and monitoring processes themselves. If confidence levels could be estimated for Reserve estimates, compliance could be judged on the upper levels of those intervals – for example within or outside 95% confidence bands. However, due to the inherent uncertainties in hydrological modelling and rudimentary understanding of biotic-abiotic links in aquatic ecosystems, as well as the multi-disciplinary nature of environmental flow estimation, such levels of confidence would be impossible to estimate. Aquatic ecosystems are complex, non-linear systems that feature exceptionally high levels of intra- and inter-annual variability. Thresholds would therefore be indefensible.

As an alternative to 'compliance', Pollard et al. (2012) suggest the Reserve be approached as a 'working hypothesis' that requires monitoring in order to assess whether it is achieving the state desired for the system at the outset of the classification process. Rather than a threshold, they suggest the Reserve be assessed by tracking trends, setting Thresholds of Potential Concern (TPCs), testing outcomes against realistic management interventions and adjusting these where necessary within the framework of an iterative, adaptive management approach. In this regard, stakeholder participations is essential, together with a willingness to engage with the data, work towards targets and show progress. In this regard, we suggest using the scoring system built into STREAM that ranks the negative or positive deviation from the EWR as a percentage. The advantage of this approach being that the scoring de-couples the assessment from less reliable quantitative estimates and links it rather to repeatable, year-on-year performance targets.

7.2 STREAM: advantages and opportunities

Jackson (2014) suggests that while water resources modelling is used widely for planning in South Africa, it is less often used for operations. STREAM, in its first iteration, is a modest attempt to address this. The advantages of STREAM include the fact that the model can be set up by someone with limited expertise in hydrological modelling, but who has some experience of regression modelling and a good knowledge of the basic principles of environmental flow science. However, a qualified hydrologist should be available from the start to review and assess the quality of the input data and model outputs. Once the model is set up for a certain catchment, it simply requires updating on an annual or quarterly basis when new rainfall and flow data become available. This task can be undertaken by personnel with moderate technical skills levels within WUAs, CMAs, regional DWS offices, conservation authorities or NGOs. The review process, and target-setting can take place within those organisations, within local government organisations, or through the DWS.

STREAM has significant advantages for supporting the operationalisation of the Reserve for a number of reasons. Firstly, it provides estimates of water balances in the catchment on a month-by-month basis. Prior to the commencement of this study, aside from Howard (2010), there was very little information on the availability of water in the Koue Bokkeveld, none of this information was accessible to a broader non-specialist audience and it was not up-to-date. Consequently, urgent decisions that needed to be made with regards to water supply and infrastructure were based on low confidence estimates and historical data.

In the future, it is believed that the use of STREAM has the potential to support directives with regards to water allocations in the catchment and that these can be issued with greater confidence in the sustainability of outcomes. The consequences of the directives – or contraventions of them such as illegal dams, water abstractions or transfers within the catchments – can be monitored and remedied more readily. Thus, while failure to meet hydrological Reserve as defined by hydrological thresholds may not constitute a legal transgression, contraventions of local authority directives such as those mentioned above certainly would.

Section 7.1 discussed STREAM within the broader context of Reserve compliance monitoring and operationalisation. In this respect, it is clear that STREAM should be used in conjunction with monitoring protocols that cover the RQOs set for the catchment. It should be acknowledged, however, that local CMAs are currently not sufficiently well-resourced to undertake regular biophysical monitoring programmes. In this respect, STREAM holds a significant advantage in that it provides a remote and continuous monitoring intervention that, in the absence of regular RQO monitoring, can provide a proxy indicator of ecological condition – provided biotic-abiotic links are well understood. Indeed, the use of STREAM – together with rainfall and flow monitoring in general – would support more focussed studies aimed at increasing understanding of the links between biotic and abiotic processes. Confidence with respect to the response of aquatic ecosystems to flow change therefore would be significantly improved and would provide valuable benchmarks against which RQO monitoring protocols and Ecostatus models (Kleynhans et al. 2008b) could be calibrated.

Like the hydrological and Reserve determination methods upon which the method is built, there is a significant amount of uncertainty in STREAM with regards to natural flow estimation. The advantage of STREAM, or similar models, is that it is objective, repeatable and its outputs can be interrogated and reviewed when more accurate data become available. This means that the identification of year-on-year trends is possible and that inherent uncertainties will reduce over time and with increased use.

7.3 General limitations and constraints of Reserve monitoring

A more widespread commitment to monitoring the Reserve in less well-resourced catchments in South Africa is being hampered by a lack of monitoring infrastructure, a poor understanding of and appreciation for the provisions contained within the Reserve, as well as the logistical and technical complexities of assimilating, analysing and interpreting Reserve flow data. In this study we selected a case study catchment which exemplifies many of these problems, i.e. a catchment deemed to be of high conservation importance (i.e. that contains FEPAs), one that has limited rainfall and flow monitoring infrastructure and technical capacity, a de-centralised abstraction and storage infrastructure with multiple users and challenging hydrology. Under these circumstances, we have strived to produce as elementary a model as possible that aims to surmount some of these impediments.

Very early in the study, in became apparent that for all practical purposes, real-time monitoring would be unachievable. This same conclusion was reached by Pollard et al. (2012). Furthermore, we found it would not be possible to monitor the Reserve using daily discharges unless certainty in the hydrological models could be improved – particularly with regards to low flows. Both these limitations were attributable to the complex nature of the catchment – a steep climatic gradient combined with extensive wetland storage areas. These factors all contributed to limiting the robustness of the hydrological models.

We therefore settled for monitoring monthly volumes as a minimum requirement and combined this with a selected number of flow indicators to provide a best estimation of the degree to which the Reserve is being met on a month-by-month, a quarterly or annual time interval. From an ecological perspective, this is less than ideal since any given monthly volume of water could have be delivered through the whole month, or over a short period of a few days. This has vastly different consequences for the biota that may require either a series of small spates, a large flood, or a constant, invariable flow of a certain magnitude over the season. The limitations of monitoring monthly volumes therefore need to borne in mind and careful attention needs to be accorded the flow hydrograph itself, as well as the set of flow indicators that have been provided in STREAM. On the other hand, the advantage of using monthly flows volumes as an indicator is that these align with DWS planning units.

An important objective of this study was to assess whether daily, quinary catchment hydrology could be used to assess flows in smaller tributaries. It soon became evident, however, that the quinary catchment flows were overestimating base flows and that they would require significant adjustment of their parameters – particularly soil depth – if they were to be of use for Reserve monitoring. For this study, we used WR2012 hydrology and scaled the hydrology to the size of the tributary catchment where required.

Perhaps the most significant constraint to the more widespread implementation of any Reserve monitoring programme in the South Africa is the cost of rainfall data provided by the SAWS. Unless this cost is reduced for legitimate research and management programmes, managing the water resources of the South Africa will remain beyond the reach of most research, conservation and government bodies.

7.4 STREAM: limitations and constraints

STREAM does not assess whether the number of floods in each season was met. This may be possible in future versions, but it is important to note that these requirements were not reported in the Government Gazette and that in future, Reserve practitioners need to ensure that both the number, frequency and magnitude of floods is available to catchment managers through the gazetted flows. On the whole, Reserve data itself is not readily available unless the organisation which determined the Reserve is approached directly. Often it is not clear who undertook the study and where the reports or data can be obtained. Significant strides could be made if the correct information was available on online – this information could then be downloaded, analysed, critiqued and reviewed by a wide variety of users which would reinforce its robustness and reliability.

For the moment, STREAM exists as a simple spreadsheet format with a combination of formulas, logical functions, pivot tables and chart outputs with step-by-step instructions of how to proceed with an analysis. Anyone with a fair level of numeracy and an understanding of Excel should be able to conduct an analysis and interpret the results with a minimum understanding of the principles guiding environmental flow science. An executable software product was beyond the scope of the current study, but should the model prove effective for the purposes for which it has been intended, as well as tested in a sufficient number of catchments and under different conditions, further development as a self-contained executable software product would be considered. For the moment therefore, an Excel-based product provides the flexibility for further adaptation and testing.

It is important to note that STREAM would not be effective as a basin-wide tool, or for dam operating rules. It is best suited for smaller, tertiary- or quaternary-scale catchments where targeted interventions may be necessary, but where budgets and capacity may be limited. At present, it can only accept five rainfall stations, more rainfall stations would require more complex spreadsheets that would make the model unwieldy and increase the likelihood of errors.

7.5 Reducing uncertainties, increasing confidence

There are two major sources of uncertainty with regards to monitoring the Reserve. The first of these relates to uncertainties around the cumulative effect of upstream storage and abstraction infrastructure, municipal effluent and agricultural return flows and how these impact the river downstream. The second source of uncertainty relates to the accuracy of the hydrological and hydraulic models themselves in estimating natural flows (Section 7.3). Hydrological models depend on a number of regionalised parameters which are not necessarily applicable at local scales (Cibin et al. 2014; Schulze et al. 2011a). An additional level of uncertainty is introduced in STREAM where linear and non-linear regression is used to relate rainfall records to the simulated hydrological data.

One of the ways of reducing these levels of uncertainty is to update and increase the sophistication of the hydrological models themselves, but this may not always be affordable in smaller, under-resourced catchments. A far better way – and one that would serve the interests of any future modelling, as well as help to reduce any immediate uncertainties with regards to rainfall-runoff relationships – is to strengthen and support local monitoring networks and by adopting ‘citizen science’ approaches to monitoring, provided the data is reliably collected. Farmers are accustomed to collecting rainfall data and this is often the only rainfall data available in some catchments. This practice needs to be encouraged and expanded.

Further sources of error relate to the accuracy of rating curves at DWS gauging weirs or natural control sites. Rating curves at DWS gauging sites are sometimes outdated, leading to errors in estimates of recorded flows. Similarly, estimations of discharges at natural control sites are made difficult by complex river topography and year-on-year changes to the channel profile. Increasing confidence in the estimation of observed flows at natural control sites is best achieved by increasing the number of measured discharges and a constant review of stage-discharge relationships (Barnard and Rooseboom 2004). A re-survey of rating curve transects at natural control sites may be necessary at 3-5 year intervals depending on the geomorphological stability of the site. Ultimately, increased certainty with regards to estimating natural and simulated flows will improve over time and with repeated use, review and adjustment of the set of models available in each catchment.

Dams or run-of-river abstractions, or augmentations – from municipal effluent or agricultural return flows – further increase the uncertainties relating to ultimate causes of alterations to river flow downstream. Unlike more sophisticated basin models such as the WReMP discussed in Section 1.3, these are not accounted for in STREAM. Upstream storage, releases and routing of water is more difficult to monitor than river flows since they are continually changing (Maaren and Moolman 1986). The Water Authorisation Registration and Management System (WARMS) is the only national dataset providing information on water use in the country. It has a number of limitations, however, including the fact that the data depends on user registration and may be under-reported. In most instances it has not been validated or verified and it does not include small-scale non-registered users (Anderson et al. 2008). This validation and verification has not taken place in the Koue Bokkeveld to date, but Howard (2010) has estimated water demand for a number of sub-catchments in the region.

With respect to estimating storage capacity in a catchment like the Koue Bokkeveld characterised by many farm dams, Hughes and Mantel (2010) developed a model for simulating the impacts of many small farm dams in South African catchments. As it stands, STREAM assumes that the difference between natural and gauged flows is attributable to agricultural and municipal water use upstream without identifying direct causal factors. However, as already noted in Section 4.3.2, a significant amount of water is stored in large wetlands and this water may not accurately be captured by current hydrological models. Should STREAM be developed further, there may be opportunities for including water demand, but the far greater priority is seen as retaining its current simplicity and increasing confidence in the estimation of natural flows.

7.6 STREAM within an Ecological Reserve Management Framework

Natural resource management is, by its nature, inherently uncertain. Adaptive management i.e. 'learning by doing', has long been considered a useful paradigm for addressing that uncertainty in a number of environmental management fields. Rist et al. (2013) define adaptive management as a method of reducing critical uncertainties by undertaking diagnostic management experiments that involving six steps: (1) defining the management problem, (2) assessing current knowledge, (3) identifying the uncertainties, (4) implementing actions, (5) monitoring the effect of those actions and (6) evaluating and reflecting on the outcomes.

Kingsford and Biggs (2011) propose a Strategic Adaptive Management (SAM) system developed specifically to maintain water quantity and quality and ecosystem services in freshwater systems located in priority or protected areas in a state desired and agreed upon by all stakeholders. The SAM system is considered a robust management cycle that is designed to cope with the complex dynamics and pronounced variability of freshwater ecosystems at multiple scales, that involve multiple uses and with a focus on climate change adaptation. Kingsford and Biggs (2011) strongly recommend that the system be based on objectivity, scientific evidence, as well as local knowledge and that instead of relying on government – managers need to be provided the autonomy to act in the face of rapidly evolving circumstances.

Locally in South Africa, Jackson (2014) provides a comprehensive review of adaptive management and its importance at the science-management-government interface in the context of managing the Inkomati River system in South Africa. There is considerable scope for incorporating STREAM, or similar basic water resource models, into the adaptive management systems of smaller, less well-resourced catchments in South Africa.

Operating rules for catchments can be implemented either through restrictions, i.e. temporary reductions in water use, or curtailments, i.e. permanent reductions in water demand – for example by reducing the area under irrigation, or by implementing compulsory licencing (Mallory 2009). It is important to bear in mind that STREAM is neither predictive, nor can it monitor Reserve flows in in real-time. The Reserve therefore needs to be reviewed retrospectively and water management interventions implemented primarily through curtailments, i.e. by improving water conservation measures and irrigation efficiency, reducing the area under irrigation, changing crops, or other similar longer-term interventions.   These interventions should be reviewed as the situation demands: the period under consideration needs to be assessed, adjustments made and targets for the following year set.

Quarterly, or biannual review of the Reserve using STREAM or a similar monitoring methodology is recommended. The frequency needs to set according to the manpower and resources available in each catchment since accessing and downloading data and running the analysis is fairly time-intensive. Because the natural discharge control sites in the Koue Bokkeveld are quite remote and access is difficult, a biannual review is considered a realistic interval. In catchments like the Riet River, where river flows are not meeting the EWR flows, it may be prudent to set smaller, more achievable goals that are assessed against the current status quo rather than forcing through compliance using measures that are punitive, unrealistic and ultimately detrimental to the economy of the region.

7.7 Calibrating EWR flows on priority rivers

Comprehensive Reserve determinations are undertaken at a select number of representative sites – usually five or six in a primary catchment. Once the WRCS process is complete, these comprehensive determinations are used to determine the EWR on tributary sites by means hydrological routing using the Desktop Reserve Model. These computations are prone to inaccuracies especially in smaller rivers that have MAR of < 30 $Mm^3.a^{-1}$ (Kleynhans et al. 2008a). This is borne out by the discrepancies evident between the WR2012 outputs and the recommended EWR flows at the Twee River Site (Section 6.1.1). Furthermore, there is no ecological input to EWR flows at sites determined by means of hydrological routing. Consequently, EWR flows may not be appropriate for local biotic and abiotic conditions, which is borne out by the analysis of flows in the Twee River. This river is one of the most important systems in the Koue Bokkeveld from a biodiversity and conservation point of view. The consequences of inaccurate EWR estimations for this river are twofold. Firstly, the ecosystem requirements will not be met. Secondly and equally importantly, if EWR flows are over-estimated, or the estimations are perceived to specious, the confidence and support of landowners in catchment will be lost. In instances like the Twee River therefore, it is recommended the EWR flows be reviewed and updated and furthermore, that basic hydraulic assessments are undertaken at a local scale to calibrate and update EWR flows. Methods like the Rapid Habitat Assessment Methods (RHAM) (Department of Water Affairs 2009) and updates of this model are especially useful in this regard. A cross-sectional survey method is also outlined by Kleynhans et al. (2008a) specifically for this purpose.

7.8 Stakeholder engagement and perceptions on Reserve monitoring in the Koue Bokkeveld

The central task of the WRCS in South Africa is to engage all stakeholders in deciding on the quality of the resource, setting MCs and assigning ECs. Thus numerous stakeholder engagement workshops were held for the Olifants-Doring catchment (Belcher et al. 2011a; Belcher et al. 2011b). Furthermore, Southern Waters Ecological Research and Consulting cc (Southern Waters) undertook the *Olifants-Doring River Ecological Reserve and Resource Protection capacity building and training project* on behalf of the Cape Action Plan for People and the Environment (CAPE) which was intended to support enforcement and compliance (Southern Waters 2009). Included in this project were training workshops on the WRCS, disaggregation of the incremental Reserve, incorporation of Water Quality Reserve templates into licences and a GIS-based summary of the Reserve. However, both the WRCS stakeholder engagement and the Southern Waters workshops dealt with the Reserve at a fairly high technical levels and broad geographical areas.

During the course of this study, it became abundantly clear that, despite the aforementioned engagements, there is still a strong need to make the Reserve more accessible and interpretable to a wider audience – and that includes landowners currently represented by WUAs. It became apparent in course of this study during interaction with stakeholders that the central interest of the landowner, i.e. 'after the Reserve, how much water will be available year-on-year for irrigation' was not being addressed. During the course of workshops and discussions it was clear that landowners had limited understanding of the principles behind environmental flows, less understanding of how to interpret the gazetted Reserve flows, or what consequences the recommended flows had for their water needs. In this respect, the study team members were able to fulfil an important role in mediating this knowledge to them. The easily interpretable, visual representation of Reserve flows provided by STREAM, made the task of communication considerably easier. Landowners responded to and engaged with the figures and were able to suggest ways in which they may, in future, address water resource issues in problem catchments. Future studies will aim at engaging more with the Koue Bokkeveld WUA and developing an adaptive management framework as outlined in Section 7.6.

7.9 Summary, recommendations and further research

By far the most challenging aspect of this study was obtaining up-to-date and reliable estimates of natural hydrology and developing simple models that could undertake the estimation on a regular, if not real-time basis. Improving hydrological certainty and regularly reviewing and updating rainfall-runoff relationships should therefore be an important component in further application or development of this, or any other similar model. Concomitant efforts to reinforce and expand the rainfall monitoring infrastructure in the Koue Bokkeveld will go a long way towards achieving this objective. Increasing the reliability and accuracy of the model – especially with regards to the rainfall-runoff relationships – should undoubtedly be the primary focus of any further research and development.

Another important learning experience of this study has been that science undertaken at the management-government interface needs to be communicated in straightforward, uncomplicated and visual ways. This should not belittle the intelligence of the end-users who are very often specialists in their own fields, but scientists and managers should not assume that comprehension of complex methodologies and systems will take place across the board among people with a diverse range of skills and experience.

This study has maintained from the outset that it is precisely the complexity of current Reserve models and systems which is constraining its broad uptake. One of our primary objectives was not just to develop a water resource model that could be regularly updated and applied by a broad group of stakeholders, but also one that would produce outputs that are readily understandable and useful in any adaptive management context. Consequently, although STREAM is capable of outputting any number hydrological indices, the team consciously avoided doing so in order to maintain simplicity and communicability. Any further development of the model should be undertaken in this spirit.

As it currently stands, the model is Excel-based and prone to the kinds of errors resulting from incorrect user inputs. A software executable version may be considered in the future, but these quickly become incompatible with updated operating systems unless they themselves are updated. Should the software route be considered, the possibility then exists of increasing the sophistication of the integrated rainfall-runoff model. In terms of immediate research and development needs, however, a priority is to continue testing the model in an adaptive management framework in the Koue Bokkeveld, to develop monitoring and response protocols around its use and to test these in a different catchment with a different set of water resource challenges. Particularly important in this regard will be ways to use the set of indicators provided in the model to set targets and assess progress. A relatively straightforward, but potentially useful adaptation of the current model would be to include an automatic curve fitting routine which could automatically find the best fit curves for each month for the catchment rainfall versus the natural flow.

In addition to further development of the model itself, recommendations with regard to the gazetting of the Reserve and the availability of Reserve data need to be stated at this point. A significant hurdle in this study was obtaining the latest Reserve rule-curves. Southern Waters provided considerable assistance in this regard, but had they not, the data would have been very difficult to source. Often, different versions of Reserve data are available as subsequent analyses and reviews are undertaken and the figures are revised and updated. Once the Reserve is gazetted therefore, the latest version of the rule-curves for each quaternary catchment should be made available and published, preferably online, to ensure consistency of use.

STREAM does not currently assess high flows (floods), but should these be included in future versions. High flow requirements must be made explicit in the gazette, this includes their classes, expected and required frequencies, as well as their timing. Furthermore, only minimum mean-daily discharge restrictions for the driest month of the year and extreme drought flows are reported in the gazette. It is suggested that these be determined and reported for each month of the year since the biotic implications will vary month-by-month. This is essentially a 'minimum flow requirement', which is not ideal from an ecological point of view, but given the complexities of flow monitoring, it may be the most realistic option given the complexities of Reserve monitoring for now.

Finally, as noted at the very outset of this study, the development of methods and approaches to operationalise and monitor the Reserve in South Africa has fallen behind those of Reserve determination; with some managers alleging that operationalisation is simply impractical (Pollard and Du Toit 2011). This study, though modest in its aspirations, has demonstrated that this perception is false. While there are certainly limits to Reserve operationalisation and monitoring, it is not completely unachievable provided that good quality and up-to-date data is at hand, that appropriate tools are available and that these are effectively applied in an adaptive management context. Nevertheless, water resources management is a complex field and private landowners and public institutions will continue to require considerable support to ensure that those adaptive management systems are functional and sustainable. It is at this grass-roots level where the day-to-day operational water resources management takes place and where models like STREAM promise to be most effective.

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APPENDIX A

E21E Monthly rainfall-runoff regression statistics

Oct	Residuals:					
	Min	1Q	Median	3Q	Max	
	-11.2132	-3.6706	0.1719	2.7192	12.6342	
	Coefficients:					
	(Intercept)	10.09541	0.87408	11.55	< 2e-16	***
	Octsub$Rain	0.12741	0.02118	6.017	6.50E-08	***
	Residual standard error: 4.997 on 73 degrees of freedom					
	Multiple R-squared: 0.3315, Adjusted R-squared: 0.3224					
	F-statistic: 36.2 on 1 and 73 DF, p-value: 6.501e-08					
Nov	Residuals:					
	Min	1Q	Median	3Q	Max	
	-5.1766	-1.4885	-0.1087	1.2545	7.9576	
	Coefficients:					
	(Intercept)	4.2455	0.37654	11.275	< 2e-16	***
	Novsub$Rain	0.0898	0.01048	8.571	9.76E-13	***
	Residual standard error: 2.477 on 75 degrees of freedom					
	Multiple R-squared: 0.4948, Adjusted R-squared: 0.4881					
	F-statistic: 73.46 on 1 and 75 DF, p-value: 9.756e-13					
Dec	Residuals:					
	Min	1Q	Median	3Q	Max	
	-1.64813	-0.53761	-0.09471	0.46644	2.32909	
	Coefficients:					
	(Intercept)	2.015325	0.128274	15.711	< 2e-16	***
	Decsub$Rain	0.018781	0.006051	3.104	0.00272	**
	Residual standard error: 0.853 on 73 degrees of freedom					
	Multiple R-squared: 0.1166, Adjusted R-squared: 0.1045					
	F-statistic: 9.634 on 1 and 73 DF, p-value: 0.002717					
Jan	Residuals:					
	Min	1Q	Median	3Q	Max	
	-0.74814	-0.28883	-0.00814	0.23954	1.2604	
	Coefficients:					
	(Intercept)	1.208137	0.054019	22.365	<2e-16	***
	Jansub$Rain	0.007498	0.003911	1.917	0.0591	
	Residual standard error: 0.3834 on 73 degrees of freedom					
	Multiple R-squared: 0.04793, Adjusted R-squared: 0.03489					
	F-statistic: 3.675 on 1 and 73 DF, p-value: 0.05914					
Feb	Residuals:					
	Min	1Q	Median	3Q	Max	
	-0.67108	-0.24584	-0.00673	0.20821	1.02435	
	Coefficients:					
	(Intercept)	1.01384	0.048848	20.755	<2e-16	***
	Febsub$Rain	0.003942	0.003689	1.069	0.289	
	Residual standard error: 0.3289 on 73 degrees of freedom					
	Multiple R-squared: 0.0154, Adjusted R-squared: 0.001913					
	F-statistic: 1.142 on 1 and 73 DF, p-value: 0.2888					
Mar	Residuals:					
	Min	1Q	Median	3Q	Max	
	-1.18768	-0.2787	-0.05052	0.16868	1.93619	
	Coefficients:					
	(Intercept)	0.831315	0.066399	12.52	< 2e-16	***
	Marsub$Rain	0.019258	0.002791	6.9	1.43E-09	***
	Residual standard error: 0.4561 on 75 degrees of freedom					
	Multiple R-squared: 0.3883, Adjusted R-squared: 0.3801					
	F-statistic: 47.61 on 1 and 75 DF, p-value: 1.43e-09					
Apr	Parameters:					
	a	0.951086	0.105172	9.043	1.10E-13	***
	b	0.019225	0.000744	25.828	< 2e-16	***
	Residual standard error: 1.521 on 76 degrees of freedom					
May	Parameters:					
	a	2.977066	0.326783	9.11	8.21E-14	***
	b	0.012641	0.000482	26.26	< 2e-16	***
	Residual standard error: 5.21 on 76 degrees of freedom					

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E21E Monthly rainfall-runoff regression statistics (cont'd)

Jun	Parameters:					
	a	7.609878	1.28052	5.943	7.94E-08	***
	b	0.009635	0.000953	10.105	1.05E-15	***
	Residual standard error: 12.32 on 76 degrees of freedom					
Jul	Residuals:					
	Min	1Q	Median	3Q	Max	
	-38.465	-9.812	-0.45	8.467	59.461	
	Coefficients:					
	(Intercept)	0.52224	3.51845	0.148	0.882	
	Julsub$Rain	0.3663	0.03257	11.245	<2e-16	***
	Residual standard error: 17.35 on 74 degrees of freedom					
	Multiple R-squared: 0.6308, Adjusted R-squared: 0.6259					
	F-statistic: 126.5 on 1 and 74 DF, p-value: < 2.2e-16					
Aug	Residuals:					
	Min	1Q	Median	3Q	Max	
	-30.931	-10.7	-2.522	12.231	41.118	
	Coefficients:					
	(Intercept)	14.22249	3.40939	4.172	8.14E-05	***
	Augsub$Rain	0.25722	0.03942	6.526	7.43E-09	***
	Residual standard error: 14.59 on 74 degrees of freedom					
	Multiple R-squared: 0.3653, Adjusted R-squared: 0.3567					
	F-statistic: 42.58 on 1 and 74 DF, p-value: 7.434e-09					
Sep	Residuals:					
	Min	1Q	Median	3Q	Max	
	-24.4709	-7.7999	0.6868	6.7552	24.5613	
	Coefficients:					
	(Intercept)	18.0429	1.72628	10.452	3.19E-16	***
	Sepsub$Rain	0.14498	0.02787	5.201	1.70E-06	***
	Residual standard error: 9.871 on 74 degrees of freedom					
	Multiple R-squared: 0.2677, Adjusted R-squared: 0.2578					
	F-statistic: 27.05 on 1 and 74 DF, p-value: 1.703e-06					

E21G Monthly rainfall-runoff regression statistics

Oct	Residuals:					
	Min	1Q	Median	3Q	Max	
	-2.246	-0.8091	-0.2463	0.7193	2.391	
	Coefficients:					
	(Intercept)	2.386702	0.188853	12.638	< 2e-16	***
	Octsub$Rain	0.013583	0.004674	2.906	0.00484	**
	Residual standard error: 1.067 on 73 degrees of freedom					
	Multiple R-squared: 0.1037, Adjusted R-squared: 0.09142					
	F-statistic: 8.446 on 1 and 73 DF, p-value: 0.004841					
Nov	Residuals:					
	Min	1Q	Median	3Q	Max	
	-1.0763	-0.3104	-0.052	0.2462	1.2171	
	Coefficients:					
	(Intercept)	0.87439	0.066573	13.134	< 2e-16	***
	Novsub$Rain	0.013487	0.001697	7.949	1.62E-11	***
	Residual standard error: 0.4385 on 74 degrees of freedom					
	Multiple R-squared: 0.4606, Adjusted R-squared: 0.4533					
	F-statistic: 63.19 on 1 and 74 DF, p-value: 1.617e-11					
Dec	Residuals:					
	Min	1Q	Median	3Q	Max	
	-0.31445	-0.1032	-0.02528	0.12056	0.41229	
	Coefficients:					
	(Intercept)	0.407242	0.025481	15.982	< 2e-16	***
	Decsub$Rain	0.004049	0.001158	3.495	0.000804	***
	Residual standard error: 0.1716 on 74 degrees of freedom					
	Multiple R-squared: 0.1417, Adjusted R-squared: 0.1301					
	F-statistic: 12.22 on 1 and 74 DF, p-value: 0.0008037					

E21G Monthly rainfall-runoff regression statistics (cont'd)

Jan	Residuals:					
	Min	1Q	Median	3Q	Max	
	-0.14523	-0.06168	-0.00592	0.044059	0.208647	
	Coefficients:					
	(Intercept)	0.248553	0.01044	23.808	< 2e-16	***
	Jansub$Rain	0.001826	0.000637	2.866	0.00543	**
	Residual standard error: 0.07566 on 73 degrees of freedom					
	Multiple R-squared: 0.1011, Adjusted R-squared: 0.08882					
	F-statistic: 8.213 on 1 and 73 DF, p-value: 0.00543					
Feb	Residuals:					
	Min	1Q	Median	3Q	Max	
	-0.13994	-0.0555	-0.00206	0.039837	0.218579	
	Coefficients:					
	(Intercept)	0.213004	0.011131	19.136	<2e-16	***
	Febsub$Rain	0.001252	0.000799	1.567	0.121	
	Residual standard error: 0.07435 on 74 degrees of freedom					
	Multiple R-squared: 0.03211, Adjusted R-squared: 0.01903					
	F-statistic: 2.455 on 1 and 74 DF, p-value: 0.1214					
Mar	Residuals:					
	Min	1Q	Median	3Q	Max	
	-0.13036	-0.05156	-0.00807	0.043251	0.198626	
	Coefficients:					
	(Intercept)	0.197132	0.010316	19.109	< 2e-16	
	Marsub$Rain	0.001415	0.000404	3.504	0.000782	
	Residual standard error: 0.07044 on 74 degrees of freedom					
	Multiple R-squared: 0.1423, Adjusted R-squared: 0.1307					
	F-statistic: 12.28 on 1 and 74 DF, p-value: 0.0007817					
Apr	Parameters:					
	a	0.128045	0.022212	5.765	1.66E-07	***
	b	0.022385	0.001115	20.075	< 2e-16	***
	Residual standard error: 0.3975 on 76 degrees of freedom					
May	Parameters:					
	a	0.619712	0.09436	6.568	5.67E-09	***
	b	0.010546	0.000641	16.454	< 2e-16	***
	Residual standard error: 1.318 on 76 degrees of freedom					
Jun	Parameters:					
	a	1.634946	0.319293	5.121	2.23E-06	
	b	0.008533	0.001107	7.705	4.04E-11	***
	Residual standard error: 2.827 on 76 degrees of freedom					
Jul	Residuals:					
	Min	1Q	Median	3Q	Max	
	-7.4091	-1.8037	-0.4057	1.1009	10.5603	
	Coefficients:					
	(Intercept)	0.98612	0.65998	1.494	0.139	
	Julsub$Rain	0.05534	0.00601	9.207	6.78E-14	
	Residual standard error: 3.204 on 74 degrees of freedom					
	Multiple R-squared: 0.5339, Adjusted R-squared: 0.5276					
	F-statistic: 84.76 on 1 and 74 DF, p-value: 6.78e-14					
Aug	Residuals:					
	Min	1Q	Median	3Q	Max	
	-5.6915	-2.4334	-0.3082	1.7831	11.2388	
	Coefficients:					
	(Intercept)	3.82112	0.75848	5.038	3.29E-06	***
	Augsub$Rain	0.03423	0.00853	4.013	0.000144	***
	Residual standard error: 3.198 on 73 degrees of freedom					
	Multiple R-squared: 0.1807, Adjusted R-squared: 0.1695					
	F-statistic: 16.1 on 1 and 73 DF, p-value: 0.0001437					
Sep	Residuals:					
	Min	1Q	Median	3Q	Max	
	-3.3822	-1.8887	0.0443	1.5327	4.2249	
	Coefficients:					
	(Intercept)	4.205141	0.352816	11.919	< 2e-16	***
	Sepsub$Rain	0.017428	0.005486	3.177	0.00217	**
	Residual standard error: 2.004 on 74 degrees of freedom					
	Multiple R-squared: 0.12, Adjusted R-squared: 0.1081					
	F-statistic: 10.09 on 1 and 74 DF, p-value: 0.002173					

E21H Monthly rainfall-runoff regression statistics

Oct	Residuals:					
	Min	1Q	Median	3Q	Max	
	-1.452	-0.5627	-0.1642	0.4987	1.7943	
	Coefficients:					
	(Intercept)	1.616978	0.129237	12.512	< 2e-16	***
	Octsub$Rain	0.01363	0.003163	4.309	4.39E-05	***
	Residual standard error: 0.7684 on 85 degrees of freedom					
	Multiple R-squared: 0.1792, Adjusted R-squared: 0.1696					
	F-statistic: 18.56 on 1 and 85 DF, p-value: 4.394e-05					
Nov	Residuals:					
	Min	1Q	Median	3Q	Max	
	-0.61252	-0.23814	-0.02667	0.15837	0.96422	
	Coefficients:					
	(Intercept)	0.660521	0.046311	14.263	< 2e-16	***
	Novsub$Rain	0.008559	0.001336	6.409	7.82E-09	***
	Residual standard error: 0.3234 on 85 degrees of freedom					
	Multiple R-squared: 0.3258, Adjusted R-squared: 0.3179					
	F-statistic: 41.07 on 1 and 85 DF, p-value: 7.824e-09					
Dec	Residuals:					
	Min	1Q	Median	3Q	Max	
	-0.26578	-0.07052	-0.02375	0.09149	0.29424	
	Coefficients:					
	(Intercept)	0.283522	0.017038	16.641	< 2e-16	***
	Decsub$Rain	0.00259	0.000786	3.297	0.00142	**
	Residual standard error: 0.1191 on 86 degrees of freedom					
	Multiple R-squared: 0.1122, Adjusted R-squared: 0.1019					
	F-statistic: 10.87 on 1 and 86 DF, p-value: 0.001423					
Jan	Residuals:					
	Min	1Q	Median	3Q	Max	
	-0.11502	-0.04286	-0.0072	0.038834	0.159533	
	Coefficients:					
	(Intercept)	0.164819	0.007673	21.479	< 2e-16	***
	Jansub$Rain	0.001551	0.000457	3.392	0.00105	**
	Residual standard error: 0.05683 on 85 degrees of freedom					
	Multiple R-squared: 0.1192, Adjusted R-squared: 0.1089					
	F-statistic: 11.51 on 1 and 85 DF, p-value: 0.001054					
Feb	Residuals:					
	Min	1Q	Median	3Q	Max	
	-0.115	-0.03827	0.000945	0.032476	0.122873	
	Coefficients:					
	(Intercept)	0.132788	0.006632	20.023	< 2e-16	***
	Febsub$Rain	0.001586	0.000347	4.573	1.60E-05	***
	Residual standard error: 0.0486 on 86 degrees of freedom					
	Multiple R-squared: 0.1956, Adjusted R-squared: 0.1862					
	F-statistic: 20.91 on 1 and 86 DF, p-value: 1.604e-05					
Mar	Residuals:					
	Min	1Q	Median	3Q	Max	
	-0.10379	-0.03623	0.000857	0.029074	0.136067	
	Coefficients:					
	(Intercept)	0.120908	0.006964	17.363	< 2e-16	***
	Marsub$Rain	0.001399	0.000294	4.757	7.84E-06	***
	Residual standard error: 0.04654 on 86 degrees of freedom					
	Multiple R-squared: 0.2083, Adjusted R-squared: 0.1991					
	F-statistic: 22.63 on 1 and 86 DF, p-value: 7.84e-06					
Apr	Parameters:					
	a	0.095997	0.006609	14.52	<2e-16	***
	b	0.020515	0.000418	49.09	<2e-16	***
	Residual standard error: 0.1132 on 88 degrees of freedom					
May	Parameters:					
	a	0.335762	0.037001	9.074	2.88E-14	***
	b	0.012415	0.00051	24.353	< 2e-16	***
	Residual standard error: 0.6042 on 88 degrees of freedom					
Jun	Parameters:					
	a	0.94807	0.10902	8.696	1.73E-13	***
	b	0.008705	0.000465	18.738	< 2e-16	***
	Residual standard error: 1.487 on 88 degrees of freedom					

E21G Monthly rainfall-runoff regression statistics (cont'd)

Jul	Residuals:					
	Min	1Q	Median	3Q	Max	
	-3.5914	-1.0136	0.0313	0.9324	4.617	
	Coefficients:					
	(Intercept)	0.65655	0.33863	1.939	0.0558	.
	Julsub$Rain	0.03628	0.00327	11.094	<2e-16	***
	Residual standard error: 1.718 on 86 degrees of freedom					
	Multiple R-squared: 0.5887, Adjusted R-squared: 0.5839					
	F-statistic: 123.1 on 1 and 86 DF, p-value: < 2.2e-16					
Aug	Residuals:					
	Min	1Q	Median	3Q	Max	
	-4.9009	-1.4449	-0.5066	1.6985	6.1484	
	Coefficients:					
	(Intercept)	3.274786	0.448658	7.299	1.43E-10	***
	Augsub$Rain	0.012564	0.004596	2.734	0.00762	**
	Residual standard error: 2.144 on 85 degrees of freedom					
	Multiple R-squared: 0.0808, Adjusted R-squared: 0.06999					
	F-statistic: 7.472 on 1 and 85 DF, p-value: 0.007623					
Sep	Residuals:					
	Min	1Q	Median	3Q	Max	
	-3.0716	-1.209	-0.0963	0.8897	3.3539	
	Coefficients:					***
	(Intercept)	2.857597	0.265192	10.776	<2e-16	**
	Sepsub$Rain	0.01306	0.004564	2.862	0.0053	
	Residual standard error: 1.464 on 85 degrees of freedom					
	Multiple R-squared: 0.08788, Adjusted R-squared: 0.07715					
	F-statistic: 8.189 on 1 and 85 DF, p-value: 0.005304					

E21L Monthly rainfall-runoff regression statistics

Oct	Residuals:					
	Min	1Q	Median	3Q	Max	
	-20.805	-6.628	-1.379	6.17	24.6	
	Coefficients:					
	(Intercept)	22.39366	1.67164	13.396	< 2e-16	***
	Octsub$Rain	0.19817	0.05318	3.727	0.000351	***
	Residual standard error: 9.783 on 84 degrees of freedom					
	Multiple R-squared: 0.1419, Adjusted R-squared: 0.1317					
	F-statistic: 13.89 on 1 and 84 DF, p-value: 0.0003508					
Nov	Residuals:					
	Min	1Q	Median	3Q	Max	
	-10.0068	-2.9068	-0.5305	2.2905	14.4599	
	Coefficients:					
	(Intercept)	9.10758	0.64248	14.176	< 2e-16	***
	Novsub$Rain	0.16408	0.02411	6.806	1.33E-09	***
	Residual standard error: 4.529 on 85 degrees of freedom					
	Multiple R-squared: 0.3527, Adjusted R-squared: 0.3451					
	F-statistic: 46.32 on 1 and 85 DF, p-value: 1.331e-09					
Dec	Residuals:					
	Min	1Q	Median	3Q	Max	
	-3.6899	-1.0832	-0.1731	1.1205	5.2729	
	Coefficients:					
	(Intercept)	4.05659	0.24507	16.553	< 2e-16	***
	Decsub$Rain	0.03984	0.01459	2.731	0.00766	**
	Residual standard error: 1.714 on 86 degrees of freedom					
	Multiple R-squared: 0.07981, Adjusted R-squared: 0.06911					
	F-statistic: 7.459 on 1 and 86 DF, p-value: 0.007657					
Jan	Residuals:					
	Min	1Q	Median	3Q	Max	
	-1.57732	-0.58856	-0.08015	0.51589	2.70069	
	Coefficients:					
	(Intercept)	2.289482	0.112755	20.305	< 2e-16	***
	Jansub$Rain	0.030966	0.008672	3.571	0.000589	***
	Residual standard error: 0.835 on 85 degrees of freedom					
	Multiple R-squared: 0.1304, Adjusted R-squared: 0.1202					
	F-statistic: 12.75 on 1 and 85 DF, p-value: 0.0005891					

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Feb	Residuals:					
	Min 1Q	1Q	Median	3Q	Max	
	-2.1088	-0.5035	-0.0931	0.3804	1.7587	
	Coefficients:					
	(Intercept)	1.831023	0.096739	18.927	< 2e-16	***
	Febsub$Rain	0.034047	0.006526	5.217	1.26E-06	***
	Residual standard error: 0.7079 on 85 degrees of freedom					
	Multiple R-squared: 0.2426, Adjusted R-squared: 0.2337					
	F-statistic: 27.22 on 1 and 85 DF, p-value: 1.263e-06					
Mar	Residuals:					
	Min	1Q	Median	3Q	Max	
	-1.9733	-0.53832	-0.02259	0.36447	2.44094	
	Coefficients:					
	(Intercept)	1.662138	0.110084	15.099	< 2e-16	***
	Marsub$Rain	0.03525	0.006003	5.872	7.91E-08	***
	Residual standard error: 0.7358 on 86 degrees of freedom					
	Multiple R-squared: 0.2862, Adjusted R-squared: 0.2779					
	F-statistic: 34.48 on 1 and 86 DF, p-value: 7.913e-08					
Apr	Parameters:					
	a	1.942998	0.180281	10.78	<2e-16	***
	b	0.022991	0.000771	29.82	<2e-16	***
	Residual standard error: 2.64 on 88 degrees of freedom					
May	Parameters:					
	a	5.343385	0.63367	8.432	6.03E-13	***
	b	0.015991	0.000709	22.558	< 2e-16	***
	Residual standard error: 10.32 on 88 degrees of freedom					
Jun	Parameters:					
	a	14.06837	1.57957	8.906	6.40E-14	***
	b	0.01104	0.00059	18.708	< 2e-16	***
	Residual standard error: 21.09 on 88 degrees of freedom					
Jul	Residuals:					
	Min	1Q	Median	3Q	Max	
	-69.948	-17.13	-1.353	14.118	91.508	
	Coefficients:					
	(Intercept)	5.20473	5.66722	0.918	0.361	
	Julsub$Rain	0.76805	0.07066	10.87	<2e-16	***
	Residual standard error: 28.75 on 86 degrees of freedom					
	Multiple R-squared: 0.5787, Adjusted R-squared: 0.5738					
	F-statistic: 118.2 on 1 and 86 DF, p-value: < 2.2e-16					
Aug	Residuals:					
	Min	1Q	Median	3Q	Max	
	-78.354	-20.279	-4.447	21.095	88.543	
	Coefficients:					
	(Intercept)	44.69917	6.47157	6.907	8.08E-10	***
	Augsub$Rain	0.26777	0.08549	3.132	0.00237	**
	Residual standard error: 30.92 on 86 degrees of freedom					
	Multiple R-squared: 0.1024, Adjusted R-squared: 0.09195					
	F-statistic: 9.809 on 1 and 86 DF, p-value: 0.002373					
Sep	Residuals:					
	Min	1Q	Median	3Q	Max	
	-43.978	-14.465	-0.866	11.758	60.481	
	Coefficients:					
	(Intercept)	39.24866	3.74725	10.474	< 2e-16	***
	Sepsub$Rain	0.27405	0.08395	3.264	0.00157	**
	Residual standard error: 21.02 on 87 degrees of freedom					
	Multiple R-squared: 0.1091, Adjusted R-squared: 0.09888					
	F-statistic: 10.66 on 1 and 87 DF, p-value: 0.001569					

APPENDIX B

Table B.1. Measured flow statistics for the Twee River E21H at Node A1.

Month-Year	Maximum daily average flow in each month ($m^3.s^{-1}$)	Average daily flow in each month ($m^3.s^{-1}$)	Daily average flow exceeded 90% of the time for each month ($m^3.s^{-1}$)	Duration of 90th percentile flow (days / month)
May 2013	0.140485	0.066	0.055	4
Jun 2013	1.871193	0.445	0.157	3
Jul 2013	1.273425	0.308	0.136	4
Aug 2013	2.085855	0.664	0.182	4
Sep 2013	1.208383	0.432	0.206	3
Oct 2013	0.233544	0.137	0.104	4
Nov 2013	0.124021	0.085	0.068	3
Dec 2013	0.071043	0.053	0.044	4
Jan 2014	0.103623	0.050	0.041	4
Feb 2014	0.046475	0.039	0.033	3
Mar 2014	0.059807	0.041	0.035	4
Apr 2014	0.091397	0.057	0.048	3
May 2014	0.150969	0.073	0.053	4
Jun 2014	1.134231	0.362	0.185	3
Jul 2014	1.990731	0.432	0.144	4
Aug 2014	2.552869	0.339	0.169	4
Sep 2014	0.441582	0.188	0.135	3
Oct 2014	0.126652	0.091	0.070	4
Nov 2014	0.116294	0.074	0.062	3
Dec 2014	0.068539	0.051	0.046	4
Jan 2015	0.045347	0.039	0.035	4
Feb 2015	0.076488	0.062	0.032	3
Mar 2015	0.079449	0.065	0.057	4
Apr 2015	0.081688	0.070	0.062	3
May 2015	0.099167	0.082	0.077	4
Jun 2015	0.252371	0.141	0.102	3

Table B.2. Measured flow statistics for the Leeu River E21G at Node R41.

Mon-Year	Maximum daily average flow in each month ($m^3.s^{-1}$)	Average daily flow in each month ($m^3.s^{-1}$)	Daily average flow exceeded 90% of the time for each month ($m^3.s^{-1}$)	Duration of 90th percentile flow (days / month)
Oct 2009	0.8	0.282	0.073	4
Nov 2009	9.205	1.686	0.044	3
Dec 2009	0.06	0.042	0.031	5
Jan 2010	0.045	0.019	0.005	6
Feb 2010	0.033	0.016	0.003	4
Mar 2010	0.025	0.004	0.000	17
Apr 2010	0.032	0.007	0.000	15
May 2010	5.824	1.535	0.025	4
Jun 2010	12.034	2.212	0.801	3
Jul 2010	4.66	1.356	0.567	4

Table B.2. cont'd

Mon-Year	Maximum daily average flow in each month ($m^3.s^{-1}$)	Average daily flow in each month ($m^3.s^{-1}$)	Daily average flow exceeded 90% of the time for each month ($m^3.s^{-1}$)	Duration of 90th percentile flow (days / month)
Aug 2010	12.191	2.089	0.476	4
Sep 2010	2.088	1.026	0.412	3
Oct 2010	5.831	1.235	0.342	4
Nov 2010	0.617	0.208	0.007	3
Dec 2010	0.035	0.012	0.004	4
Jan 2011	0.02	0.007	0.003	8
Feb 2011	0.019	0.006	0.003	19
Mar 2011	0.012	0.004	0.003	26
Apr 2011	0.018	0.012	0.003	6
May 2011	5.936	0.292	0.005	7
Jun 2011	24.394	4.477	0.184	3
Jul 2011	6.962	2.057	0.630	4
Aug 2011	4.863	2.262	1.313	4
Sep 2011	17.809	2.621	0.686	3
Oct 2011	1.553	0.406	0.096	6
Nov 2011	0.173	0.066	0.019	3
Dec 2011	0.018	0.011	0.009	7
Jan 2012	0.012	0.007	0.005	8
Feb 2012	0.008	0.006	0.005	20
Mar 2012	0.012	0.008	0.006	4
Apr 2012	0.167	0.039	0.007	6
May 2012	0.517	0.125	0.009	9
Jun 2012	15.551	2.800	0.010	3
Jul 2012	8.134	2.501	1.193	4
Aug 2012	28.352	6.670	1.017	4
Sep 2012	22.723	3.815	1.408	3
Oct 2012	3.415	0.987	0.233	4
Nov 2012	0.068	0.028	0.015	4
Dec 2012	0.033	0.022	0.010	7
Jan 2013	0.025	0.014	0.011	7
Feb 2013	0.008	0.008	0.008	3
Mar 2013	0.014	0.009	0.008	27
Apr 2013	2.07	0.254	0.008	6
May 2013	0.424	0.064	0.008	14
Jun 2013	21.436	4.777	1.361	3
Jul 2013	18.469	4.067	1.735	4
Aug 2013	27.604	10.659	2.538	4
Sep 2013	26.808	8.138	3.347	3
Oct 2013	3.461	1.079	0.381	4
Nov 2013	0.399	0.080	0.007	4
Dec 2013	0.01	0.007	0.006	5
Jan 2014	0.042	0.011	0.005	4
Feb 2014	0.036	0.011	0.007	6
Mar 2014	0.039	0.025	0.008	4
Apr 2014	0.062	0.027	0.006	3
May 2014	1.276	0.246	0.010	4
Jun 2014	14.099	4.822	1.976	3
Jul 2014	30.16	7.775	1.930	4

Table B.2. cont'd

Mon-Year	Maximum daily average flow in each month ($m^3.s^{-1}$)	Average daily flow in each month ($m^3.s^{-1}$)	Daily average flow exceeded 90% of the time for each month ($m^3.s^{-1}$)	Duration of 90th percentile flow (days / month)
Sep 2014	9.293	3.155	1.432	3
Oct 2014	1.466	0.430	0.012	7
Nov 2014	0.11	0.017	0.006	8
Dec 2014	0.006	0.005	0.005	29
Jan 2015	0.005	0.005	0.004	9
Feb 2015	0.007	0.005	0.004	17
Mar 2015	0.011	0.007	0.006	14
Apr 2015	0.006	0.006	0.006	30
May 2015	0.017	0.007	0.006	27
Jun 2015	2.881	0.240	0.006	12
Jul 2015	8.076	0.960	0.009	4

Table B.3. Measured flow statistics for the Riet River E21A-E at Node R43.

Mon-Year	Maximum daily average flow in each month ($m^3.s^{-1}$)	Average daily flow in each month ($m^3.s^{-1}$)	Daily average flow exceeded 90% of the time for each month ($m^3.s^{-1}$)	Duration of 90th percentile flow (days / month)
Jun 2013	0	0.000	0.000	30
Jul 2013	0	0.000	0.000	31
Aug 2013	12.1	2.081	0.000	4
Sep 2013	16.52	3.740	0.566	3
Oct 2013	0.67	0.141	0.024	4
Nov 2013	0.06	0.015	0.001	3
Dec 2013	0.00	0.000	0.000	26
Jan 2014	0	0.000	0.000	31
Feb 2014	0	0.000	0.000	28
Mar 2014	0	0.000	0.000	31
Apr 2014	0	0.000	0.000	30
May 2014	0	0.000	0.000	31
Jun 2014	0.011	0.001	0.000	27
Jul 2014	18.014	2.047	0.011	4
Aug 2014	8.592	1.624	0.501	4
Sep 2014	6.530	0.957	0.102	3
Oct 2014	0.252	0.053	0.001	4
Nov 2014	0.0009	0.000	0.000	23
Dec 2014	0	0.000	0.000	31
Jan 2015	0	0.000	0.000	31
Feb 2015	0	0.000	0.000	28
Mar 2015	0	0.000	0.000	31
Apr 2015	0	0.000	0.000	30
May 2015	0	0.000	0.000	31

Table B.4. Measured flow statistics for Doring River at Aspoort E21A-L at Node R37.

Mon-Year	Maximum daily average flow in each month ($m^3.s^{-1}$)	Average daily flow in each month ($m^3.s^{-1}$)	Daily average flow exceeded 90% of the time for each month ($m^3.s^{-1}$)	Duration of 90th percentile flow (days / month)
Oct 2009	5.061	3.008	1.712	4
Nov 2009	42.44	7.907	1.179	3
Dec 2009	1.888	0.912	0.517	4
Jan 2010	0.455	0.186	0.071	4
Feb 2010	5.37	0.426	0.054	3
Mar 2010	0.466	0.204	0.131	4
Apr 2010	0.446	0.309	0.234	3
May 2010	34.769	6.988	0.402	4
Jun 2010	67.001	9.963	3.961	3
Jul 2010	12.908	5.322	3.451	4
Aug 2010	36.484	7.350	2.798	4
Sep 2010	8.199	4.576	2.869	4
Oct 2010	17.421	4.590	2.179	4
Nov 2010	3.512	1.675	0.791	3
Dec 2010	2.157	0.660	0.272	4
Jan 2011	0.537	0.135	0.003	4
Feb 2011	4.302	0.546	0.071	3
Mar 2011	0.096	0.024	0.006	4
Apr 2011	0.355	0.221	0.174	3
May 2011	21.568	2.509	0.540	4
Jun 2011	138.823	25.878	3.539	3
Jul 2011	37.697	10.481	4.418	4
Aug 2011	27.311	9.439	6.436	4
Sep 2011	48.514	8.719	3.887	3
Oct 2011	5.755	2.594	1.558	4
Nov 2011	1.9	1.254	0.981	3
Dec 2011	0.72	0.463	0.328	4
Jan 2012	1.271	0.190	0.035	4
Feb 2012	0.045	0.007	0.000	16
Mar 2012	0	0.000	0.000	31
Apr 2012	1.884	0.393	0.000	11
May 2012	2.212	1.040	0.699	4
Jun 2012	72.443	11.460	0.905	3
Jul 2012	34.642	10.155	6.077	4
Aug 2012	109.218	26.658	5.535	4
Sep 2012	71.432	17.017	7.379	3
Oct 2012	14.075	5.730	2.999	4
Nov 2012	2.121	1.106	0.654	4
Dec 2012	5.899	0.901	0.377	5
Jan 2013	0.316	0.122	0.021	4
Feb 2013	0.01	0.002	0.002	25
Mar 2013	0.024	0.004	0.000	14
Apr 2013	13.091	2.120	0.094	3
May 2013	5.336	1.494	0.875	5
Jun 2013	110.446	27.703	7.887	3
Jul 2013	57.918	16.519	6.447	4
Aug 2013	155.869	46.722	9.732	4

Table B.4. cont'd

Mon-Year	Maximum daily average flow in each month ($m^3.s^{-1}$)	Average daily flow in each month ($m^3.s^{-1}$)	Daily average flow exceeded 90% of the time for each month ($m^3.s^{-1}$)	Duration of 90th percentile flow (days / month)
Oct 2013	18.413	7.558	4.516	4
Nov 2013	5.525	2.780	1.469	3
Dec 2013	1.308	0.721	0.347	4
Jan 2014	7.646	1.108	0.249	4
Feb 2014	0.414	0.212	0.108	3
Mar 2014	0.956	0.278	0.120	4
Apr 2014	1.851	0.844	0.627	3
May 2014	5.155	1.689	0.662	4
Jun 2014	69.604	20.168	8.778	3
Jul 2014	190.054	33.817	6.828	4
Aug 2014	154.282	27.037	11.481	4
Sep 2014	43.9	15.319	7.626	3
Oct 2014	7.992	3.788	1.790	4
Nov 2014	2.721	1.516	1.001	3
Dec 2014	1.418	0.535	0.281	4
Jan 2015	0.262	0.113	0.049	4
Feb 2015	0.051	0.032	0.021	3
Mar 2015	0.235	0.058	0.013	4
Apr 2015	0.35	0.219	0.158	3
May 2015	0.523	0.439	0.362	4
Jun 2015	12.164	3.441	1.168	3
Jul 2015	65.223	6.518	1.775	4