

Testing a Methodology for Environmental Water Requirements in Non-perennial Rivers

THE MOKOLO RIVER CASE STUDY

MT Seaman, M Watson,
MF Avenant, AR Joubert,
JM King, CH Barker,
S Esterhuyse, D Graham,
ME Kemp, PA le Roux,

B Prucha, N Redelinghuys,
L Rossouw, K Rowntree,
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Report to the
WATER RESEARCH COMMISSION

by

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Centre for Environmental Management, University of the Free State

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Private Bag X03
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orders@wrc.org.za or download from www.wrc.org.za

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EXECUTIVE SUMMARY

BACKGROUND

This project (Phase III: K5/1798) follows on from a one-year project (Phase I: WRC K5/1414; Rossouw et al., 2005) and a three-year project (Phase II: WRC K5/1587; Seaman et al., 2010), both of which were recently completed. All three projects focused on the Environmental Water Requirements (EWRs) for non-perennial rivers.

- In Phase I, the existing EWRs completed on some non-perennial rivers in South Africa were evaluated and problems identified.
- In Phase II, the ecological functioning of a non-perennial river was investigated and a prototype EWR method (Arid-Proto) for non-perennial rivers was developed using the Seekoei River as a case study.
- In Phase III, the Arid-Proto EWR method was tested on the Mokolo River (a semi-permanent river) and a revised method namely the Drift-Arid method was developed. The groundwater-surface water interaction hydrological modelling, using MIKE-SHE software, of the Mokolo River was also investigated and it was found that it was not possible to apply the model to arrive at useful management answers due to the lack of fundamental data. The MIKE-SHE model did however have the potential to model system changes in the Mokolo River, a semi-permanent river.

This report should be read in conjunction with the WRC report no TT 459/10 (Seaman et al., 2010) where the ecological functioning of non-perennial rivers and the prototype methodology developed is explained in detail.

Research into the development of a non-perennial EWR method started in 2005 using the Seekoei River (a non-perennial southern tributary of the Orange River) as a case study (Seaman et al., 2010). Results from the study showed that the interaction between groundwater and surface water is of critical importance in non-perennial rivers, and probably also in perennial rivers, and that the methods used to determine the EWR should take this into consideration. It was further found that the existing standard hydrological models are inadequate for describing and predicting the hydrology of the full spectrum of non-perennial rivers (episodic to semi-permanent). Licenses for the abstraction or release of water in these rivers would therefore have to be based on a specific understanding of the ecology of non-perennial rivers and a hydrological model that can address surface and groundwater interaction.

Due to the shortage of hydrological and ecological data on non-perennial rivers it is difficult to determine the reference/natural ecological conditions in the rivers being studied. It was therefore decided, by the team, that an approach beginning with present day (as most specialists have data for the present) was needed. It was also evident from the study on the Seekoei River that monthly flow data were insufficient to capture the variability of flow in non-perennial rivers and that daily flow data should be used for hydrological modelling. The social and economic aspects of the catchment were also deemed important and needed to be included in the method. Keeping the abovementioned aspects in mind the team involved in the Seekoei River case study examined current EWR methods used in South Africa namely Ecoclassification (Kleynhans and Louw, 2007), DRIFT (Downstream Response to Imposed Flow Transformations; Brown et al., 2008 and 2008a) and HFSR (Habitat Flow Stressor Response; O Keeffe et al., 2002) and found that the DRIFT method included all of the aspects mentioned above and could possibly be used and modified where necessary.

A prototype EWR method for non-perennial rivers was then developed using the Seekoei River as case study and for the purpose of this report the prototype method will be named **Arid-proto**.

The main objective of the current study was then to test the Arid-proto method for non-perennial rivers on a variety of non-perennial rivers in South Africa.

The specific terms of reference were to:

- Test the Arid-proto method in one or more of the catchments adjusting as necessary.
- Select suitable catchments where the methodology can be tested.
- Set up a programme that focuses on specific questions.
- Select researchers and determine the specific tasks that they will carry out to answer questions and to test the methodology in the field.
- Determine in which sub-systems of the catchments sites for fieldwork should be selected.
- Examine the available information for each catchment and set up a programme for fieldwork.
- Carry out the fieldwork.
- Evaluate the Arid-proto methodology.
- Improve on the reliability of data.

To test the Arid-proto method on a variety of non-perennial rivers the team needed to identify suitable catchments, select sites in each of these catchments, collect field data, identify suitable indicators and scenarios of change. The hydrology for each chosen scenario then needed to be simulated and a Decision Support System (DSS) used to capture specialist knowledge to predict the change in the catchment at each site selected for each scenario chosen.

The Arid-proto method was improved and adapted as the project progressed and a revised **DRIFT-Arid** method was developed using the Mokolo River as case study.

An intermediate EWR had already been completed on the Mokolo River in 2008 (DWA, 2008) and the testing of the **Arid-proto** method on the Mokolo River is therefore not an attempt to redo or replace this study but to specifically test a prototype method for the EWR determination of non-perennial rivers.

SELECTION OF SYSTEM ON WHICH THE ARID-PROTO METHOD COULD BE TESTED

Data on flow is needed for any EWR study as flow is one of the major drivers in any river system. A catchment chosen for the study therefore needed to have some reliable gauging weir data available. Discharge data for several catchments in South Africa were examined and the team with the approval of the Steering Committee decided on three possible catchments for the study namely, the Swartdoring River (episodic = no flow at least 76% of the time); the Touws River (ephemeral = no flow 26-75% of the time) and the Mokolo River (semi-permanent = no flow 1-25% of the time).

The team then completed a desktop review of data (hydrological and ecological) available in these catchments as well as determining when an appropriate time (according to expected flow) would be to sample the catchments. A decision was then taken to test the Arid-proto method on the Mokolo River as it had the most data available.

The original aim of the study was to test the Arid-proto method on all three chosen catchments but as the study on the Mokolo River progressed it became obvious that the integrated surface and groundwater modelling was very important to the success of the method and with the permission of the Steering Committee funds allocated to the other two catchments (Swartdoring and Touws) were reallocated to the hydrological modelling of the Mokolo River catchment.

ARID-PROTO METHOD TO DETERMINE EWRs FOR NON-PERENNIAL RIVERS

The Arid-proto method was developed using the Seekoei River as case study. The Arid-proto method more or less follows the same steps as the South African generic perennial RDM procedure for Preliminary Reserve determinations approach (see summary in King and Pienaar, 2011) but the details in the steps have been adjusted. The discipline methods are also different, i.e. *specialists needed to adjust individual methods to determine the Present Ecological State (PES)*.

Step 1: Initiate the preliminary study. This is the same for both methods although in the Arid-proto method the type of river is evaluated, i.e. is it an episodic, ephemeral or semi-permanent river as a different suite of specialists is needed for each type of river.

Step 2: Define Resource Units. This is similar in both methods although in Arid-proto, Runoff Potential Units (RPU) are determined which are homogenous units in terms of soil type; catchment slope; infiltration rate; vegetation cover; rainfall intensity and flow accumulation. As non-perennial rivers have very few data on flow, the catchment characteristics and climate data are used as a surrogate together with any flow data available to determine the instream flow characteristics. Catchment data are also used in the Arid-proto method and Combined Response Units (CRUs) are identified by using a GIS overlay of the Natural Response Units (NRUs) and Management Response Units (MRUs).

Step 3: Ecoclassification: Several changes were made in this step in the Arid-proto method as specialists needed to adjust the perennial methods in their disciplines to suit non-perennial conditions and to determine the PES. DRIFT is one of the methods used in the South African generic approach for perennial rivers but a step forward from the original DRIFT method was that specific indicators, which describe the non-perenniality of the rivers being studied, i.e. period of no flow, start of flow after dry period, depth of pools, etc. were incorporated.

Step 4: Ecological Water Requirements. This step is similar to the approach used for perennial rivers. In the Arid-proto method specific development scenarios are chosen and not just the recommended future ecological condition and alternative conditions either side of this. The flow, hydraulic and biological data for each chosen scenario is processed using an excel spreadsheet and the EWRs for each scenario is then provided.

Step 5: Ecological consequences of operational scenarios. This step is also similar to the perennial approach although in the Arid-proto method a simplified excel based method is used to determine the consequences of each chosen scenario.

Steps 6-9: DWA Management classes; Reserve and Resource Quality Objectives (RQOs) specification and Implementation strategy. These steps were not developed for the Arid-proto method. The output that needs to be provided to the DWA has also not been finalised.

The Arid-proto method was tested on the Mokolo River and several adjustments (activities added, rearranged and some changed) had to be made, leading to an alignment with the DRIFT method (as described in Brown et al., 2013). The revised method to determine the EWR for non-perennial rivers (developed on the Mokolo River) is illustrated in Figure 1. It comprises 11 phases and 29 activities.

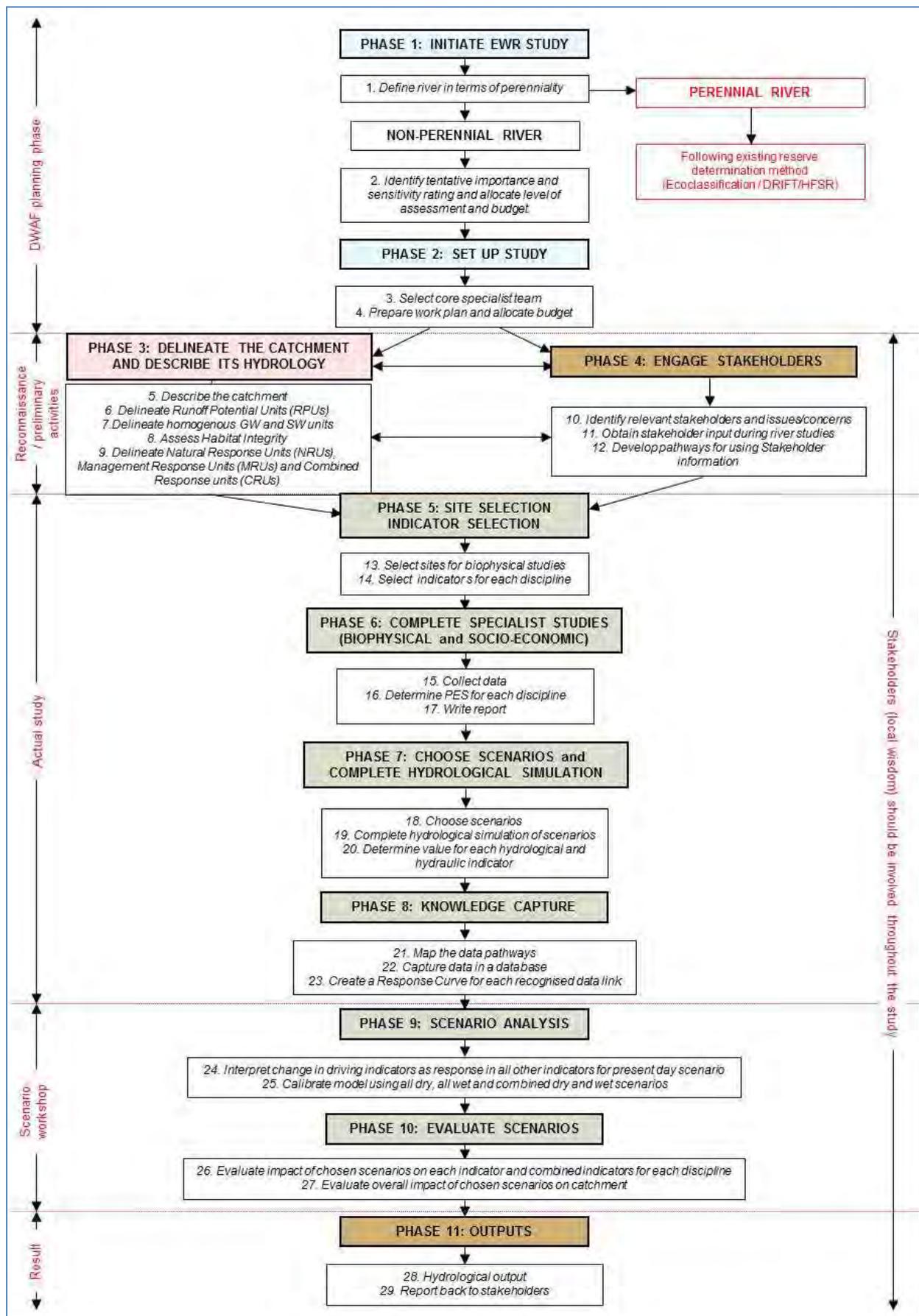


Figure 1. DRIFT-Arid method for determining the EWR of a non-perennial river

The DRIFT method is based on capturing specialist knowledge of a specific catchment in a structured database that is then used to determine the ecological and socio-economic impacts of a future development scenario, or range of scenarios, on the river or site.

The available discharge record of gauging weirs in the river is used to determine the degree of perenniality and if the river is a non-perennial river, the DRIFT-Arid method could be followed. Catchment data are collected and used to delineate homogenous units (Combined Response Units; CRUs) in terms of natural and management aspects. These CRUs are then prioritised and the most important CRUs are chosen which would represent the units that specialists regard as important in terms of their specific disciplines. According to the level of EWR determination and the budget available, sites are then chosen in the most important CRUs. These sites represent the whole CRU and should have the characteristics which are dominant in the CRU.

Once sites are chosen, the team complete their specialist studies. The data collected by the specialists is used to determine the present ecological state (PES) for the site which is used as the basis from which change in the specific discipline under different scenarios is determined.

Data collected in each discipline needs to have links to flow or water depth. Specialists also identify indicators which are variables that can be expected to respond to changes in flow or water levels. They should cover the main physical, chemical, biological and social aspects of the river ecosystem, including issues of interest or concern to stakeholders where possible. For non-perennial rivers, it is suggested that the list of indicators should be short and, with trial and error, possibly generic for all such rivers. The indicators chosen as well as links between indicators (driving and responding indicators) are incorporated into a DRIFT-Arid DSS.

Planned future scenarios for the catchment or site are identified using data from the stakeholders, the DWA and any other relevant reports. An integrated (surface and groundwater) hydrological model is used to simulate the hydrology for each scenario chosen and these data are used to determine the values (means and standard deviation) for the hydrological and hydraulic indicators chosen. The values for each chosen scenario are entered into the DRIFT-Arid DSS. These data are automatically incorporated into the individual discipline datasheets and they are then sent to the specialists.

Each specialist now draws Response Curves for each indicator and links chosen for each site. Response curves describe how a responding indicator will respond to a driving indicator. Each specialist data entry file is pre-populated, with a list of flow indicators, the particular indicators for the discipline, and other standard information such as site and scenario names. The summary statistics (values from the hydrological simulation) for the driving indicators are incorporated in the Response Curve as present day median value, range and standard deviation. Each Response Curve describes the relationship on the assumption that only those two indicators are changing, with the rest of the ecosystem remaining unchanged.

A seasonal time series for each indicator under each scenario is built up (in the DRIFT-Arid DSS) from the Response Curves and the time-series of input values for each discipline. Also produced in the DSS in each specialist file are various summaries, including an annual time-series. Specialists now have to calibrate their particular Response Curves input by using hydrology data from three fictitious scenarios that are also included in the DSS. The 'all' wet scenario includes values from the wettest years throughout the time series so that it appears as though the river has wet years throughout. The 'all dry' scenario includes values from the driest years throughout the time series and the 'combined wet and dry' scenario includes values from the wettest years for half of the time series and for the driest years flow for the remaining half of the time series. Once all the response curves

have been calibrated and returned to the modeller, the DRIFT-Arid DSS is run and results indicating the impact of all scenarios chosen on each discipline as well as on the combined disciplines are produced. This is then presented to the stakeholders and the DWA so that they can decide which scenario is acceptable.

The output to the DWA on the specific management options for each scenario has not been finalised and needs to be researched in a future project with the input from prominent hydrologists, geohydrologists, DWA officials, hydrological modellers as well as staff involved in actual implementation of the Reserve. A possible solution is to setup a real time hydrological model such as MIKE SHE and then to implement the Ecological Reserve on a day to day basis but this would need highly specialised modellers to run.

Key features in the DRIFT-Arid method

The key features in the DRIFT-Arid method are:

- A structured GIS based approach to determine the homogenous units (CRUs) in the catchment is used based on catchment characteristics. The input of all specialists is included.
- Site selection process is streamlined and sites are chosen that represent the most important units in the catchment and here all specialists input is also included and not only input from the hydrologist and biologist. Sites represent the habitat, biotopes and socio-economic characteristics of the homogenous unit.
- New flow (and hydraulic) indicators are included in the DRIFT-Arid DSS which are relevant for non-perennial systems and the indicators can be switched off (not included) if they are not relevant for a specific site.
- Weighted (as opposed to un-weighted) lag periods have been created, such that more recent results have a greater influence than those further in the past (now also incorporated in DRIFT); and
- Links within disciplines have been included (already in DRIFT and pilot tested in the Mokolo River).
- An integrated surface and groundwater hydrological model is used to simulate the hydrology for each chosen scenario.

EVALUATION OF THE DRIFT-ARID METHODOLOGY

Overall the team was satisfied with the output from the DRIFT-Arid model and the resilience of the model where a different indicator for different types of rivers or sites could be used, i.e. the method does not restrict the specialists to use a specific type of biotope (stones in current) or indicator (sensitivity of riffle dwelling taxa) but provides the opportunity to choose relevant indicators.

The use of the present day situation as a baseline is also suited to the data-scarce non-perennial rivers as most specialists have knowledge of the present day situation but do not always have knowledge of the reference condition of the site or river.

The structured process of selecting sites worked well and using GIS to determine the CRUs provided a process which was easy to follow, although an experienced GIS specialist needs to be included in the team.

The main difficulty in the suggested DRIFT-Arid method is the integrated surface and groundwater hydrological modelling. Several problems were identified in applying the MIKE SHE model to the Mokolo River catchment namely:

- It is a model that requires a large dataset and data for non-perennial rivers are few. The results from the MIKE SHE model could however be used in a non-perennial river and it has the advantage of being a real time model which can be improved as data are collected. An

approach that would be possible is to first develop a simple, non-data intensive integrated model (MIKE SHE LIGHT) using easily obtainable data and then to increase complexity if and where needed.

- It was difficult to calibrate the model to periods of no-flow, likely due to a combination of irrigation issues (lack of accurate data), topographic resolution/accuracy and also because the model cannot distinguish between surface and subsurface flow so cannot accurately pinpoint times of cessation of surface flow. DHI therefore had to post process the data obtained from the MIKE SHE model to produce the zero flows observed in the gauging weir data.
- The calibrated model largely reproduced the long-term, regional-scale flow behaviour observed in the Mokolo catchment. Particularly in the groundwater, the lack of observations and field data meant that the simulated groundwater response was only generally correct. The network of dikes and faults probably compartmentalizes the regional groundwater flow system, which cannot be simulated in the current model. This may partly explain the difficulty in simulating non-perennial flows, since groundwater baseflow is likely a very local process.
- The model generally reproduced the expected direction of changes in flow associated with the scenarios chosen. However, the absolute magnitudes as well as the relative magnitudes of change were less certain given uncertainties in model inputs and the difficulties with non-perennial conditions.

The DRIFT-Arid DSS could provide the comparison between the chosen scenarios and the team was generally satisfied with the output.

CONCLUSIONS

The research in the current (WRC 1798) and the previous related EWR projects (Rossouw et al., 2005 and Seaman et al., 2010) have contributed considerably to the knowledge of the ecological functioning of non-perennial rivers and the testing of a method to determine the EWR for non-perennial rivers.

The DRIFT-Arid method developed in these projects is based on DRIFT which was developed by Southern Waters for use in perennial rivers. The DRIFT-Arid method was used with success in the semi-permanent Mokolo River but is not recommended for use on all non-perennial rivers until it has been tested on an episodic river to verify its applicability for use. It is possible that only thresholds for pools in non-perennial rivers should be determined instead of using a traditional EWR method as applied in perennial rivers.

Hydrology is one of the main drivers of DRIFT-Arid method and the importance of groundwater in non-perennial rivers was emphasised in the previous two WRC projects (Rossouw et al., 2005 and Seaman et al., 2010). A first attempt at using an integrated surface and groundwater hydrology model (MIKE SHE) was included in the current project.

An important output of the MIKE SHE modelling of the Mokolo River catchment was the identification of data gaps and the implications of this for reliable modelling. It also highlighted the type of data that should be prioritised in the data collection process. The sensitivity of the integrated model to vegetation (especially riparian vegetation characteristics), subsurface and soil data emphasises the need for more studies in these disciplines.

The calibrated MIKE SHE model largely reproduced the long-term, regional-scale flow behaviour observed in the Mokolo catchment. Particularly in the groundwater, the lack of observations and field data meant that the simulated groundwater response was only generally correct. The network of dikes and faults probably compartmentalizes the regional groundwater flow system, which could not be

simulated in the current model. This may partly explain the difficulty in simulating non-perennial flows, since groundwater baseflow is likely a very local process.

The calibrated model had difficulty simulating some peak flow responses. This can also be attributed to the lack of sub-daily precipitation data and the lack of information associated with instream weirs and farm dams.

In data-scarce rivers it would probably be easier to model the hydrology than in a data rich system where data are inaccurate, but calibration is difficult if not impossible if gauging data are not available. In systems with sparse data, the modeller could use climate data as a surrogate for gauge data. A recurring theme in all projects where hydrology is modelled is the lack of accurate data. This needs to be addressed and in South Africa where functioning gauging weirs are scarce alternative methods need to be developed to collect data on flow.

RECOMMENDATIONS FOR FUTURE RESEARCH

The DRIFT-Arid method has been tested with success on an ephemeral and semi-permanent river and now needs to be tested on an episodic river.

Pools act as refugia in non-perennial rivers and the presence of these pools is critical to the functioning of the river. An alternative method to determine the EWR for non-perennial rivers based on pools could be developed. Abstraction from pools needs to be regulated and this can only happen if the dynamics of pools are better understood. Fundamental studies in all disciplines on different types of pools (permanent and temporary) are needed.

Questions that need to be answered relate to the value of pools in non-perennial systems and systems without pools also need to be addressed in terms of value. What kind of objectives or basic management rules need to be defined to protect non-perennial systems? How can non-perennial systems be integrated into catchment management planning?

Due to the data (hydrological and ecological) shortage and inaccurate data available in non-perennial rivers we need a rapid method to follow until more reliable data are available. A fast approach to determine the EWRs in non-perennial rivers needs to be developed. An alternative option in place of the comprehensive/intermediate DRIFT-Arid method is a rapid DRIFT-Arid LITE where a countrywide assessment is done to identify non-perennial rivers and how they are adapting to development. It would probably be necessary to study rivers in different ecoregions, etc. This can be used to look at the impact of scenarios on similar rivers. Very coarse rules could possibly then be determined on how non-perennial rivers react to development and this could then help predict how a river would react to a specific type and scale of development

It would be advisable to proceed with a MIKE SHE (or other hydrological integrated model) LITE where less data are needed. Intensive research to understand non-perennial rivers should be done in parallel with the development of the model.

Although the Mokolo River is a relatively data rich system and data are probably available it was not always possible to find the data and data were not always accurate. A database should be housed either at the DWA or the WRC where all raw data from projects are made available to users. Each project funded by taxpayer money should be made available to the public. Data from projects completed by private consultants (funded by taxpayer money) should also be kept at a central store in the DWA or WRC and raw data collected in these projects should be housed on the database.

A recurring theme throughout the current project has been that more data are needed – to improve the hydrological modelling; to improve methods used for the PES determination in each discipline and to improve the selection and hydrological simulation of scenarios, etc.

Several versions of irrigation data were obtained from the DWA and irrigation boards in the Mokolo Catchment and the databases did not correspond. Accurate (GPS referenced) data on the source for irrigation (groundwater – springs, alluvial aquifer, surface water – river, farm dams, pools, etc.) as well as accurate abstraction amount is needed to enable accurate hydrological modelling.

A review of the river network compared to the 21 m DEM and aerial imagery obtained from the DWA (and ESRI world file imagery) indicated problems with the original river shape file for the Mokolo River. The DWA or the WRC should engage in a project to improve the digitisation of South African rivers.

Studies are needed in each discipline in non-perennial rivers where the link between habitat and flow availability is determined. For most of the disciplines the variability in habitat and flow available has led to generalist animals and plants that are able to survive the conditions. These generalists are not sensitive to flow and habitat alteration in the same sense that sensitive species are in perennial rivers. Studies need to determine what the critical stage in habitat and flow change is before these generalist species are affected.

Data on vegetation in South Africa are available but very few are available for the riparian zone. Data on riparian zone delineation, root depths, Leaf Area Index (LAI), etc. are needed, especially in non-perennial river catchments as vegetation is often the only ecological indicator that can be used to determine the present state of the river, in the absence of water quality, fish and macro-invertebrate indicators.

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ABBREVIATIONS

AET	Actual evapotranspiration
ASPT	Average score per taxon
CPUE	Catch Per Unit Effort
CRUs	Combined Response Units
CV	Coefficient of Variation
DEA	Department of Environmental Affairs (previously known as DEAT – Department of Environmental Affairs and Tourism). Name changed in 2010.
DEM	Digital Elevation Model
DHI	Danish Hydraulic Institute
DRIFT	Downstream Response to Imposed Flow Transformations
DSS	Decision Support System
DTM	Digital terrain model
DWA	Department of Water Affairs (previously known as DWAF – Department of Water Affairs and Forestry). Name changed in 2010.
EC	Electrical conductivity
EWR	Environmental Water Requirement
ExtWater	External water as a result of interbasin transfer
FRAI	Fish Response Assessment Index
FZ	Flood Zone
GIS	Geographic Information Systems
GPS	Global Positioning System
GSFLOW	Coupled Ground-Water and Surface-Water Flow Model
GW	Groundwater
HI	Hydrological Index
IBI	Index of Biotic Integrity
IHI	Index of Habitat Integrity
LAI	Leaf Area Index
NGA	National Groundwater Archive
NRU	Natural Response Unit
ME	Mean error
MIRAI	Macro-invertebrate Response Assessment Index
MODIS NDVI	Moderate Resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index (NDVI)).
MRU	Management Response Unit
OKASS	Okavango Assessment System
OL	Overland
PD	Present Day
PES	Present Ecological State
PET	Potential Evapotranspiration
RPU	Runoff Potential Unit
RQO	Resource Quality Objective
SASS5	South African Scoring System for Macro-invertebrates version 5
SF	Surface Flow
SRTM	Shuttle Radar Topography Mission
Subsurface flow	The groundwater water flow along the river path. Even in times when the river bed is dry, this subsurface flow may exist beneath its bed
SW	Surface Water

SWMM	Storm Water Management Model
TDS	Total Dissolved Solids
VEGMAP	Vegetation map
VEGRAI	Vegetation Response Assessment Index
WLRT	Worsely Likelihood Ratio Test
WRC	Water Research Commission
WRCS	Water Resource Classification System

GLOSSARY

Azonal vegetation	vegetation type which is influenced more by soil characteristics than by climate
Baseflow	the net groundwater flow into the river. This is the groundwater water flow coming laterally into the river. Even when there is no runoff (surface water) coming into the river. There may be water inflow into the river through the groundwater
Biome	a high-level hierarchical unit having similar vegetation structure exposed to similar macroclimatic patterns, often linked to characteristic level of disturbances such as grazing and fire (Mucina and Rutherford 2006)
Bioregion	a composite spatial terrestrial unit defined on the basis of similar biotic and physical processes at a regional scale (Mucina and Rutherford (2006)
Diabase	Fine- to medium-grained, dark grey to black intrusive igneous rock
Ephemeral	no flow at least 26-75% of the time (available hydrological record)
Episodic	no flow at least 76% of the time (available hydrological record)
Interflow	traditionally refers to a build-up of saturation in the shallow hill slope near a river that offers infiltrating rainfall a preferential pathway to the river
Non-Perennial river	Rivers that experience intermittence (or disruption) of surface flow
Semi-Permanent river	no flow 1-25% of the time (available hydrological record)
Underflow	Saturated zone flow beneath (and parallel to) the river
Vegetation units	a complex of plant communities ecologically and historically (both in spatial and temporal terms) occupying habitat complexes at a landscape scale (Mucina and Rutherford, 2006)

1 INTRODUCTION AND OBJECTIVES

1.1 Introduction

This project (Phase III: K5/1798) follows on from a one-year project (Phase I: WRC K5/1414; Rossouw et al., 2005) and a three-year project (Phase II: WRC K5/1587; Seaman et al., 2010), both of which were recently completed. All three projects focused on the Environmental Water Requirements (EWRs) for non-perennial rivers.

- In Phase I, the existing EWRs completed on some non-perennial rivers in South Africa were evaluated and problems identified.
- In Phase II, the ecological functioning of a non-perennial river was investigated and a prototype EWR method (Arid-Proto) for non-perennial rivers was developed using the Seekoei River as a case study.

The South Africa National Water Act (Act 36 of 1998) requires that an Environmental Reserve be proclaimed before licenses are issued for water use from a specific water source. To determine the Environmental Reserve a EWR needs to be completed for the river. Methods that are currently in use to determine the EWR for rivers in South Africa were developed on perennial rivers. Research carried out, in the projects mentioned above, revealed certain deficiencies in these methods and found that they could not always be applied to non-perennial rivers in their present form.

A non-perennial river's hydrology differs from that of a perennial river, as they are hydrologically distinctive with highly variable runoff (high Coefficient of Variance (CV) generally greater than 1 (Bull and Kirkby, 2002; Thoms and Sheldon, 2002) and a high hydrological index), flooding and length of inundation period, which makes them unpredictable to researchers. There is usually a negative correlation between the antecedent moisture and runoff, i.e. following a dry period, high runoff may occur. The rivers are mostly event driven and subject to constant and sometimes extreme fluctuations in hydrology and other physical conditions. Sediments loads are also high, with a relatively high proportion of bedload compared to humid area perennial rivers. The high variability of non-perennial rivers means that many rivers exhibit disequilibrium so it may not be possible to apply the general hydraulic geometry relationships established for perennial systems (Rowntree and van der Waal, 2012). The fauna are unstructured (spatial patterns are less clear), physically controlled and under constant stress (Uys, 1997).

Research into the development of a non-perennial EWR method started in 2005 using the Seekoei River (a non-perennial southern tributary of the Orange River) as a case study (Seaman et al., 2010). Results from the study showed that the interaction between groundwater and surface water is of critical importance in non-perennial rivers, and probably also in perennial rivers, and that the methods used to determine the EWR should take this into consideration. It was further found that the existing standard hydrological models are inadequate for describing and predicting the hydrology of the full spectrum of non-perennial rivers (episodic to semi-permanent). Connectivity and the presence of pools acting as refugia are also of particular importance for the biota in non-perennial rivers. Management for the abstraction or release of water in these rivers will therefore have to be based on a specific understanding of the ecology of non-perennial rivers and a hydrological model that can address surface and groundwater interactions.

Non-perennial rivers are subjected to high levels of variability and disturbance with extended periods of zero flow during which the storage and quality dynamics of static pools (if present) may play a significant ecological role (Hughes, 2008). The characteristics of individual non-perennial systems will depend to a large extent on the nature of the interactions between surface and groundwater processes. Non-perennial rivers developed on extensive alluvial aquifers are expected to have very

different characteristics to those that are developed on or above hard rock aquifers. The depth of the regional ground water table will be very significant in the latter case (Hughes, 2008). As pools represent potential refugia for biota during no-flow periods, these are expected to be ecologically important. However, understanding their quantity and quality dynamics will also require that the source of water to the pools be understood as well. This is a critical issue as far as the hydrological modelling of non-perennial rivers is concerned (Hughes, 2008).

Groundwater is present in all catchments and the interaction of surface and groundwater depends on the geomorphology and climate in these catchments. A stream in a wet climate may receive groundwater inflow but a stream in an identical geomorphological setting in a dry climate may lose water to groundwater. An added complication is that some rivers are gaining or losing systems but some could be both and this can change along the length of the river as well as in different seasons. The fact that there are few, if any, rainfall or gauging weirs in these rivers results in low confidence hydrological modelling with very little calibration possible. Hydrological models developed for use on perennial rivers could be underestimating the environmental water requirements of non-perennial rivers (Rossouw et al., 2005). Mackay (2001) and Hughes (2008) both stress that surface and groundwater interaction is an aspect that has been poorly researched in South Africa, probably due to the complex nature of this interaction and also because surface and groundwater specialists have traditionally worked separately and have developed their fields of expertise in isolation. It is however evident that a surface and groundwater interactive approach is needed in EWR studies, particularly those for non-perennial rivers, and this cannot be ignored any further.

Due to the shortage of hydrological and ecological data on non-perennial rivers it is difficult to determine the reference conditions in the rivers being studied. It was therefore decided, by the team, that an approach beginning with present day (as most specialists have data for the present) was needed. It was also evident from the study on the Seekoei River that monthly flow data were insufficient to capture the variability of flow in non-perennial rivers and that daily flow data should be used. The social and economic aspects of the catchment were also deemed important and needed to be included in the method. Keeping the abovementioned aspects in mind the team involved in the Seekoei River case study examined current EWR methods used in South Africa namely Ecoclassification (Kleynhans and Louw, 2007), DRIFT (Brown et al., 2008 and 2008a) and HFSR (O'Keeffe et al., 2002) and found that the DRIFT method included all of the aspects mentioned above and could possibly be used and modified where necessary.

King et al. (2004) describe the DRIFT method as a holistic, scenario based method that is essentially a data-management tool, allowing data and knowledge, from a multidisciplinary team of specialists, to be used to their best advantage in a structured process. An underlying philosophy of DRIFT is that most researchers take as their starting point in understanding any river, its nature and condition at the time of their studies (present day). The researcher would then use this knowledge and any other data on that particular river or a similar river to predict how the system would change under different development scenarios. DRIFT includes a custom-built Excel based Decision Support System (DSS) software program that is used to generate summary flow categories from daily hydrological data and to provide a graphic relationship between flow volumes/distributions and river condition (Brown et al., 2006). Hydrological modelling is an essential part of the DRIFT method and a suitable hydrological model needed to be found that would suit non-perennial river conditions.

A prototype EWR method for non-perennial rivers was then developed using the Seekoei River as case study and for the purpose of this report the prototype method will be named Arid-proto, and the method eventually developed using the Mokolo River and described here was called DRIFT-Arid as it

is an adapted DRIFT method for non-perennial rivers that are mostly present in arid to semi-arid regions.

1.2 Summary of project objectives

The main objective of this study was to test the Arid-proto method for non-perennial rivers on a variety of non-perennial rivers in South Africa.

The specific terms of reference were to:

- Extend the communication strategy of the programme.
- Test the Arid-proto method in one or more of the catchments adjusting as necessary:
- Select suitable catchments where the methodology can be tested.
- Set up a programme that focuses on specific questions.
- Select researchers and determine the specific tasks that they will carry out to answer questions and to test the methodology in the field.
- Determine in which sub-systems of the catchments sites for fieldwork should be selected.
- Examine the available information for each catchment and set up a programme for fieldwork.
- Carry out the fieldwork.
- Evaluate the Arid-proto methodology.
- Improve on the reliability of data.

1.3 Project details

1.3.1 Project workplan

The project consisted of 5 phases namely a selection of systems, selection of sites, collection of field data and identification of indicators and possible future development scenarios, application of the method, automated model and final report. Each of the phases consisted of several activities as indicated in **Figure 2**.

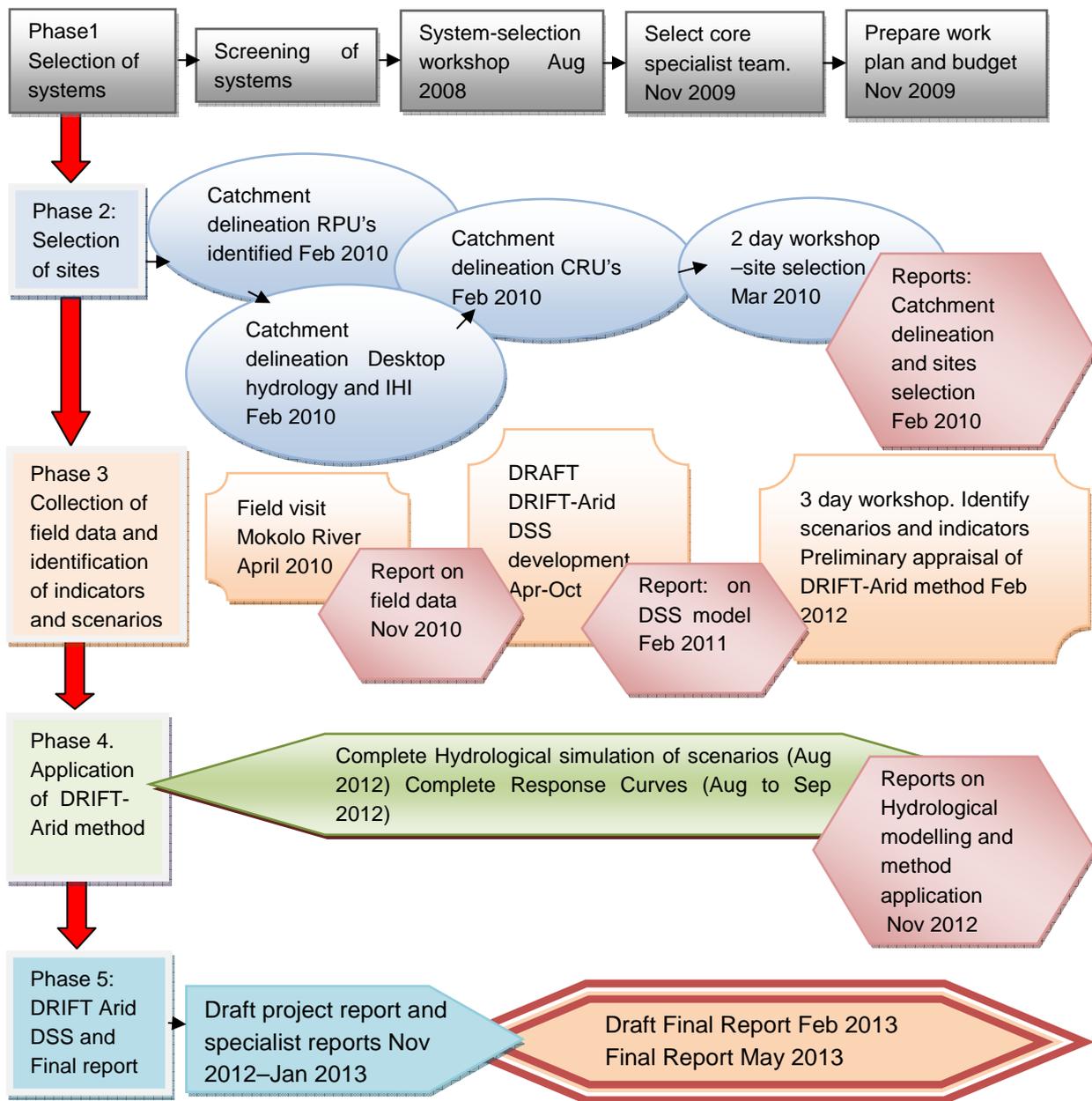


Figure 2. A graphic representation of the workplan for the project

1.3.2 Selection of system on which the Arid-proto method could be tested

The following criteria were considered during the selection of suitable non-perennial systems (rivers that experience flow for less than 80% of time in the historic hydrological record) on which the Arid-proto method would be tested:

- The availability of relevant, reliable flow data: both historic and current.
- Systems selected should be located in different parts of South Africa.
- Systems chosen should be representative of the different types of non-perennial rivers (semi-permanent, ephemeral or episodic).
- The catchment should not be too densely populated or developed (the ideal would be systems where the local human communities are also directly reliant on the river and there is future development planned).
- No or few large dams as these would have too great an influence on the natural flow regime.

- The availability of existing scientific data (whether relating to water quality, groundwater, vegetation, etc.).

Ewald Steyn, a hydrologist from the DWA in the Northern Cape was consulted to determine the nature and availability of hydrological data obtainable for the various non-perennial rivers in South Africa. From this investigation, possible systems that could be used for testing were proposed. Steyn (2008) examined the reliability of discharge records for gauging stations in these systems and presented his findings at a workshop in August 2008.

At the workshop a decision was taken to focus the study on the Swartdoring River (episodic = no flow at least 76% of the time), the Touws River (ephemeral = no flow 26-75% of the time) and the Mokolo River (semi-permanent = no flow 1-25% of the time) (see Table 1 and Figure 3). This decision was approved by the Project Steering Committee at the inaugural meeting at the Water Research Commission offices on 28 September 2009.

Table 1. The possible river systems chosen for the study

River	Locality	% no flow	Gauging Station	Type of non-perennial river
The Mokolo River	Northern Province	7-18%	A4H005	Semi-permanent
The Touws River	Western Cape	72%	J1H018	Ephemeral
The Swartdoring River	Northern Cape	88%	F5H001	Episodic

As three catchments were to be studied in this project it was decided by the team that the order in which the catchments are sampled was important to the planning of the project and a one day workshop was held on 13 November 2009. Using the information presented on flow in the catchments and the data available on each catchment, the team decided to sample the Mokolo River first in April 2010. An intermediate EWR study (DWA, 2008) had already been completed on the Mokolo River using an existing EWR method (Ecoclassification: Louw et al., 2005) developed for perennial rivers in South Africa.

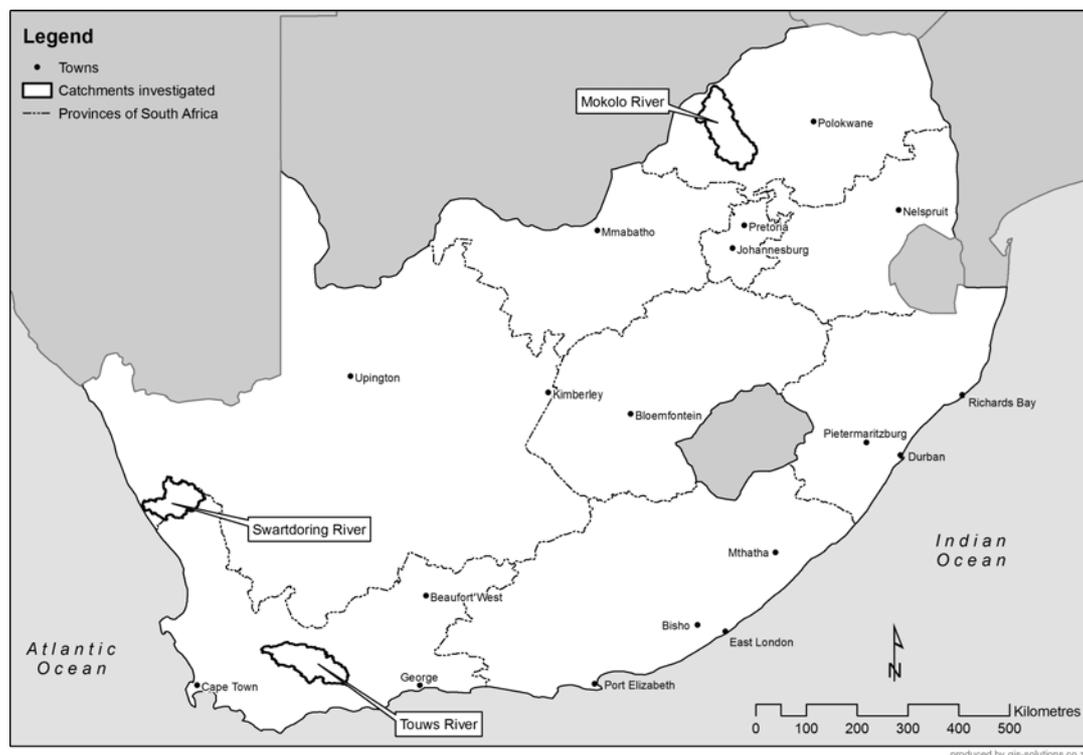


Figure 3. Location of chosen non-perennial river catchments in South Africa

1.3.3 Project limitations and constraints

It must be noted that this project aimed to test an EWR methodology and was not an actual EWR study. Only some of the results (only from some sites) will be discussed as this is only to demonstrate if the method is suitable or not.

Due to budget and time constraints it was originally decided that the study would focus on three rivers, an episodic, an ephemeral and a semi-permanent river.

Field work on the Mokolo River was planned for April 2010. The catchment experienced very high rainfall in early 2010 and this resulted in very high flow in the river. Specialists experienced difficulties with sampling and results were therefore compromised. The budget also only allowed for one sampling session and this was not adequate for an Intermediate or Comprehensive EWR and data from other studies (DWA, 2008a) was used to compliment data collected in the field.

The simulation of hydrological data for surface and groundwater interaction also did not proceed as planned due to the appointed specialist leaving the project before the modelling was completed. The surface and groundwater integrated model suggested by Dr. Ingrid Dennis namely GSFLOW (Coupled Ground-Water and Surface-Water Flow Model) was tested after fieldwork was completed in April 2010 but it could not produce the results needed on pool hydrology and the SWMM (Storm Water Management Model) model was then tested. Before the results of the SWMM model could be evaluated Dr. Dennis resigned from the team in June 2011. This led to a search for a new hydrology modeller and resulted in a delay in the project. Following her resignation the team consulted with hydrologists (Dr. André Görgens, Dr. Hans Beuster, a team from UMVOTO including Dr. Chris Hartnady and Ms Rowena Hay, Stephen Mallory and Prof. Simon Lorentz) who all agreed that the integrated modelling was needed but that it would be a difficult task with implications for time and budget. A training course on MIKE SHE was presented at the University of the Free State and Douglas Graham (presenter and modeller) from DHI (Danish Hydraulic Institute) indicated that the model would be able to produce the results needed for non-perennial rivers. The WRC project steering committee agreed at a meeting in September 2011 that integrated surface and groundwater modelling was very important and that the budget allocated to the Swartdoring and Touws Rivers should be used for MIKE SHE modelling of the Mokolo River. The specialists eventually appointed to complete the hydrological modelling are from the consultancy firm (DHI) that developed MIKE SHE. A model simulation of the surface and groundwater hydrology, for present day, and four other scenarios, using the MIKE SHE model was completed in August 2012. This delay in the project reduced the time available for the team to complete other phases of the project.

1.3.4 Team members and disciplines

The multidisciplinary project team consisted of 28 members (Table 2) of which 5 withdrew before the project was completed. Most of the specialists were from the University of the Free State and most had worked on non-perennial rivers as part of the previous WRC 1587 project. As the project progressed it was found that soil scientists were an invaluable addition to the project team especially when the hydrological modelling was done. Specialists in hydrological modelling (MIKE SHE modelling) were also included at a later stage in the project.

Table 2. The study team and their specific field of expertise involved in the Mokolo River study

Name	Discipline	Institution
Maitland Seaman	Project leader	Centre for Environmental Management (CEM), University of the Free State (UFS)
Marie Watson	Project co-ordinator and macro-invertebrate specialist	CEM, UFS
Jackie King	Project Advisor	Water Matters
Alison Joubert	DRIFT DSS designer and modeller	Southern Waters
Marinda Avenant	Fish specialist	CEM, UFS.
Charles Barker	Geomorphologist and GIS specialist	Geography Department, UFS
Surina Esterhuys	Groundwater specialist	CEM, UFS.
Marthie Kemp	Riparian Vegetation specialist	CEM, UFS.
Douglas Graham	MIKE SHE modeller	DHI
Marcelo Lago	MIKE SHE modeller	DHI
Pieter le Roux	Soil specialist	Soil, Crop and Climate Sciences Department, UFS
Bob Prucha	MIKE SHE modeller	DHI
Nola Redelinghuys	Sociologist	Sociology Department, UFS
Kate Rowntree	Fluvial geomorphologist	Geography Department, Rhodes University
Linda Rossouw	Water quality specialist	Private consultant
Frank Sokolic	GIS specialist	CEM, UFS
Leon van Rensburg	Soil moisture specialist	Soil, Crop and Climate Sciences Department, UFS
Johan van Tol	Soil scientist	Soil, Crop and Climate Sciences Department, UFS
Tascha Vos	Water quality and algae specialist	CEM, UFS.
Hendrik Louw	Student assistant	CEM, UFS.
Ina Ferreira	Student assistant	CEM, UFS.
Joan Adendorff	Student assistant	CEM, UFS.
Falko Buschke	Student assistant	CEM, UFS.
*Denis Hughes	Surface water specialist (advisor)	Institute for Water Research, Rhodes University
*Ingrid Dennis	Groundwater and surface water specialist	Institute for Groundwater Studies, UFS
*Klaudia Schachtschneider	Advisor and plant groundwater specialist (additional study)	CSIR
*Mahlet Bekele	Administration and communication.	Student assistant
*Johann du Preez	Riparian Vegetation Specialist – advisory role	Plant Sciences Department, UFS

Dr. Denis Hughes, Dr. Ingrid Dennis, Dr. Klaudia Schlachtschneider, Mahlet Bekele and Prof. Johann du Preez, withdrew from the project due to other work obligations.

1.4 Report setup

In this report, Chapter 2 is a discussion of the constraints and challenges experienced when working in non-perennial rivers, and Chapter 0 provides a comparison of the Arid-Proto method tested on the Seekoei River with the perennial EWR method. Chapter 4 discusses the DRIFT-Arid method developed on the Mokolo River. Chapter 5 includes the application of the DRIFT-Arid method on the Mokolo River including the approaches followed by the specialists and a summary of the results of the field work on the river. Chapter 6 explains the groundwater and surface water interaction model used and the results for sites 1 and 4 of the Mokolo River study. Chapter 7 is a discussion of the DRIFT-Arid DSS and Chapter 8 provides results from the DSS in terms of the scenario implications for site 4 of the Mokolo River. Chapter 9 provides an evaluation of the DRIFT-Arid methodology as it was applied to a non-perennial river and Chapter 10 relates the lessons learnt in the hydrological modelling and the DRIFT-Arid DSS. Chapters 11 and 12 give the conclusions and recommendations and include possible future projects needed to improve the methodology proposed.

2 SUMMARY OF CONSTRAINTS AND CHALLENGES ENCOUNTERED WHEN WORKING IN NON-PERENNIAL RIVERS.

2.1 Introduction

Approximately two-thirds of South Africa is semi-arid to arid (Digout, 2002) and rivers in these areas are mostly non-perennial with complex hydrological interactions between surface and groundwater (King and Pienaar, 2011). These rivers are flood driven, carry high sediment load and the riparian vegetation is highly sensitive to changes in flow and water availability (often linked to shallow groundwater aquifers) (Rowntree and van der Waal, 2012). EWR methods developed and used for perennial systems do not necessarily work well in such systems, and a new approach, building on the knowledge gained working in non-perennial rivers, was developed. This method is named the DRIFT-Arid method as it is mainly based on the original DRIFT method developed by Southern Waters (Cate Brown, Jackie King, Alison Joubert and others)

A team from the University of the Free State, Centre for Environmental Management have been studying non-perennial rivers from the early 1990s. As the team applied the standard perennial river sampling and interpretation methods, used by the DWA for Present Ecological State (PES) and Reserve determination studies, it became obvious that these methods were not suitable as they are and several constraints and challenges were identified. A detailed discussion of some of these is provided in the previous WRC project (see Chapter 3 in Seaman et al., 2010) that used the Seekoei River as case study and only a summary of these will be provided in this chapter.

The team involved in the current WRC project using the Mokolo River as case study also identified several constraints and challenges in applying methods in non-perennial rivers and a summary of these will also be included in this chapter.

2.2 Constraints and challenges in applying current perennial EWR methods in non-perennial rivers

2.2.1 Timing of field sampling

Non-perennial rivers are unpredictable due to the variability of flow ranging from periods of no-flow to floods. Timing a field visit when conditions are suitable for sampling using the standard prescribed (perennial) sampling methods is not always possible.

Following an application for a water licence, a project to determine the ecological reserve is initiated by the DWA. In non-perennial rivers these are mostly projects that require a Rapid Reserve study where only one field trip is recommended. There is also usually a deadline specified for the project as the applicant needs to be informed as soon as possible whether or not a licence can be awarded. A once off sample in these rivers is often unreliable as the flow is either too high or there is no-flow. Even when flowing, the time when flow started is critical as some biota need more than six weeks for recolonisation and, if sampling is undertaken before this time several taxa would be absent from the river.

As more studies are completed on non-perennial rivers, specialists could develop methods of sampling that would suit most flow conditions. For instance, sampling in pools, which are mostly present in these rivers even during periods of no to low flow, is an option but detailed ecological studies are needed to improve understanding of pool dynamics.

2.2.2 Hydrological modelling

Hydrological models suited to perennial rivers may be inappropriate for simulating the hydrological nature of non-perennial rivers (Hughes, 2008). Their catchments have few, if any, rainfall and runoff gauge sites, and any existing rainfall-runoff data sets are usually of insufficient length to detect trends. Calibration is thus difficult. The links between surface and groundwater in these systems are poorly understood, although groundwater appears to play a significant role in their hydrological nature. The disaggregation of simulated monthly data to describe individual flood events in such systems requires a high degree of specialisation, is not usually feasible and may be quite inaccurate, so flood events are poorly described, if at all (King and Pienaar, 2011; Seaman et al., 2010).

An international integrated surface and groundwater hydrological model (MIKE SHE) has been tested and could be adapted for local use, with hydrologists, geohydrologists, soil scientists and catchment specialists working together to set it up. A challenge in using this model is a lack of detailed data. Often data are referred to in consultant reports as well as the DWA and WRC reports but this data are difficult to obtain as it is not always stored in an accessible database.

2.2.3 Reference conditions

Environmental Water Requirement methods for perennial rivers that are based on default Reference (natural) conditions do not work well for the more extreme non-perennial rivers as these may naturally be very poor in species. Most biota inhabiting these rivers are also generalists and not particularly sensitive to a change in habitat, water quality or flow. If the Reference conditions used in South Africa were applied to non-perennial rivers, even those which are pristine are reflected as degraded because of their low species counts and absence of sensitive species (Rossouw et al., 2005).

The DWA and the WRC are currently funding a project to determine the PES for all rivers in South Africa. Specialists throughout the country are consulted and data are being collected and entered into a database which will become available once completed. This could help in determining Reference conditions but the lack of data on rivers in the semi-arid to arid regions of South Africa where very little research has been completed is still a challenge.

A method, based on the original DRIFT method, that does not rely on the pristine/natural conditions as a Reference condition, but that makes present-day conditions the starting point, has been tested and further developed for non-perennial rivers. Supporting this, new or modified ways are being developed for describing the Present Ecological State (PES) (see specialist reports available of accompanying CD) of the full suite of biophysical indicators.

2.2.4 Pools

Isolated pools are one of the most distinguishing characteristics of non-perennial rivers and are important refugia for many riverine plant and animal species. It is usually not known why they occur where they do and so it is not possible to easily predict where they are likely to occur in an unstudied river or how they would change under proposed management plans. Groundwater is likely to significantly influence both the water quality of the pools and their persistence in dry times, but it is not possible to confidently predict the chemistry or biota of individual pools, or even of pools within one river reach or longitudinal zone, as each pool is likely to be different (King and Pienaar, 2011; Seaman et al., 2010).

Scientists are investigating a landscape-level approach linked to the surface and groundwater integrated hydrological model to provide insights into the distribution and nature of pools (King and

Pienaar, 2011). The MIKE SHE model could be used as a first step in incorporating the knowledge of the catchment with the hydrology to predict where pools are likely to occur.

2.2.5 Connectivity

Connectivity between pools is one of the most important attributes of non-perennial rivers. Connected flow along the whole river occurs intermittently, but when it does sediments and nutrients are transported along the system, gene pools mix, organisms are able to move to other refugia and poor-quality pool water is diluted. Because of the poor coverage of flow gauging stations and uncertain nature of hydrological data for such systems, connectivity is not well recorded and cannot be simulated with great accuracy (Seaman et al., 2010).

An integrated hydrological model has been assessed in terms of how well it can describe connected flow along the system. The MIKE SHE model can simulate flow throughout the river, however this depends on the quality and quantity of data available. Detailed data are needed for geology (surface and subsurface), rainfall (at least hourly) and cross sections (at least upstream, in and downstream of pools) for the model to produce relatively accurate flow and predict the connectivity between pools and this is not always available.

2.2.6 Extrapolation

Under the high levels of physical, chemical and biological unpredictability, extrapolation of ecosystem attributes over long stretches of river is of uncertain value mostly because much of the time the data will be from isolated pools that are behaving differently. For any extrapolation to be true it would have to be at such a coarse level that it could well be meaningless as, for instance, by predicting that a pool would have aquatic invertebrates (of unknown families, genera and species) (Seaman et al., 2010).

At present, understanding of the rivers remains at the level of individual study sites. No extrapolation of data is recommended in non-perennial rivers. Long term data are being collected from various non-perennial rivers to improve understanding and to search for patterns which can be used to predict differences or similarities between rivers/reaches and sites using statistics (King and Pienaar, 2011).

2.3 Constraints and challenges identified by specialists in applying EWR methods in non-perennial rivers.

2.3.1 Geomorphology

Geomorphologists have been involved in EWRs for South African rivers since the 1990s and have contributed to the standard methodology for determining the Environmental Reserve (Rowntree and Wadeson, 1998; Rowntree and Du Preez, 2008). These methods were developed in the context of perennial systems and may need to be modified for non-perennial ones.

The high variability of non-perennial rivers means that many of these rivers exhibit disequilibrium so it may not be possible to apply the general hydraulic geometry relationships established for perennial systems. Channels exhibit 'memory' of the last extreme flood event, with smaller more frequent events reconstructing a more equilibrium channel form. Defining the channel forming discharge is also problematic. The annual flood (recurrence interval of 1 year) is not a meaningful statistic if many years do not experience any flood event. The mean annual flood may be a better surrogate for the channel forming discharge than the flood with a return period of 1 to 2 years. Increased channel complexity linked to flow variability also makes it difficult to define the 'bankfull' stage.

Pools are an expression of channel geomorphology, therefore various pool characteristics were included as indicators. Constructing response curves, however, proved difficult as there is little empirical information available relating pool response to flood discharge, even for perennial systems

A possible approach to assessing changes to hydraulic habitat (depth and velocity) is to develop a suite of curves that describe the at-a-station hydraulic geometry for different river types. These curves would describe how width, depth and velocity change at a cross-section as discharge changes. These relationships could be used effectively in a data poor environment to describe the relationship between hydraulic habitat and discharge. These at-a-station relationships can change at a site due to an altered channel-cross section in response to threshold changes. It would therefore be the task of the geomorphologist to predict under what conditions they would change, and the direction of change.

2.3.2 Water Quality

The lack of water quality data remains the single most challenging aspect of determining the water quality status of a river, perennial and non-perennial, especially the lack of historical data. One should be cautious in interpreting once-off sampling data or patchy historical data. The confidence in the data used for the EWR sites is low in many instances as a result of either very few data to no data or patchy historical data.

The only way to compensate for a lack of data is to use expert knowledge, local knowledge and catchment information (land use, potential pollution sources, soil types, land cover and geology).

2.3.3 Riparian Vegetation

Due to the unique setting of the riparian zone in the landscape, the riparian zone is a very dynamic interactive zone where ground- and surface water meet at the interface of both the terrestrial and aquatic ecosystems.

Challenges identified in non-perennial river systems in terms of riparian vegetation ranged from a lack of knowledge on species specific data such as the critical wilting point of a particular plant species, to the question on where the riparian zone is getting its water from during the dry season. What would the critical minimum drainage upper limit (DUL) and lower limit (LL) be before the riparian vegetation reaches critical wilting point? Where is the water coming from? Is there a larger or smaller contribution from lateral flow from the hillslope landscape or is the riparian zone being fed from the baseflow? How will this change in the dry/wet season? What will happen if flow in the river stops for extended periods? Consequently, how long will the riparian zone be able to sustain its ecological function?

Can the storage capacity of the riparian zone be determined? Soil water and groundwater are two sources of water. Can the “users/vegetation” be identified by looking at species composition alone? Or should there be other checks and balances in place? In assessing the species composition of the riparian zone, shouldn't we also be looking at the functionality of a group of species? Rooting depth and density of riparian species will be extremely valuable in determining the effect a change in groundwater level will have on a particular species. In completing the VEGRAI model (developed for perennial rivers) it was found that in some cases there are no indicator riparian species that are sensitive enough to detect change in non-perennial catchments. This applies to both woody and non-woody species.

2.3.4 Macro-invertebrates

In perennial rivers floods have a marked effect on macro-invertebrate community structure (density usually decreases and community composition changes) but in non-perennial rivers this effect is

exacerbated by the antecedent conditions in the rivers. Long periods of low or no flow would affect the community (invertebrates that cannot survive the dry period leave the system) and then when flow resumes usually in the form of a flood or very high flow the macro-invertebrates that have survived the dry period are washed downstream and have to recolonise the site again.

The variability of the habitat/flow available in non-perennial rivers increases the difficulty in predicting which invertebrates would be present at a certain time or place. This makes using any method which relies on the prediction of macro-invertebrate presence (reference list or reference condition) virtually impossible (with confidence) as there are too many variables (season, flow, depth, temperature, antecedent conditions, habitat type, etc.) to consider. Differences between samples could be a result of human disturbance but could also be as a result of natural disturbance and methods developed for use in perennial rivers cannot distinguish between the different types of disturbance in a non-perennial river.

2.3.5 Fish

The constraints and challenges of conducting fish studies in non-perennial rivers depend, to a large extent, on the level of non-perenniality of the river under study. Rivers towards the episodic end of a continuum, representing various hydrological gradients between episodic and perennial, are generally characterised by highly variable, unpredictable and intermittent flow (Uys and O’Keeffe, 1997). In contrast, rivers towards the perennial end of the continuum have continuous, predictable flow, except during severe droughts. The aquatic communities found at these two extremities are obviously subjected to very different structuring forces. Environmental conditions become increasingly harsh towards the episodic end of the continuum, with biota being subjected to variable and unpredictable surface flow, large disturbances such as droughts and floods, varying periods of flow intermittence and surface water connectivity, being confined in isolated pools, high turbidity, large fluctuations in water temperatures, etc. (Bowmaker et al., 1978; Gaigher et al., 1980; Allanson et al., 1990; Kingsford et al., 2006). Fish species, which are directly dependent on the presence of surface water for their survival, are often absent from episodic and ephemeral river systems due to insufficient surface water. Fish communities occurring in ephemeral rivers are generally species-poor and dominated by tolerant, generalist or opportunistic species (Bowmaker et al., 1978; Gaigher et al., 1980; Unmack, 2001; Kingsford et al., 2006). This, together with the large variability in community composition as a result of the variable states of hydrological fragmentation that exist in these rivers (Leigh and Sheldon, 2008), make it difficult to apply existing biological indices in episodic and ephemeral rivers (Bramblett and Fausch 1991; Kleynhans, 1999a and Avenant, 2010). Biological indices were, for example, found unable to detect anthropogenic environmental degradation due to the fact that the fish community was naturally adapted to large disturbances (Bramblett and Fausch, 1991). However, the application of biological indices in semi-permanent rivers that are generally more species rich and diverse, such as the Mokolo River, should not be problematic.

The hydrological character of ephemeral and episodic rivers also holds practical difficulties for sampling fish communities. The high flow variability (both within and between years), extended periods of surface flow intermittence and large disturbances (floods and droughts) make it difficult to plan and conduct field surveys. The inability to sample effectively during a survey has further consequences in that good historical records are often absent to complement poor results. This may impede the application of biological indices and the interpretation of the results, thereby reducing the overall confidence in the results of the assessment.

Limnological research on non-perennial rivers have been neglected in the past (Davies et al., 1994; Hamilton et al., 2005) and we are just beginning to understand the implications and effects of high flow variability on aquatic communities (Kingsford and Thompson, 2006).The scarcity of historical data and information on many of these rivers, makes it difficult to determine reference conditions and to interpret present data.

2.3.6 Socio-economics

The main limitation with including socio-economics as part of a study like this pertains to the fit between the socio-economic and environmental indicators used. A limitation with the use of socio-economic data in river catchments is that socio-economic data generally corresponds to political areas, i.e. district and local municipal areas. This data does not correspond accurately with the boundaries of catchments, which is the preferred entity for analysis in water-related studies.

For a study such as this there is a strong reliance on quantifiable data and in the case of socio-economic data, secondary data sources such as Census data and Household Survey data were mainly used. However, in order to truly reflect the unique relationships between different non-perennial systems and the populations reliant on these systems, gathering primary quantifiable data obtained through community surveys would yield more accurate results.

3 BACKGROUND TO THE DEVELOPMENT OF THE ARID-PROTO METHODOLOGY

3.1 Introduction

In a previous WRC (WRC K5/1587) project a prototype EWR method (Arid-proto) was developed to determine the EWR for a non-perennial ephemeral river (Seekoei River). The purpose of the current study (WRC K5/1798) is then to test the applicability of the Arid-proto method on a semi-permanent river (Mokolo River) and to modify where necessary, leading to the development of the DRIFT-Arid method.

The development of the original DRIFT method for perennial rivers followed on from a series of studies and workshops (to develop a method) held in South Africa from the late 1980s. One of the first methods to be developed was the Building Block Methodology (BBM) which was based on knowledge from international and local studies. This was also the first method that focussed on the whole ecosystem but it was deemed to be prescriptive by society and so new methods (HFSR and DRIFT), that included stakeholder involvement and focussed on possible future development scenarios, were developed. The development of these methods were guided by three assumptions namely: flow is a major determinant of the nature of the river and therefore it should be the starting point in any method; not only low flow but all parts of the flow regime are important to the functioning of a river ecosystem and all should be included; the river consists of the instream channel as well as the floodplains, estuary, wetlands and groundwater and all aspects of the river ecosystem should therefore be included. To accommodate these three aspects in the method multidisciplinary teams needed to be appointed to determine the EWR for rivers (Brown and Louw, 2011).

The EWR methods developed also needed to fit into the proposed Water Resource Classification System (WRCS; Dollar et al., 2007) which became a legal requirement in terms of the National Water Act (Act 36 of 1998). Each river in South Africa needs to be classified in terms of whether it is minimally, moderately or heavily used. Once the classification has been completed, the Ecological Reserve (amount of water needed by the river to fulfil its ecosystem services to people and remain sustainable) is determined. Basic Human needs from the resource (river) are also determined and only then can water be allocated for off stream uses. Following this the river needs to be monitored to establish if the use of the particular resource is sustainable.

Four levels of EWR determination are prescribed by the DWA and they include: Desktop (to produce fast results with no fieldwork included and used mainly for planning – confidence level low); Rapid (used mostly in evaluating licence applications in areas where there is no high conflict over water allocated, only a once-off field study is included – confidence level low); Intermediate and Comprehensive (used in areas of high ecological importance or/and sensitivity and where conflict over water allocated is high. It includes detailed field assessments and the confidence is medium to high) (Brown and Louw, 2011). The Arid-proto method developed to determine the EWR for non-perennial rivers in the previous project is at an Intermediate to Comprehensive level at present and it should be possible, with the knowledge gained from application to other non-perennial rivers, to produce a more rapid method.

3.2 South Africa's generic RDM procedure for Preliminary Reserve determinations for perennial rivers

The South African generic RDM procedure for preliminary Reserve determinations (EWR) approach developed for perennial rivers follows eight basic steps as set out in Table 3.

Table 3. South Africa's generic RDM procedure for preliminary Reserve determinations (EWR) for perennial rivers (Brown and Louw, 2011)

Step	Activity	Details
1	Initiate the preliminary study	<ul style="list-style-type: none"> • Delineate study area • Choose level of method to be used • Appoint a study team
2	Define Resource units	<ul style="list-style-type: none"> • Delineate ecoregions, geomorphological river zones and landuse • Use these to select Reserve sites
3	Eco-classification	<ul style="list-style-type: none"> • Use to determine reference condition, present Ecstatus (PES), and Ecological Importance and Sensitivity • Determine the recommended future ecological condition (A-E) and identify alternative conditions on either side of that
4	Ecological Water Requirements	<ul style="list-style-type: none"> • Collate flow, biological, hydraulic water quality per site • Describe the EWRs for all three conditions
5	Ecological consequences of operational scenarios	<ul style="list-style-type: none"> • Evaluate scenarios in terms of their impact on ecosystem
6	DWA management classes	<ul style="list-style-type: none"> • DWA reaches a decision on the ecological category that will be used to set the Preliminary Reserve
7	Reserve and RQOs specification	<ul style="list-style-type: none"> • Summarise the Reserve requirements in the Reserve Template • Set ecological RQOs (Ecospecs)
8	Implementation strategy	<ul style="list-style-type: none"> • Implement the Reserve flows and any other mitigation measures • Design and implement a programme to monitor ecospecs

In the generic perennial river approach for EWR determinations either DRIFT, EcoStatus or the HFSR method can be used in Step 3. A hydrological time series of data are the starting point for all these methods. In non-perennial rivers hydrological as well as ecological data are scarce as very few studies have been completed. Daily hydrological data are difficult to obtain due to only a few functional gauging weirs being present in non-perennial rivers. Many people rely on groundwater in the more semi-arid to arid regions where most non-perennial rivers are found and the importance of groundwater in these systems necessitates integrated surface and groundwater hydrological modelling. Paucity of data on the ecological functioning of these rivers makes it difficult to determine the natural conditions. All of the abovementioned aspects motivated the team to look for a method that could start from present day include integrated hydrological modelling and is also structured in such a way that the information from experts could be included in an organised way.

3.3 The Arid-proto method for determining the EWR for non-perennial rivers tested on the Seekoei River.

A set of characteristics that needed to be included in a suitable method for non-perennial rivers were determined by the team of experts involved in the Seekoei River case study: The method needed to:

- fit in with the current EWR method for perennial rivers;
- start with hydrology/flow indicators;
- start at present condition;
- incorporate pool dynamics;
- determine changes due to major floods and drought;
- include groundwater;
- include stakeholder input and use local knowledge;
- determine change in PES under different scenarios (this should only be a coarse indication of change using categories like pristine or heavily degraded and not specific numbers as data on which to base decisions are sparse in these rivers); and
- be specific for each reach or site.

All of these are DRIFT processes except perhaps the greater attention to pools and the inclusion of groundwater. The team therefore applied a very simplified DRIFT method, using specialist knowledge and experience working on non-perennial rivers as well as information and data collected on the Seekoei River, adding extra activities and modifying as deemed necessary. The prototype method developed (on the Seekoei River) will be referred to as the Arid-proto method for the purpose of this report.

The Arid-proto method only relates to the equivalent of steps 1-5 in the generic perennial approach illustrated in colour in Table 3. Steps 6-8 of the generic perennial approach would remain the same in a non-perennial method with the exception of the Reserve Template. A table of recommended monthly flows for each scenario would need to be adjusted as it would be difficult to recommend a certain flow in a river that often does not flow and where flow cannot be regulated.

The Arid-proto method, developed on the Seekoei River, contains 11 phases and 28 activities which are illustrated in Table 4. It focuses on using catchment data, available hydrological data and indicators of change in each discipline (e.g. geomorphology, vegetation, water quality, invertebrates, fish and socio-economic) to determine the expected overall change, in the river, reach or site, due to possible future scenarios.

For a detailed explanation of the Arid-proto method please see Chapter 4 in Seaman et al. (2010).

Table 4. Arid-proto method for determining EWRs for non-perennial rivers

Step	Phase	Activity	Details
1. DWA PLANNING	1. Initiate EWR study	*1. Define river in terms of perenniality. 2. Identify tentative importance and allocate level of assessment.	<ul style="list-style-type: none"> • *If river is perennial follow perennial method if not proceed with activity 2. • According to importance a desktop, rapid or intermediate/comprehensive EWR will be done and budget allocated accordingly
	2. Set up study	Select core specialist team Prepare workplan and allocate budget	<ul style="list-style-type: none"> • *According to type of river (Episodic to semi-permanent) a multidisciplinary team will be appointed. The different levels need different (team for episodic river would not include fish and macro-invertebrate specialists) specialists.
2. RECONNAISSANCE/PRELIMINARY ACTIVITIES	3. Delineate catchment and describe hydrology	5. Describe catchment *6. Delineate hydrological response units/Runoff Potential Units (RPU). 7. Describe the catchment hydrology 8. Assess habitat integrity *9. Delineate combined response units (CRUs)	<ul style="list-style-type: none"> • All information on catchment is collected (geology, landuse, climate, etc.), • *The catchment is delineated into homogenous hydrological/Runoff Potential Units using gauging weir data, climate and catchment data and each of these units are described in terms of instream flow expected. • The habitat integrity is determined using the standard method prescribed by the DWA (Kleynhans et al., 2008) • *All information from specialists, hydrological units, habitat integrity and social impacts are combined to determine the Combined Response Units (CRUs).
	4. Engage stakeholders	10. Identify relevant stakeholders and issues. 11. Obtain stakeholder input during field studies 12. Develop pathways for using stakeholder information.	<ul style="list-style-type: none"> • Socio-economic specialist is involved throughout the project and provides input from stakeholders on current conditions in catchment as well as future development planned for catchment.

Step	Phase	Activity	Details
3. ACTUAL STUDY	5. Site and indicator selection	13. Site selection for biophysical studies 14. Indicator selection	<ul style="list-style-type: none"> Sites are selected in the most important Combined Response Units and they need to represent the specific homogenous unit in terms of habitat available, etc. Using data collected in field as well additional information, the team selects indicators in their specific discipline. .
	6. Choosing scenarios and completing hydrological simulation	15. Choosing scenarios 16. Hydrological simulation of scenarios	<ul style="list-style-type: none"> The team selects possible future scenarios for the catchment using information collected by socio-economic specialist from stakeholders. *A groundwater surface water interaction hydrological model is used to simulate the hydrology for the chosen scenarios (Present day, natural and other scenarios chosen).
	7. Complete specialist studies	17. Collect data *18. Determine PES 19. Write report	<ul style="list-style-type: none"> Data collected by specialists needs to have specific links to flow and also must be used to determine change in indicators. *PES is determined using methods adapted for non-perennial rivers
	8. Knowledge capture	*20. Map the data pathways 21. Create a response curve for each recognised datalink 22. Capture information in database	<ul style="list-style-type: none"> Using information from field studies each specialist must identify links between their indicators chosen and the indicators from other specialist's disciplines. * Indicators are specifically chosen for non-perennial rivers and links between biophysical indicators are also included. Specialists draw response curves which indicate how a responding indicator would react to change in a driving indicator. All the response curves data are captured in a DSS (Decision Support System)
4. SCENARIO WORKSHOP	9. Scenario analysis	23. Ascertain value of each driving hydrological indicator 24. Interpret change in driving indicators as response in all other indicators 25. Add weightings	<ul style="list-style-type: none"> Using algorithms on daily time step data for each scenario, values for each hydrological indicator is calculated. The DSS is then used to interpret the response of each indicator to all the others according to the links determined by the specialists.
	10. Evaluate scenarios	26. Assess the distribution of values for severity ratings of change	<ul style="list-style-type: none"> The change in the ecosystem integrity for each scenario is determined by a set of rules.
5. RESULT	11. Outputs	27. Hydrological output 28. Report to stakeholders	<ul style="list-style-type: none"> The hydrological output is provided to DWA for each scenario (no specific required flow data to be used for management can be provided at present) The impact of each scenario on the catchment is presented to stakeholders.

NB: Colours in Table 3 and Table 4 indicate a correspondence in steps for each method.

* and Bold = new or adjusted activities developed as part of the Arid-proto method.

3.4 Differences between the Arid-proto method and the South Africa generic perennial method

The Arid-proto method more or less follows the same steps as the South African generic perennial approach (for summary see King and Pienaar, 2011 and Table 3) but the details in the steps have been adjusted. The discipline methods are also different, i.e. *specialists needed to adjust individual*

Step 1: Initiate the preliminary study. This is the same for both methods although in the Arid-proto method the type of river is evaluated, i.e. is it an episodic, ephemeral or semi-permanent river as a different suite of specialists is needed for each type of river.

Step 2: Define Resource Units. This is similar in both methods although in Arid-proto, Runoff Potential Units (RPU) are determined which are homogenous units in terms of soil type; catchment slope; infiltration rate; vegetation cover; rainfall intensity and flow accumulation. As non-perennial rivers have very few data on flow, the catchment characteristics and climate data are used as a surrogate together with any flow data available to determine the instream flow characteristics. Catchment data are also used in the Arid-proto method and Combined Response Units (CRUs) are identified by using a GIS overlay of the Natural Response Units (NRUs) and Management Response Units (MRUs).

Step 3: Ecoclassification: Several changes were made in this step in the Arid-proto method as specialists needed to adjust the perennial methods in their disciplines to suit non-perennial conditions and to determine the PES. DRIFT is one of the methods used in the South African generic approach for perennial rivers but a step forward from the original DRIFT method was that specific indicators, which describe the non-perenniality of the rivers being studied, i.e. period of no flow, start of flow after dry period, depth of pools, etc. were incorporated.

Step 4: Ecological Water Requirements. This step is similar to the approach used for perennial rivers. In the Arid-proto method specific development scenarios are chosen and not just the recommended future ecological condition and alternative conditions either side of this. The flow, hydraulic and biological data for each chosen scenario is processed using an excel spreadsheet and the EWRs for each scenario is then provided.

Step 5: Ecological consequences of operational scenarios. This step is also similar to the perennial approach although in the Arid-proto method a simplified excel based method is used to determine the consequences of each chosen scenario.

Steps 6-9: DWA Management classes; Reserve and Resource Quality Objectives (RQOs) specification and Implementation strategy. These steps were not developed for the Arid-proto method. The output that needs to be provided to the DWA has also not been finalised.

3.5 Problems identified when the Arid-proto method was tested on the Seekoei River and that needed to be addressed in the current project.

The Arid-proto method was tested in the Seekoei River as part of a previous WRC project (K5/1587; Seaman et al., 2010) and several problems were identified. The identified problems (discussed below in 3.5.1 to 3.5.4) needed to be dealt with in the current project where the Arid-proto method was tested and developed further using the Mokolo River as case study.

3.5.1 Delineation of homogenous river units

Background: It was proposed in the Seekoei River project that Combined Response Units (CRUs) would be delineated by superimposing the Runoff Potential Units (RPU) with information from the Hydrological Model and Habitat Integrity Assessment. CRUs identified would then be Response Units that are relatively homogenous in terms of geomorphological characteristics, hydrology, anthropogenic impacts and habitat types. The CRUs would assist the team in identifying the areas where the system is under the most stress (where added development or impacts would alter the integrity of the system the most) or an area that is close to natural (or contains critical habitat for biota) and therefore needs to be assessed. Sites would then be selected within each CRU or if this would require too many sites to be assessed only the critical CRUs could be selected where sites should then be identified (Seaman et al., 2010).

Problem: In the Seekoei River project homogenous regions were delineated by identifying the RPU's in the catchment. The hydrological analysis of the catchment was completed and the results were given per quaternary catchment. It was difficult to combine the RPU's and the hydrological analysis results as they were produced on a different scale with the RPU's being at a fifth order stream scale and the hydrological analysis on a quaternary catchment scale (Seaman et al., 2010).

Solution: A revised method was proposed in the current Mokolo River study where GIS was used to delineate the CRU's in the catchment.

- Step 1: Data and GIS maps (geology, topography, climate (precipitation, evaporation), groundwater, vegetation, landcover and landuse, ecoregions, geomorphic provinces, geomorphic zones, macro-reach analysis, soil) on the catchment were collected and prepared and then distributed to all the specialists involved in the project.
- Step 2: The catchment geomorphologist delineated the catchment into RPU's using soil type, catchment slope, infiltration rate, vegetation cover, rainfall intensity and flow accumulation data.
- Step 3: The hydrologist described the catchment hydrology (surface and groundwater) using all available information and identified homogenous regions which were digitised by the GIS specialist.
- Step 4: A habitat integrity study (based on approved method by Kleynhans et al., 2008) was used (a habitat integrity study had already been completed as part of the Intermediate Reserve study of the Mokolo River (DWA, 2008a) and this was used) which identifies homogenous regions in terms of impacts on the catchment and this was also digitised.
- Step 5: Each specialist, using all available information mentioned in steps 1-4 and data in their individual disciplines, identified homogenous regions, i.e. the water quality specialist would use information on geology, landuse, etc. to identify areas in the catchment that would have the same type of water quality as a result of human impact and also natural features such as geology. These regions were indicated on a base map of the catchment and the GIS specialist then digitised them to produce a map of homogenous regions for each discipline.
- Step 6: Following the same concept as proposed in the Resource delineation method for perennial rivers (Kleynhans and Louw, 2007a), Natural Response Units (NRU's) were identified using an overlay of geomorphological zones, macro-reaches, level II ecoregions (this already includes physiography, climate, rainfall, geology and potential natural vegetation, terrain morphological classes, slopes, relief and altitude (Kleynhans et al., 2007b), and Runoff Potential Units (RPU's). As climate data are already incorporated in the level II Ecoregions as well as in the RPU's and the RPU's also include the runoff to the river, it was not deemed necessary to include the hydrology specifically in the delineation. NRU's are then homogenous response units where the natural characteristics of the river are similar. Management Response Units (MRU's) were then identified by overlaying maps of the water quality units (identified by water quality specialist), socio-economic distinct units (identified by socio-economic specialist) and habitat integrity results. The MRU's then represent a homogenous unit where the human impact (management) on the river is similar. The NRU's and MRU's were then overlain and Combined Response Units (CRU's) were identified that represent units that are similar in terms of natural and human impacts.
- Step 7: The map of CRU's was then sent to all specialists and, using the data from the homogenous regions identified as part of step 5, they were asked to rank the CRU's in terms of importance (where they would need or want to sample the river to get the most representative data). Depending on the budget available sites are chosen in the most important CRU's (the number of sites depend on if the river is very important or sensitive and the budget the DWA provides for the study).

3.5.2 Hydrological modelling

Background: Hughes (2008) provides a detailed description of the approach for simulating the hydrology of non-perennial rivers. In terms of the indicators chosen the outputs of this simulation should include, per selected hydrological modelling site, information on connectivity, general indication of the flooding regime likely to influence channel morphology and sediment delivery (Seaman et al., 2010).

Problem: The hydrology of the Seekoei River was completed by Prof. Denis Hughes using the Pitman monthly model and the daily VTI model. The high flow component was done in parallel modelling using the Nash-Muskingum routing mode. The hydrological indicators chosen for the Seekoei River study were channel maintenance floods, sediment delivery and connectivity. Problems identified in the hydrological modelling were:

- Most of the real observations were taken from a gauging weir situated at the outlet of the catchment and it was later established that this weir only represented the flow approximately 15 km upstream of the weir and not the upstream sections of the river. Flow in the upstream sections could therefore not be verified. The hydrological model was based on estimated rainfall and runoff and some team members were not comfortable with this approach. Some of the team also felt that a range of factors should be taken into account in the modelling such as soil permeability, etc.
- The model used could not produce results for indicators of sediment delivery and channel maintenance floods (only available for Sites 3 and 4 and not for the upstream two sites).
- One of the main criticisms of the hydrological model used in the Seekoei River is that it did not integrate the surface and groundwater in the catchment. This was one of the aspects identified as being very important in non-perennial rivers as many of the inhabitants in the catchment use groundwater and this would probably impact on the hydrology of the catchment. It was also felt that the groundwater input into the river was important to biota and water quality of the river and that there should be specific indicators identified which would represent this.

Solution: The MIKE SHE model was used to model the hydrology of the Mokolo River and is a physically based distributed and comprehensive watershed, fully integrated surface and groundwater hydraulic flow model. The benefit of using a fully integrated code, such as MIKE SHE, is the flexibility to develop a model that includes all of the relevant processes. The processes can be simulated in greater or lesser detail to match the degree of information available. In other words, a fully integrated MIKE SHE model can always be built with some basic core data that is typically available in all basins. The basic data includes climate data (daily and if possible sub-daily rainfall, evapotranspiration, etc.) as well as geology, soil data, subsurface data, etc. therefore incorporating most of the data suggested by the previous study. Where gauging weir data are not available climate data can be used to calibrate the model. As data becomes available it can be added to the model which can be rerun to get more accurate results.

Various hydrological indicators were used in the Mokolo River study and the model could produce data for all except for the velocity indicators that needed more accurate input data particularly on cross sections, etc.

The sediment delivery indicator was not included in this exercise so the problems associated with this have not been sorted out in this project although the MIKE SHE model is capable of modelling sediment delivery to a catchment. With regard to water quality, the MIKE SHE model can simulate sediment, nutrient, and pesticide transport in the model area.

3.5.3 PES for indicators

Background: The PES is used in the scenario evaluation to indicate the change at the EWR site from the present to the state expected under that particular scenario. The PES for each of the disciplines needs to be determined before the scenario workshop. Most of the non-perennial rivers have little to no historical data and it is virtually impossible to determine a natural condition with any confidence. Most of the current methods used to determine PES rely strongly if not completely on a comparison of observed data and natural data. As the natural condition cannot usually be defined for a non-perennial river, there is no high confidence PES method for such rivers and specialists therefore need to use expert opinion supported by collected field data and historical records (if available) to provide a PES category. Explanations and motivation for the PES category decided on have to be included by each specialist (Seaman et al., 2010).

Problem: In the Seekoei River study it was found that the current methods used to determine the PES for various disciplines in perennial rivers could not be used and this was mainly due to the lack of historical data that complicated setting reference conditions. Each specialist in this study therefore had to use expert opinion, data collected during fieldwork and any other knowledge of the functioning of non-perennial rivers to determine the PES for each discipline. No formal method was therefore used.

Solution: As the Mokolo River is a data rich system it was possible for the specialists to use the perennial methods to determine the PES for each discipline (see section 5.6.3). This however did not solve the problem identified in the previous project. It is envisaged that when the method is tested on an episodic river the specialists would need to develop alternative methods to determine the PES. Specialists involved in the project are however aware of the challenges associated with determining the PES in non-perennial rivers and are currently identifying projects needed to gather data in order to develop methods suitable for use in these rivers.

3.5.4 Capturing expert knowledge, creating response curves, scenario analysis and evaluation

Background: In early EWRs, scenario predictions of change were the results of the specialists attempting to synthesis all the likely influences – in effect, running an ecosystem model in their heads – and producing an overall prediction of change for any one indicator. One of the more recent procedures for knowledge capture involves creating Response Curves of all major identified relationships, between a river's flow regime and its ecological condition (e.g. the relationship between floods and a fish guild), its ecological condition and social welfare (e.g. the relationship between water quality and human health) and its ecological condition and resource economics (e.g. the relationship between riparian vegetation and household incomes through construction materials) and more. These Response Curves tease out the individual driving and responding parts of the ecosystem for any particular flow change, allowing each specialist to concentrate on their own part of the ecosystem model without being obliged to anticipate how other parts might be behaving. The Response Curves are constructed by the EWR team. Team members should be senior experts in their fields and have a deep understanding of local conditions and non-perennial rivers. Explicitly, this is not a task for generalists, as data are to a large extent being replaced by expert opinion (Seaman et al., 2010).

Problem: The data capture process was done manually in the Seekoei River study using the Arid- proto excel spreadsheets. Response Curves drawn were only for a change in abundance, area or concentration in each indicator and no change in ecosystem integrity was drawn. Specialists did however indicate if a change in abundance, etc. was a change toward or away from natural (a DRIFT procedure) which acted as a surrogate for ecosystem integrity. This led to several problems for instance the away (As) and toward (Ts) ratings often cancelled each other out and a decision then

had to be made if this indicated an improvement in ecosystem integrity or not. The manual method was also cumbersome.

Solution: The perennial DRIFT method was more closely followed than in the Arid-Proto method and the DRIFT-DSS was used in the Mokolo River study and adjustments were made to suit the characteristics of non-perennial rivers, thus forming the DRIFT-Arid DSS. The DSS is an excel-based model which is much less cumbersome than the initial method used in the Seekoei River study. A description of the DRIFT-Arid DSS for non-perennial rivers is given in Chapter 7 and the DRIFT-Arid method is described in Chapter 4.

4 DRIFT-ARID METHOD TO DETERMINE EWRs FOR NON-PERENNIAL RIVERS

The Arid-proto method was developed using the Seekoei River as case study (see Chapter 3). The Arid-proto method was then tested on the Mokolo River and several adjustments (activities added, rearranged and some changed) had to be made. The revised DRIFT-Arid method to determine the EWR for non-perennial rivers (developed on the Mokolo River) is illustrated in Figure 4. It comprises 11 phases and 29 activities. For detail on how the method is applied to a non-perennial river see Chapters 5 to 8.

4.1.1 PHASE 1: Initiate the EWR Study

The same procedure as described in the Arid-proto EWR method for non-perennial rivers (Table 4) is followed and as this is a phase to be completed by the DWA it will not be discussed in detail here.

Activity 1: Define river in terms of non-perenniality

Using the available gauging stage data in the catchment the period of no-flow in the river is calculated. This is then used to place the river in a category of perennial (always flowing); semi-permanent (no-flow for 1-25% of the time); ephemeral (no-flow for 26-75% of the time) or episodic (no flow >76% of the time).

Activity 2: Identify tentative importance and sensitivity rating and allocate level of assessment and budget.

A revised importance and sensitivity study by the DWA for all the rivers in South Africa is currently underway and this should be published in 2013. Data from this study would be then used to determine the importance and sensitivity of the catchment on which the EWR is to be completed and according to this the DWA will allocate a budget and level (desktop, rapid, Intermediate or comprehensive) of EWR determination. The level of confidence required also influences the choice of EWR level. Only a comprehensive method has been developed for non-perennial rivers to date and until a rapid and intermediate method have been developed only the comprehensive method can be used.

4.1.2 PHASE 2: Set up the study

Activity 3: Select core specialist team

According to budget and level of EWR determined by the DWA a team will be selected. The type of river (episodic, ephemeral or semi-permanent) also determines which specialists should be included, i.e. in an episodic river no fish or macro-invertebrate specialist is needed (refer to Table 49).

Activity 4: Prepare work plan and budget

Depending on level of EWR and specialist team chosen, a budget and work plan is setup. For a rapid determination a smaller budget, less fieldwork and fewer specialists are appointed when compared to a comprehensive determination study.

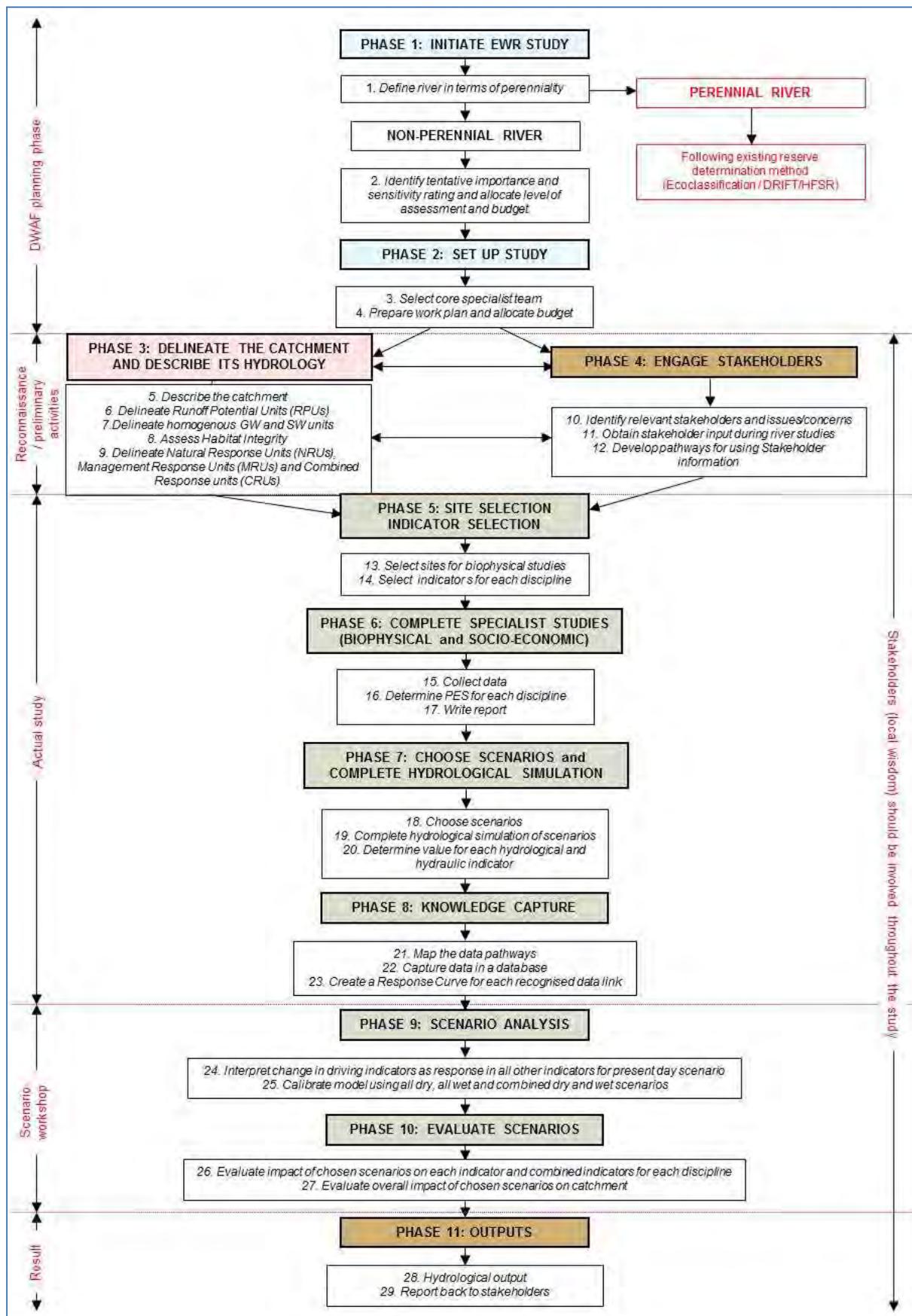


Figure 4. DRIFT-Arid method for determining the EWR of a non-perennial river

4.1.3 PHASE 3: Delineate the catchment and describe its hydrology

In non-perennial rivers, where data are limited and extrapolation to unstudied reaches is uncertain, new approaches may be of use to help describe and understand the system. One key characteristic of the DRIFT-Arid EWR methodology is an intensive use of catchment data to help understand the nature of the river. This is linked with desktop hydrological analyses, habitat integrity assessment, Runoff Potential Units (RPU), homogenous water quality and socio-economic units to produce a division of the catchment into Combined Response Units (CRUs) that represent homogeneous units in terms of natural and management features. The Combined Response Units (CRUs) are similar to the Integrated Units of Analysis produced by the DWA's Water Resource Classification System (Dollar et al., 2007), and the Reserve Assessment Units (RAUs) of Kleynhans and Louw (2007a), and time might prove that these should be harmonized into one concept and one term. The Combined Response Units (CRUs) would then guide the selection of sites for the EWR (Seaman et al., 2010).

Activity 5: Describe the catchment

Data, reports and maps of the catchment are collected by the team. Data on the study area (catchment), topography, climate (especially precipitation and evaporation), geology, catchment and fluvial geomorphology (geomorphic provinces and macro reach analysis), soil, landuse, landcover, ecoregions, geomorphological zones, geohydrology, surface hydrology, vegetation and any specific data on each discipline are used by the specialists to develop an understanding of the catchment and to delineate homogenous units (i.e. units where similar habitat types, flow, social-economic conditions, etc. are expected) in terms of their specific discipline.

Activity 6: Delineate Runoff Potential Units (RPU)

It is the contention of the catchment geomorphologist (Dr. Charles Barker) that information from the whole catchment, and not just instream areas, should be used in river delineation and in determining the location of sampling and monitoring sites. Catchment geomorphology is one of the most important drivers of processes such as erosion, hydrology and sedimentation.

The method proposed and described uses Geographic Information Systems (GIS) as a tool to analyse and model geomorphic processes and to provide team specialists with detailed background catchment data. Description of the RPU could also be used by the hydrologist to assist in the description and modelling of the catchment hydrology.

The fundamental boundary for a RPU would be the boundaries of drainage basins as delineated by hydrological modelling tools. It is proposed that a primary RPU consists of basins at least one order lower than the highest order catchment in the study area. The quaternary catchments are used to delineate an initial catchment boundary. It should be noted that the demarcation of the WR90 catchments does not follow natural watersheds and that a final watershed would need to be delineated later in the study. The quaternary catchments are dissolved and buffered to 5km in order to provide a single boundary for the study area. It is recommended that the coordinate system for the data at this stage is set to WGS84 (the Hartebeesthoek '94 datum is not accepted for raster data in ArcGIS Desktop). The extent of the layer provides a reference in order to find the relevant base maps (topographical, etc.) needed for the study. These data are overlaid on 1:250 000 topo-cadastral (TIFF) and 1:50 000 topographical maps (TIFF and shp) to explore the catchment's general characteristics such as settlements, farms and other major natural features such as rivers, dams, roads, railways, etc. Satellite images (file extension .img) could also be used.

Drainage features: A DTM (Digital terrain model) is constructed from SRTM (Shuttle Radar Topography Mission) data and serves as the basis for the delineation of the final catchment boundaries (watersheds). Drainage features (streams and catchments) are derived from the DTM.

Runoff Potential Units (RPU) are then determined using drainage features, slope, cover, soil (clay content) and rainfall intensity data following the method explained in the Arid-proto method in Seaman et al. (2010). A steep slope, high rainfall intensity, high clay content and low cover would possibly produce higher runoff therefore an overlay of clay content, slope, rainfall intensity and cover would give an indication of areas where runoff is expected to be high or low. Slope is directly derived from the DTM constructed by using SRTM data. For the soil component, the average clay content of landtypes is used and for cover, the MODIS NDVI (Moderate Resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index (NDVI)) data are used.

Activity 7: Delineate homogenous Groundwater (GW) and Surface water (SW) Units

Non-perennial systems have specific characteristics that depend on the climate, geology, topography, soils and vegetation, combined with highly interdependent impacts. One of the most important components of any hydrological study of semi-arid regions is therefore the development of a conceptual idea of the main processes that occur within the specific catchments (Hughes, 2008). The process and method used to describe the catchment hydrology is provided in Hughes (2008).

Data collected for the RPU (see Activity 6) delineation could also be used in assisting the hydrologist in accessing the knowledge needed on climate, topography, geology, soils, vegetation and drainage pattern which can in turn provide a great deal of information about possible active processes in the study area.

A general description of the catchment hydrology in terms of ground and surface water is then provided using a desktop analysis of available information from gauging weirs in the catchment and any available reports.

Surface Water units (homogenous regions in terms of surface water) are also delineated using the following information:

- Ecoregions
- Geomorphic zones
- Land cover
- Presence of dams and other operational aspects
- The physical nature of the river (reaches, characteristics of river bed, etc.)

Groundwater units are identified in the catchment using historical data and data from recent groundwater reports. Aspects such as recharge potential, groundwater use, geology, groundwater, presence and type of aquifers and springs, etc. and potential surface and groundwater interaction areas are included.

Activity 8: Assess Habitat Integrity (IHI)

Procedure remains the same as in the Arid-proto method (Seaman et al., 2010) and uses the IHI method developed by Kleynhans et al. in 2008.

Activity 9: Delineate Natural Response Units (NRUs), Management Response Units (MRUs) and Combined Response Units (CRUs).

In the 1998 National Water Act it was stated that rivers need to be classified and the Reserve for each determined. Methods used in the past and present to do this include:

- Source Directed Controls (the traditional management methods) and
- Resource Directed Measures that were introduced in 1998 and include:
 - Water Resources Classification System (classifies catchments)
 - Ecological Reserve (how much water is needed for river maintenance)
 - Resource Quality Objectives (the measurable variables for monitoring purposes).

The Water Resources Classification System classifies catchments in terms of their nature and use which leads to decisions on water allocation. It includes the following:

- divide the catchment into homogeneous units based on sub-basin hydrological boundaries (major tributaries, etc.) and social zones.
- produce a finer resolution of river ecosystem at nodes (example see Figure 5) and
- define flows needed at each node to maintain A (natural), B, C or D (largely modified) condition (no river may drop below D)

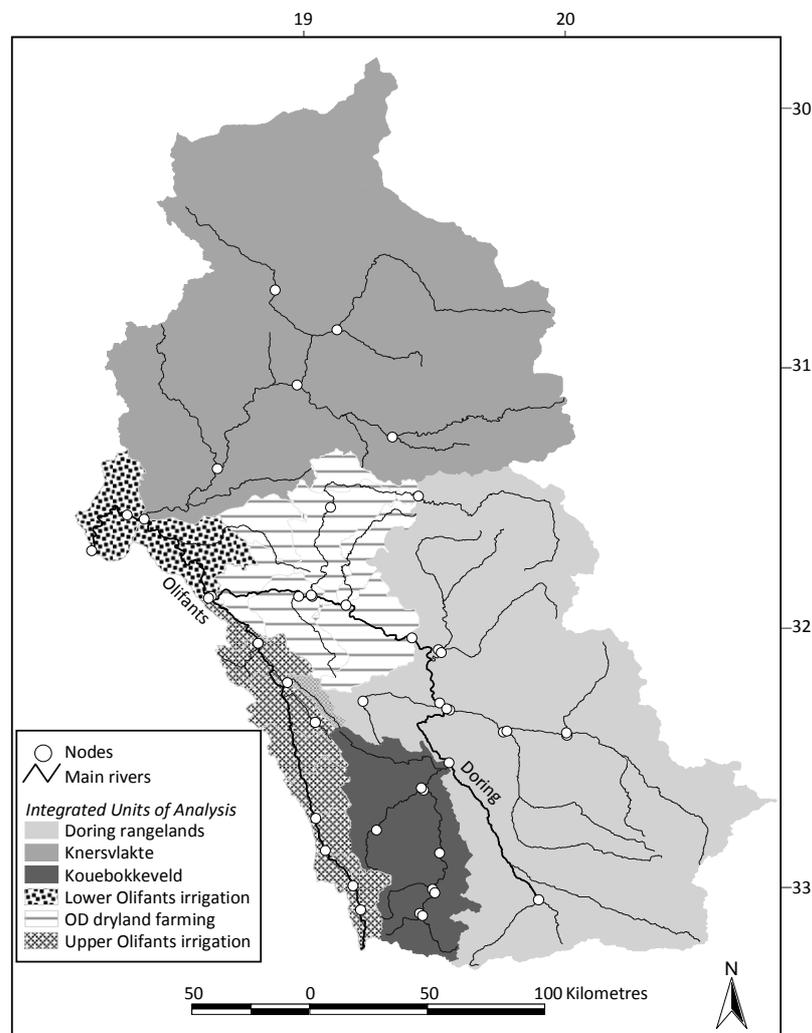


Figure 5. Example of classification and nodes identified in the Olifants-Doring River

As there is usually very few or no flow data available in non-perennial rivers the team in this project decided that:

- catchment data would be used to provide clues to the nature of the river system (Natural Response Units) and Management Response Units would be delineated according to social issues.
- Combined (catchment) Response Units (CRUs) in the river would then be identified by looking at a combination of the following:
Natural aspects (NRUs) based on:
 - Runoff potential Units
 - Geology
 - Land types
 - Groundwater and surface water
 - Geomorphological Zone and Macro-ReachesManagement aspects (MRUs) based on:
 - Water quality (use of water in catchment leading to present water quality)
 - Habitat Integrity (use of river leading to present habitat integrity)
 - Social (aspects such as type of development and use of river)

Many CRUs could be present in a catchment (Figure 6). Sites would be identified within the CRUs and the number of sites chosen would depend on the budget and level of assessment. Each site would represent its whole CRU. Some CRUs may not be represented depending on how important the team feels the CRU is in terms of representing an area in the catchment which is of importance to the management of the catchment (Figure 6)

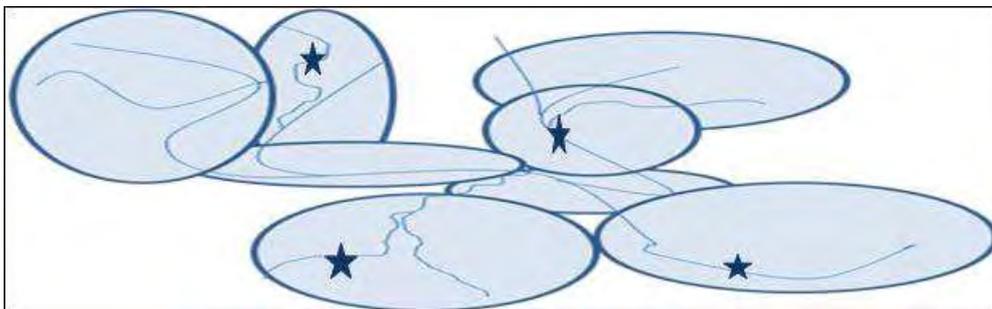


Figure 6. Sites (★) identified in each important CRU

In the DRIFT-Arid method, **Natural Response Units (NRUs)** are delineated by using overlays of ecoregion level II (Kleynhans et al., 2007b), geomorphological zones (Rowntree and Wadeson, 1999), Macro-Reaches and RPU.

The Water Quality Units (homogenous units identified by water quality specialist using historic data and expert opinion), Habitat Integrity Units (identified by using IHI method, Kleynhans et al., 2008) and the Socio-Economic units (homogenous units identified by Socio-economist using historic data and expert opinion) are overlain to identify **Management Response Units (MRUs)**.

The **Combined Response Units (CRUs)** are then delineated by overlaying the NRUs and MRUs and using any other relevant information such as desktop surface and groundwater hydrology and units/areas identified by specialists as being critical to their specialist field (e.g. critical habitat available to fish, etc.).

An alternative method (to replace the CRU determination) is suggested if the MIKE SHE model is used in future in the EWR determination of non-perennial rivers where a 'desktop' integrated model is developed of the entire system (i.e. the Mokolo basin) using MIKE SHE. The model could then be run, with the core set of data (i.e. topography, climate, vegetation, simple geology, simple soil and stream drainages), and the results used to define 'homogeneous' areas and preliminary study sites.

4.1.4 PHASE 4: Engage Stakeholders

A detailed description of this phase is set out in Seaman et al. (2010). The socio-economic specialist is involved in the project from the beginning and collects as much desktop information on the catchment as possible.

Activity 10: Identify stakeholders and issues of concern

The stakeholders in the catchment are identified from information collected on the catchment as well as through public announcements and meetings. The major issues of concern in the catchment and the proposed development are identified by informal as well as formal interviews, meetings and public participation workshops. This information is passed on to the team and a questionnaire is developed by the socio-economic specialist for the team to take to the field.

Activity 11: Obtain stakeholders input during river studies,

The socio-economic specialist accompanies the team to the field and interviews the stakeholders (farmers, farm workers etc.). The team also interviews the stakeholders asking questions relevant to their discipline, i.e. are there fish in all the pools on the farm, which pools dry out and which are permanent etc.

Activity 12: Develop pathways for stakeholders' information to be included in later phases of the EWR.

The information from the stakeholders is used to develop future scenarios and it also guides the team in data collection, indicator identification etc. The stakeholders are also informed about the impacts of proposed scenarios at the end of the EWR study.

4.1.5 PHASE 5: Site and indicator selection

Activity 13: Site selection

The first part of the desktop analysis to choose sites is the choice of the most important CRUs in which sites will be located. Criteria used for the selection of important CRUs should be agreed on by the team in consultation with the DWA, and could include:

- areas with high numbers of people dependent on the river
- areas of high conservation importance or great scenic beauty
- areas in which major water-resource developments are planned or possible
- areas in which the river is in need of rehabilitation through improvement of the flow regime
- areas where the river has rare species, habitats or features
- river zones that are particularly sensitive to manipulations of the flow regime

Each specialist is also asked to identify homogenous units/areas in the Mokolo Catchment according to their specific discipline requirements, i.e. where the specialist would expect the macro-invertebrates (fish, soil, water quality, groundwater, etc.) to be different in terms of their presence, abundance or species composition. The specialist should use catchment delineation information (see section 4.1.3), historical data, recent data as well as expert opinion including local knowledge where available. The

homogenous units identified by the specialist are then used to inform the ranking of the CRUs identified by the team.

Each specialist now needs to rank the CRUs from important to not important using a scale from 1 (important) – # (not important) where # depends on number of CRUs identified in catchment, i.e. if nine CRUs are identified then the ranking will be from 1-9.

Each specialist is then asked to complete a table where the specialist field, criteria chosen and ranking of the CRUs is included (Table 5).

Table 5. Example of importance ranking table completed by each specialist for CRUs identified

Specialist Field		Fluvial geomorphology	
Criteria chosen		<ul style="list-style-type: none"> scenic value rehab through flow regime (currently impacted by upstream water use) areas which best characterise river types sensitivity to flow regime degree of present impact (PES) 	
CRU	Ranking	Motivation	
A	8	Least sensitive to flow regime; scenic value	
B	7	Highly modified channel; rehab potential	
C	2	Important river type site; scenic value; high upstream water use.	
D	5	Alternative for E. Similar river type.	
E	3	Important river type site; scenic value	
F	9	Highly impacted by dam	
G	4	Alternative for H; possible scenic value	
H	1	Important river type site; rehab potential – impacted by upstream dam	
I	6	Alternative for H	

The ranking of CRUs by each specialist is then combined to determine the final ranking of the CRU. Different CRUs could have the same ranking and it is therefore necessary to standardise the ranking from each specialist to produce the same total throughout. The total of $1+2+3+4+\dots+\# = x$ and therefore each specialist's ranking is then standardised to a total of x. The ranking for each CRU is then totalled and arranged from lowest to highest (Table 6). The lowest score would indicate the most critical/important CRU. Sites are then chosen in each of the most important (critical) CRUs. The sites chosen would represent the homogenous nature of the CRU. The number of sites to be sampled is determined by the complexity of the river, the budget available and the level of EWR to be done.

Table 6. Example of a Combined and Standardised Combined specialist CRU ranking in terms of importance for sampling

CRU	Water Quality		Soil		Fish		Macro-invertebrates		Vegetation		Fluvial Geomorphology		Catchment Geomorphology		Socio-economic		Ranking		Final Rank	
	O	S	O	S	O	S	O	S	O	S	O	S	O	S	O	S	O	S	O	S
H	2	6	1	2	5	5	1	1	2	3.5	1	1	5	5	1	1	18	24.5	1	1
D	2	6	1	2	3	3	2	2	2	3.5	5	5	6	7.5	2	2	23	31	2	2
G	1	2.5	3	5	4	4	3	3	2	3.5	4	4	5	5	8	8	30	35	3	3
B	1	2.5	9	8	1	1	6	6	6	8	7	7	2	1	4	4	36	37.5	6	4
E	1	2.5	3	5	7	7	8	8	1	1	3	3	6	7.5	7	7	36	41	5	5
C	2	6	9	8	2	2	7	7	5	7	2	2	7	9	3	3	35	44	4	6
F	1	2.5	3	5	8	8	9	9	2	3.5	9	9	3	2.5	6	6	41	45.5	8	7
I	4	8.5	1	2	6	6	4	4	3	6	6	6	5	5	9	9	38	46.5	7	8
A	4	8.5	9	8	9	9	5	5	7	9	8	8	3	2.5	5	5	50	55	9	9
TOT	45		45		45		45		45		45		45		45					

O=Original Specialist Ranking, S=Standardised Ranking

Once the important CRUs are chosen a desktop analysis should follow where a potential study site within each is identified. This analysis should employ maps, satellite imagery, aerial photographs and any other appropriate information, and consider criteria such as:

- accessibility, both in terms of roads, and landowner's permission
- suitability as a future monitoring site
- proximity to a gauging weir
- the degree to which the site would represent the CRU
- availability of scientific or/and social data
- a point for which hydrological modelling can be done.

The final choice of site locations will be done at the river, and should preferably be done at times of low flow when the general physical nature of the river bed can be seen. Additional criteria to consider at this stage are:

- input from the landowner on the nature of the river
- a physical diversity that characterises the river within the CRU
- inclusion of flow-sensitive habitats, such as riffles, if they exist
- banks and the active channel in good ecological condition
- suitability for hydraulic modelling, if such is planned, such as sites where the river flows straight, in a single channel, with a relatively un-complex flow pattern; it may be necessary, however, to model more complex sites, for instance, where flow floods over to floodplains.

Activity 14: Select indicators

As used in DRIFT, indicators are attributes of the system that can be used in the scenarios to describe change. They should be variables that can be expected to respond to changes in flow or water levels. They should cover the main physical, chemical, biological and social aspects of the river ecosystem, including issues of interest or concern to stakeholders where possible. For non-perennial rivers, it is suggested that the list of indicators should be short and, with trial and error, possibly generic for all such rivers (Seaman et al., 2010). The guiding criterion for indicators is that they should be amenable to some level of prediction of how they would change with catchment developments (Rossouw and Vos, 2010).

In a recent article on non-perennial rivers it was suggested that there are three broad management objectives in these rivers namely: "*preservation or restoration of aquatic-terrestrial habitat mosaics, preservation or restoration of natural flow regimes*" (not meaning flow augmentation which changes temporary to perennial) "*and identification of flow requirements for highly valued species and ecological properties*". Habitat mosaics may include geomorphic structures such as pools, bars, islands, sediment augmentation and provision of large floods. These structures would interact with water levels and produce shifting aquatic-terrestrial habitat mosaics. Preservation or restoration of natural flow regimes would include large floods as well as periods of no-flow. Identification of flow requirements for highly valued species and ecological properties could include flows to support rare species, high gamma diversity (species richness of entire site/combined area, etc.) and absence of invasive non-native species. Flow requirements such as floods, low flows and zero flow periods should be determined for these high value species and properties (Larned et al., 2010).

The above mentioned objectives could help the specialists in non-perennial rivers focus their attention on indicators which would give some insight into these highly relevant aspects.

The team need to choose a list of indicators which would react to change in the system and which can be measured. These indicators need to be specifically linked to changes in flow or water level. They

are measurable entities that change in abundance/area/quantity/ or concentration with change in flow/water. They should describe a specific 'thing' not a process. They can't be processes such as recruitment or drift (in invertebrates), etc. Biophysical indicators would then describe how ecosystems would change from the present state under different scenarios. The resulting socio-economic changes due to the change in ecosystem services will then be identified. Socio-economic indicators also need to be river-linked indicators – they should reflect changes in the river ecosystem.

Each specialist needs to identify indicators and links in their specific discipline using the following as guideline:

Indicators

- are used to describe the status of the ecosystem and its users
- can be different in different parts of the river
- must be expected to change as water regime changes
- may respond to more than one 'driver' or input
- may become driver/input for another indicator
- should be restricted to 4 per discipline

Examples of Indicators are:

- biophysical indicators (abundance, area/cover, concentration):
 - fish habitat-guild A (abundance)
 - vegetation community B
 - nitrates (concentration)
 - sand banks (area)
 - height of water table (number)
- socio-economic indicators (linked to biophysical):
 - household income from river resources
 - drinking water
 - food security
 - wellbeing
 - tourism income

Each indicators needs to be linked to other indicators (Figure 7).

The list of indicators chosen for each discipline would guide the specialist in the type of data that needs to be collected during field work so that potential changes in the indicators resulting from various development scenarios (change in flow or/and habitat) can be determined.

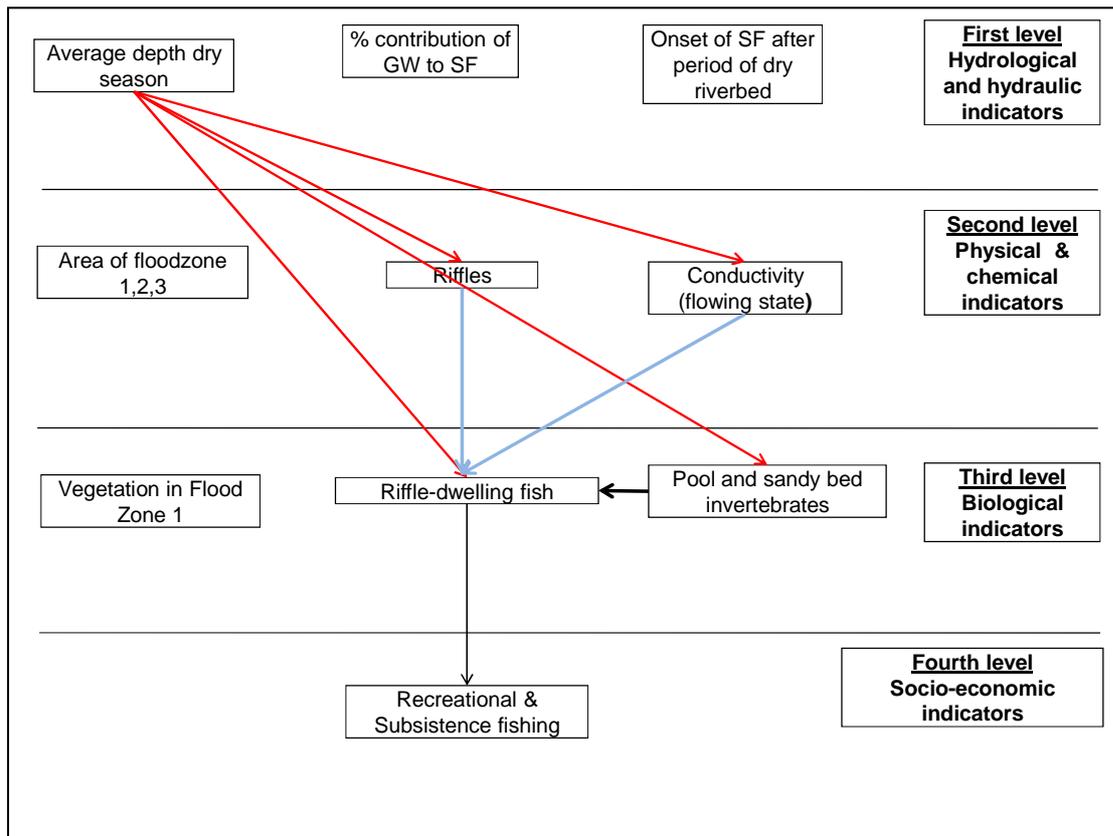


Figure 7. Example of levels of indicators chosen and some possible links

4.1.6 PHASE 6: Complete specialist studies

Once the sites have been chosen for the EWR study the specialists can continue with the field work.

Activity 15: Collect data

Data from specialist studies are used to understand the functioning of the ecosystem and the relationship between it and its users, in order to develop a predictive capacity of how all could change with flow change. The specialists need to be able to develop an understanding of the relationship 1) between flow/water level changes (drivers) and each indicator, or 2), between indicators, so that flow/water changes can be transformed into changes in the value of indicators (Seaman et al., 2010).

At present, no formal method has been developed for collection of data on non-perennial rivers in the different disciplines. Specialists collect and analyse data from each EWR site using their own good-practice methods. Seasonal (summer and winter or if possible in all four seasons) data collection is necessary as well as sampling in a wet and dry year if possible. Most methods available are developed for use in perennial rivers and either has to be adapted using expert opinion or results have to be interpreted keeping the differences between perennial and non-perennial rivers in mind (Seaman et al., 2010).

Activity 16: Determine the Present Ecological State (PES) for each discipline

The PES is used in the scenario evaluation to indicate the change at the EWR site from the present to the state expected under that particular scenario. The PES for each of the disciplines therefore has to be determined before the scenario workshop. No formal method to determine the PES for the different disciplines has been developed for non-perennial rivers at present. Most of the non-perennial rivers

have little to no historical data and it is virtually impossible to determine a reference (natural) condition with any confidence. Most of the current methods used to determine PES rely strongly if not completely on a comparison of observed data and expected data (reference data). As the reference condition cannot usually be defined for a non-perennial river, there is no high confidence PES method for such rivers and specialists therefore need to use expert opinion supported by collected field data and historical records (if available) to provide a PES category. Generic PES categories are summarised in Table 7. Explanations and motivation for the PES category decided on has to be included by each specialist (Seaman et al., 2010).

Table 7. Generic ecological categories for PES (modified from Kleynhans, 1996 and Kleynhans, 1999b)

ECOLOGICAL CATEGORY	DESCRIPTION SCORE	(% OF TOTAL)
A	Unmodified, natural	90-100
B	Largely natural with few modifications. A small change in natural habitats and biota may have taken place but the ecosystem functions are essentially unchanged.	80-89
C	Moderately modified. Loss and change of natural habitat and biota have occurred, but the basic ecosystem functions are still predominantly unchanged.	60-79
D	Largely modified. A large loss of natural habitat, biota and basic ecosystem functions has occurred.	40-59
E	Seriously modified. The loss of natural habitat, biota and basic ecosystem functions is extensive.	20-39
F	Critically / Extremely modified. Modifications have reached a critical level and the system has been modified completely with an almost complete loss of natural habitat and biota. In the worst instances the basic ecosystem functions have been destroyed and the changes are irreversible.	0-19

Activity 17: Write Report

Each specialist needs to write a report which includes:

- Executive summary
- Methods used
- Indicators chosen with reasons
- Results including data collected as well as historic data available
- PES method used as well as results with explanations
- Discussion of data collected in terms of specific indicators chosen
- References

At the end of the project the specialist also needs to add a section on Response Curves and an evaluation of the scenario results for the particular discipline.

4.1.7 PHASE 7: Choose Scenarios and complete hydrological simulation of scenarios

A method which allows for the analysis of possible management (usually development) scenarios has been chosen for this project. Each scenario begins with the simulation of the flow regime that would pertain under that development, followed by the predicted physical, chemical and biological responses of the river ecosystem and finishes with the predicted positive and negative social, resource-economic and macro-economic impacts. Where data are few – the most common situation – it is best to choose fewer rather than more scenarios as there will not be the knowledge to make predictions that distinguish between many similar scenarios. A prioritised list of four to six scenarios is a useful starting point, with those chosen being as dissimilar as possible in terms of the likely future changes within the catchment. The final choice of scenarios should be made in consultation with the DWA and after stakeholder consultation. Input from the hydrologist and modellers is important as the

scenarios chosen must be amenable to hydrological modelling and potentially be able to demonstrate quite different future flow regimes (Seaman et al., 2010).

Activity 18: Choose scenarios

During the fieldwork specialists as well as the socio-economic specialist would interview stakeholders such as farmers, farm workers, irrigation boards, water boards, agricultural societies, government departments and businesses in the catchment. All future or planned activities are noted and the team then uses this information to decide on future scenarios for the project. The scenarios chosen need to have an effect on the flow and water available in the catchment. It is important to choose scenarios that result in an increase as well as some that result in a decrease in flow. A quantity and quality of data are needed to produce appropriate results from the hydrological model and it is important to determine the availability of such data before the scenario is chosen. For instance if the scenario chosen involves an interbasin transfer some of the data that would be needed are:

- Where will the water be transferred from?
- Where will the water be transferred to?
- How much water will be transferred, when and for how long?
- What will the water be used for?
- How will the transfer change the operating rules of dams in the catchment?

Activity 19: Complete hydrological simulation of scenarios

A hydrological model is used to simulate a daily time series of flow for each of the scenarios chosen. Hughes (2008) investigated using various models available in South Africa and concluded that very few data are available on non-perennial rivers and any model used would produce results of relatively low confidence. The models used also need to be run by experienced hydrologists who have specific experience in non-perennial rivers. In systems where the regional groundwater level is well below the river channel the channel transmission loss processes need to be modelled and current South African methods do have the components to do this but they are untested. Where the system has a channel developed on alluvial aquifers, the exchange between groundwater and surface water is complex and current models have not been tested sufficiently to model this at present. This is one of the areas that should be included in any future modelling of these systems. As the integration between groundwater and surface water is so complex it is important to develop a common conceptual understanding of the main processes involved in driving the system and for this geohydrologists and hydrologists need to work together.

It is therefore recommended that the following aspects be included when the hydrology of the chosen scenarios is simulated namely:

- A daily model and not a monthly model should be used
- An hydrologist and geohydrologist with extensive experience in working in non-perennial rivers be included in the team
- A integrated surface and groundwater model be used
- The variability of flow and climate in non-perennial river catchment should be taken into account when data are interpreted.

An integrated surface and groundwater model should therefore be used to simulate the daily time series of flow for the chosen scenarios. The process should start with the present day scenario. A daily time series of data should be provided to the team on the river discharge, river stage, depth to groundwater beneath river, baseflow to river and subsurface flow beneath the river.

The hydrological model first needs to be calibrated and the results of the calibration presented to the team so that they can see if the simulated results are as close as possible to actual data. The team also need to establish if the model can produce the type of data needed for the chosen scenarios. The model can then be run to provide the output for the rest of the scenarios.

Activity 20: Determine value for each hydrological and hydraulic indicator

The hydrologist/geohydrologist on the team determines the value (median and standard deviation) for the flow and hydraulic indicators from the daily time series of flow produced from the hydrological model used. The DRIFT DSS does include a module which can determine the indicator values for perennial rivers but not for the specific non-perennial rivers indicators chosen for this study.

4.1.8 PHASE 8: Knowledge capture

Knowledge of each indicator and how it reacts to the other indicators is captured in the DSS database by drawing a map of the links identified and a Response Curve for each link which incorporates the best available understanding of the specialists and then inserting the data into the DRIFT-Arid DSS.

Activity 21: Map the data pathways

The physical and chemical specialists construct flow diagrams that show the links that exist between the hydrological and hydraulic driver indicators (number of days without surface flow, depth of water in channel, etc.) and their indicators (species composition of vegetation on the lower floodzone, abundance of riffle and rapid dwelling fish and invertebrate species, etc.). For pools, for instance, length of time without surface flow could be seen as potentially affecting pool size/number and so this will show as one of the links feeding into “Pools”. Once the hydrological, physical and chemical links have been satisfactorily captured then the biologists repeat the process with their indicators, showing any direct links from any of the earlier ones to any of theirs. Finally, the sociologists repeat the exercise, showing the hydrological, physical, chemical and biological indicators linked to each of their indicators.

The final result is a diagram of how information flows through the team as they make their predictions. In effect, this is the layout of the ‘ecosystem model’. An excerpt of such a flow diagram can be seen in Figure 7.

Activity 22: Capture data in a database

The data for each of the disciplines, indicators and links is now captured in the DRIFT-Arid DSS database. In the scenario interface file, the site names, scenario names, indicator names and other required information is entered. Each of the specialist files has direct links to this information. The first file that needs data entered is the hydrology specialist file for each site. The flow indicators are entered into these files for each scenario. The values are entered as a table with a row for each year and a column for each indicator. In other words there is a time series of values for each flow indicator. Various calculations are automatically made within this file, such as finding the median value across the years for the particular indicator. This information (e.g. median and ranges across the baseline scenario and across the scenarios) is used to automatically populate the Response Curves in all the other specialist files. Once the flow indicators have been entered into the site hydrology files for at least the baseline scenario (present day or natural), a macro can be operated from the scenario interface file (by pressing the appropriate “button”), which populates each specialist data entry file with the appropriate flow indicator values and thus prepares the Response Curves for the specialists to complete.

Activity 23: Create a Response Curve for each recognised data link

For every arrow on the ecosystem model (each link between indicators), a Response Curve has to be drawn. For instance, if the vegetation specialist has just 1 indicator and it links to 6 other indicators, and occurs at 4 sites, then potentially that specialist has 24 Response Curves to draw. If she has 6 indicators and each link to 6 others, then there could be 144 Response Curves to draw!!! This means that each specialist needs to make sure that only the most important indicators are chosen.

Once the specialists have reviewed, and amended if necessary, the indicator lists they draw the Response Curves directly onto DRIFT DSS data-entry sheets.

Severity Ratings are used to describe relative change in indicators from present day Median values. The rate of change is therefore interpreted using severity ratings which are grouped into five categories (see Table 8).

Table 8. Severity ratings

Severity rating	Severity change	Equivalent Loss (i.e. abundance retained)	Equivalent gain
0	None	No change	No change
1	Negligible	80-100	1-25
2	Low	60-79	26-67
3	Moderate	40-59	68-250
4	Large	20-39	251-500
5	Very large	0-19	501-∞ (to pest proportions)

A Response Curve (Figure 8), which describes how a responding indicator will respond to a driving indicator, is drawn for each identified indicator. The summary statistics for the driving indicator is incorporated in the Response Curve as present day median value, range and standard deviation. Each Response Curve describes the relationship on the assumption that only those two indicators are changing, with the rest of the ecosystem remaining unchanged.

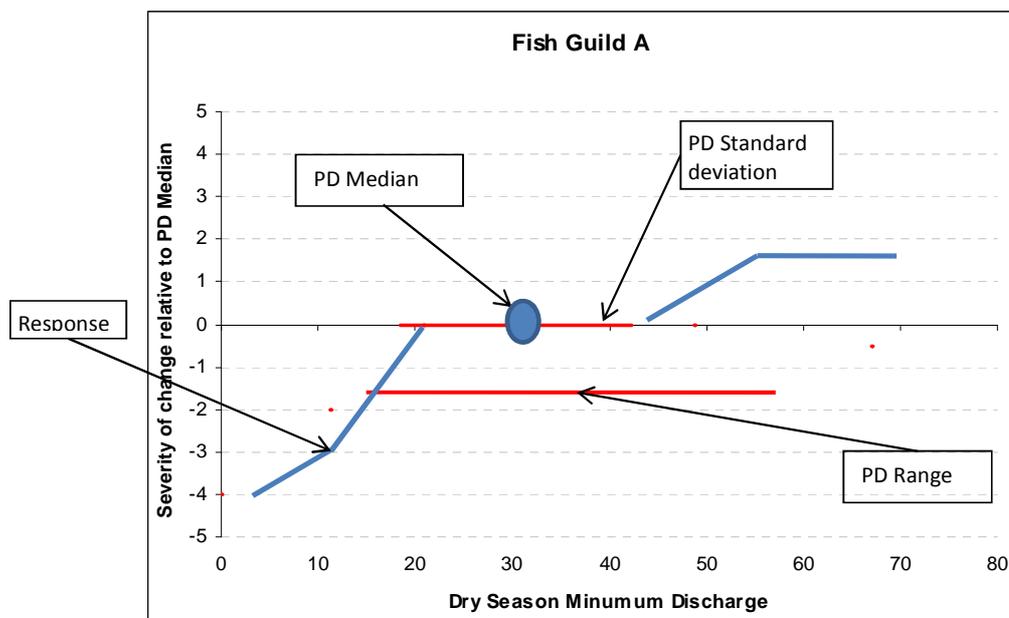


Figure 8. An example of a response curve indicating the response of one indicator to minimum dry-season flows in a year

4.1.9 PHASE 9: Scenario analysis

Activity 24: Interpret change in driving indicators as response in all other indicators for present day scenario

The data sheets (Response Curve values) created by the specialists are then used to configure the DRIFT-Arid DSS (set up its 'brain'). The DRIFT-Arid DSS can then be used to predict the impacts of any flow scenario in relation to present day as indicated in Figure 9 by red arrows. If for instance there are 120 days with no surface flow then the abundance of deep pool dwelling fish will decrease by approximately 5% (from 100% under present day to 95% under specific scenario chosen).

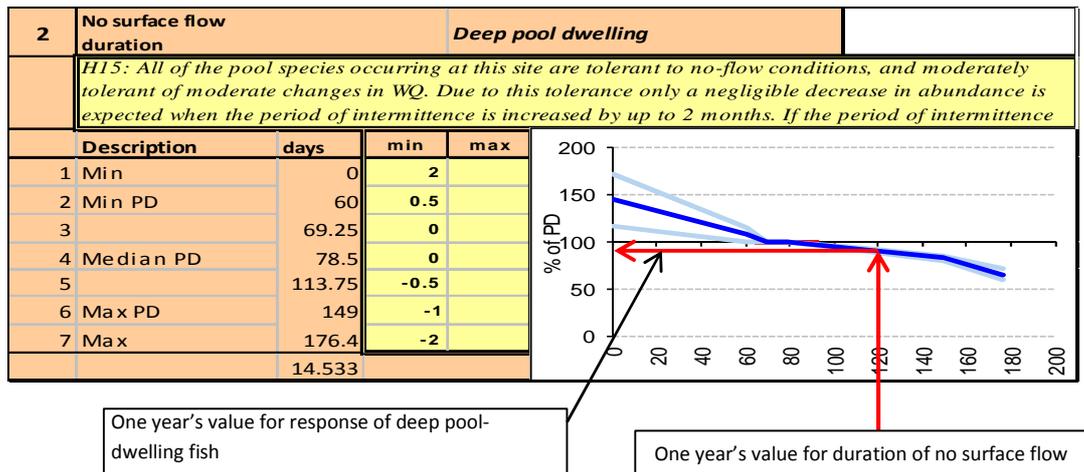


Figure 9. An example of how a response curve in the DRIFT DSS is used to predict changes under a certain scenario

Responses from all the driving response curves are aggregated per indicator to give an overall response to each point in time (season) (see Figure 10).

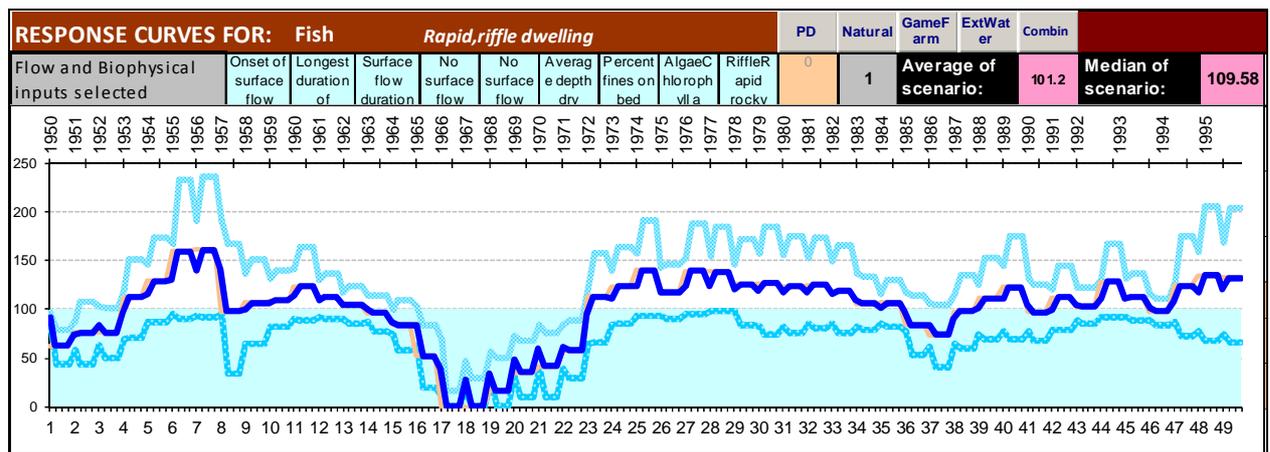


Figure 10. An example of the overall response for Rapid/Riffle dwelling fish species under present day scenario. Bright blue line is the overall response to all indicators and the pale blue lines are the range

Activity 25: Calibrate model using all dry, all wet and combined dry and wet scenarios

The average of the present day scenario should be in the region of 100% (see value indicated for average of scenario in Figure 10). The present day scenario is calibrated by each specialist by

adjusting the response curves input in each indicator so that in the overall response of the indicator, the average of the present day scenario is between 95% and 105% (close to 100%).

Hydrology data from three fictitious scenarios are also included in the DSS. The 'all' wet scenario includes values from the wettest years throughout the time series so that it appears as though the river has wet years throughout. The 'all dry' scenario includes values from the driest years throughout the time series and the 'combined wet and dry' scenario includes values from the wettest years for half of the time series and for the driest years flow for the remaining half of the time series.

The specialists now calibrate the response curves for each of their indicators by using the 'all wet', 'all dry' and 'combined' scenarios. For example, it would be expected that the abundance of riffle rapid dwelling fish species would increase in the 'all wet' scenario and decrease drastically in the 'all dry' scenario.

4.1.10 PHASE 10: Evaluate scenarios

Activity 26: Evaluate impact of chosen scenarios on each indicator and combined indicators for each discipline

In a workshop situation each specialist is given their particular DSS file with all the data from the other specialists included. The specialist is then asked to evaluate the impact of the chosen scenarios on their particular discipline and decide if the results are acceptable or not.

Activity 27: Evaluate overall impact of chosen scenarios on catchment

The team evaluates the impact of the scenarios on the ecosystem integrity of the river by using a graph (Figure 11) produced by the DSS that incorporates all the impacts of the chosen scenarios at a particular site on the river.

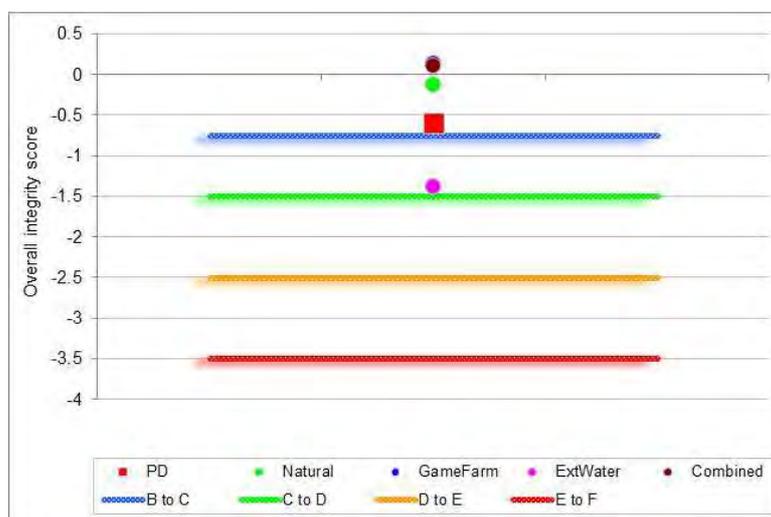


Figure 11. An example of the overall ecosystem integrity for a site in a river as a result of the impact of chosen scenario

4.1.11 PHASE 11: Outputs

The outcome of the EWR study has to be provided to the DWA as well as to the stakeholders in the catchment as they now have to make a decision on how to manage the catchment in future and if the licences that have been applied for should be granted or not.

Activity 28: Hydrological output

The scenarios together with the hydrology (groundwater and surface water) expected are presented to the DWA. This is also a step (step 5) that is included in the Water Resource Classification System (WRCS) of the DWA (Dollar et al., 2007).

Activity 29: Report back to stakeholders

The outcome of the chosen scenarios is now also presented to the stakeholders in the catchment (Step 6 in the WRCS). The presentation should also include a visual presentation (Figure 12) of the combined impacts so that stakeholders can see how the different scenarios would impact on the reach of river where their particular interest lies.

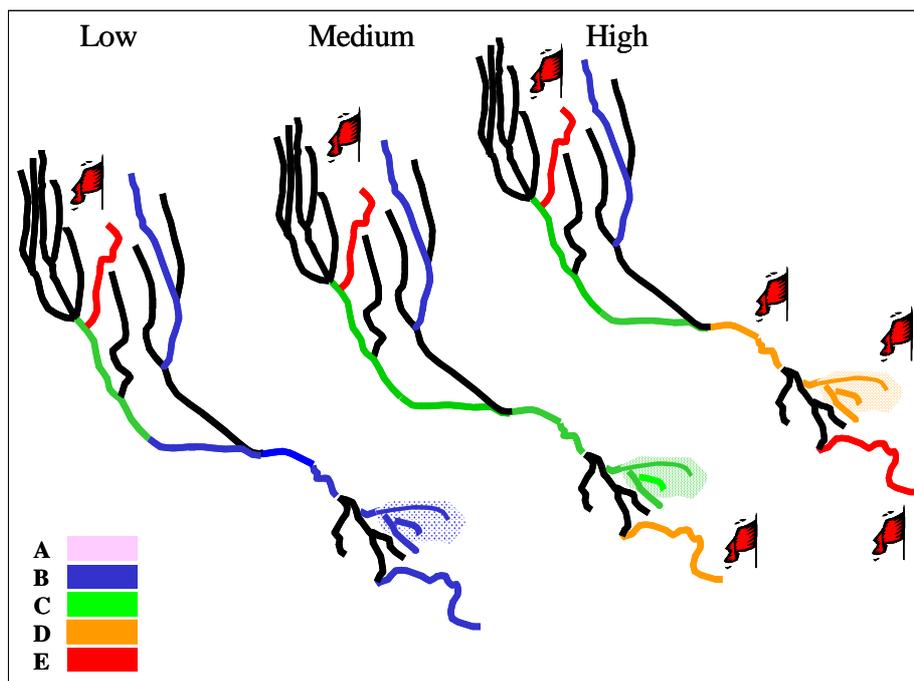


Figure 12. An example of a summary of DRIFT predicted changes in ecosystem condition for chosen (low, medium and high water use) scenarios for the Okavango River system (OKACOM, 2011). A = natural and E = critically modified

The stakeholders together with the DWA will then make a decision on how the catchment will be managed.

5 APPLICATION OF DRIFT-ARID METHOD TO THE MOKOLO RIVER

5.1 Introduction

The original aim of the current project was to test the Arid-proto method on a range of non-perennial rivers in South Africa and the phases and activities set out in Table 4 were initially followed. As the project progressed the team however found that the method needed to be adjusted and a revised method (now named DRIFT-Arid; see Chapter 4) was developed.

5.2 PHASE 1: Choice of catchment and degree of non-perenniality

The degree of non-perenniality of the three possible catchments (Swartdoring, Touws and Mokolo River) recommended for the study by Steyn (2008; see supporting report on CD), was determined using daily flow data, for each gauging weir in the catchments, available from the DWA Hydrological Services Department (Table 9).

Table 9. The river systems chosen for study

River	Locality	% Flow	Gauging Station	Type of non-perennial river
The Mokolo River	Northern Province	72%	A4H005	On the border of semi-permanent and ephemeral
The Touws River	Western Cape	28%	J1H018	Ephemeral
The Swartdoring River	Northern Cape	12%	F5H001	Episodic

At a workshop in March 2010 it was decided by the team that the Mokolo River would be the first catchment tested as it already had a large dataset (an Intermediate Reserve had been completed by DWA in 2010) compared to the Swartdoring and Touws Rivers that are data-scarce catchments.

One of the main activities in the DRIFT-Arid method is the integrated surface and groundwater water hydrology and due to the complexity experienced, with the hydrological modelling in the Mokolo River catchment and the budget that needed to be allocated to this, it was agreed by the Steering Committee that only the Mokolo River would be tested in this project and that the other two catchments (Swartdoring and Touws) could be included in a future project.

PHASE 2: the setup of the study will not be discussed here as this was not an actual EWR and the team, workplan and level of study had already been determined by the WRC project.

5.3 PHASE 3: Catchment description and delineation

A detailed description of the Mokolo River catchment is needed as this information is used by the specialists and hydrological modellers in the course of the EWR process.

5.3.1 Activity 5: Describe the catchment

The Mokolo River falls in the Limpopo Water Management area (WMA1) and consists of tertiary basin A42 including quaternary catchments A42C – J (Figure 13). The river has its origin in the western part of the Waterberg Mountains and includes the upper reaches of the Sand River, the Mokolo Dam and a number of tributaries that join the main Mokolo River up to its confluence with the Limpopo River (African Development Bank, 2009).

The total area of the Mokolo River catchment is approximately 8437 km² (Prucha and Graham, 2012), encompassing several tributaries, namely the Sand (A42A), Sandspruit (A42B), Grootspuit (A42B), Klein Sand (A42C), Frikkiesloon (A42D), Grootfonteinspruit (A42D), Sterkstroom (A42D), Klein

Vaalwaterspruit (A42E), Jim se Loop (A42E), Dwars (A42E), Sondagsloop (A42E), Heuningspruit (A42E), Brakspruit (A42E), Taaibospruit (A42F), Malmanies (A42F), Bulspruit (A42F), Poer se Loop (A42G), Rietspruit (A42 G), Tambotie (A42H), Duiker (A42H) and Sandloop (A42J) (Figure 14).



Figure 13. Quaternary catchments of the Mokolo River

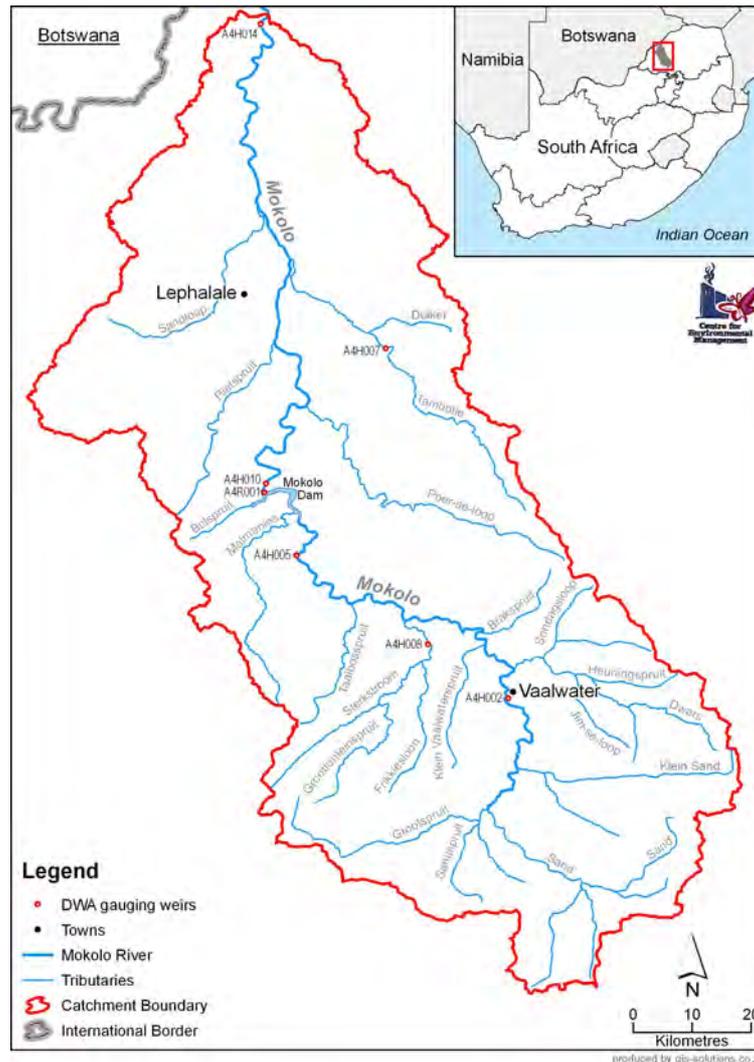


Figure 14. Location of Mokolo River including tributaries, towns and DWA gauging stations

5.3.1.1 Topography, Geology and Geomorphology

5.3.1.1.1 Topography

The catchment is divided by the Sand River Mountains (part of the Waterberg range) through which the Mokolo River has eroded a narrow gap. The general topographical drainage system is poorly developed and drains in an easterly direction towards the Mokolo River (810 masl) (African Development Bank, 2009). The relief of the catchment (Figure 15) is roughly 1000 masl (ranging from between 1500 and 1700 m at the origin, and 800 and 1000 m where it flows through the Limpopo Flats and enters the Limpopo River (Partridge et al., 2010)).

Slope in the study area ranges from 0° to >30° with the northern portions of the catchment having the lowest slopes and the steepest occurring in the middle and mountainous southern parts (Figure 15). The total river slope is 0.0026 m/m.

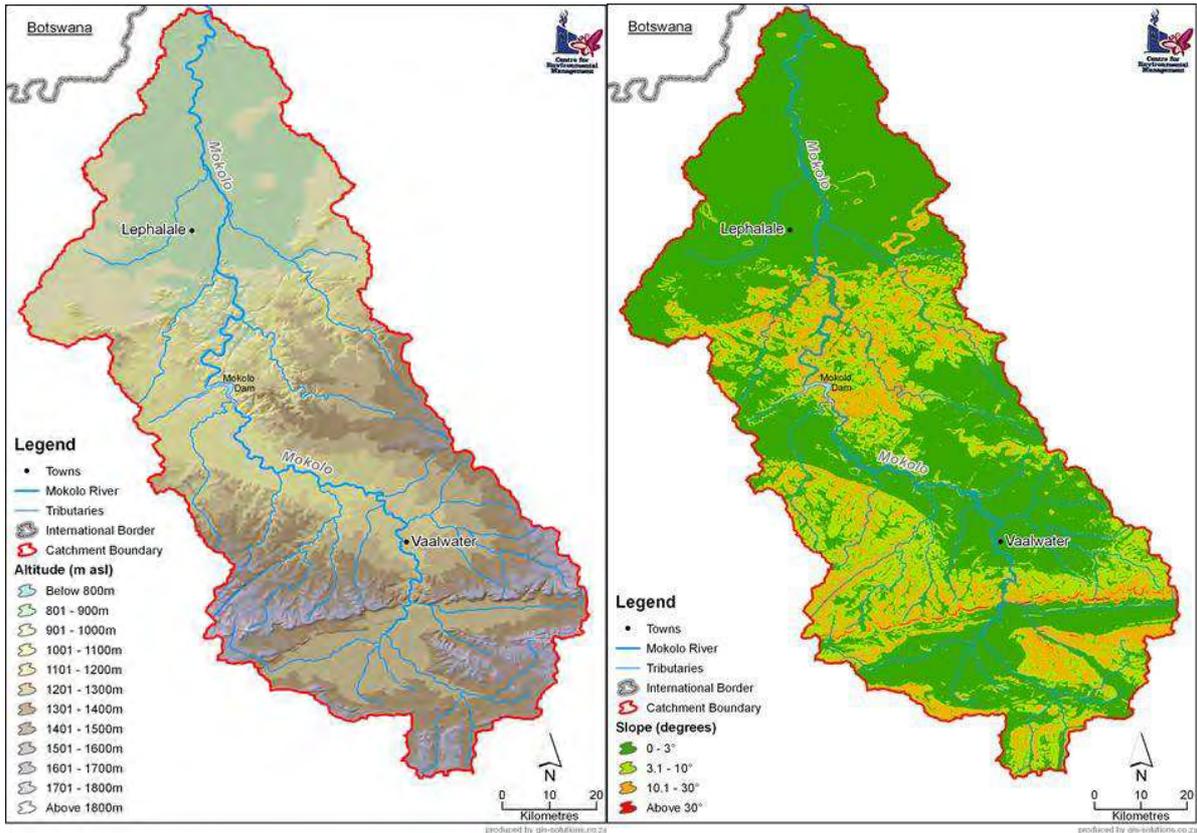


Figure 15. Left (a): Relief and Right (b): Slope of the Mokolo River Catchment

5.3.1.1.2 Geology

A detailed geology report is available as a supporting document on the accompanying CD.

The geology of the upper catchment is dominated by sandstone of the Waterberg group, with local outcrops of conglomerate and dolerite. In the lower catchment the surface rocks belong to the more recent Karoo Supergroup of Permian to Triassic age (Figure 16). These include both sandstones and mudstones. Superficial deposits in the lower catchment are of quaternary age and consist of sandy alluvium. Given the predominance of sandstone in the catchment, sediment entering the channels from hillslopes is likely to be dominated by sand with low silt content (Rowntree and van der Waal, 2012).

The major geological units are the Karoo Supergroup in the north of the study area, the Waterberg Group in the centre of the study area and the Transvaal Supergroup sediments in the southern part of the study area.

Quaternary deposits cover large portions of the Basement Complex (Limpopo Mobile Belt) and the northern reaches of the Waterberg Formation. Sediments such as calcrete, ferricrete, gravel red sand and alluvium are found throughout the northern parts of the Mokolo Catchment (Brandl, 1996). Alluvium with a thickness of up to 5 meters with a coarse sandy base is present along the Mokolo River and serves as an important local aquifer especially during the summer (rainy) seasons.

The Waterberg sandstone rocks were laid down by a very long-lived river system that drained from a mountainous region to the north-east, more or less where Tzaneen is today, during the period 1900-1500 million years ago. In the course of their journey, the sediments carried by these rivers

became clean and well-sorted, resulting in a huge pile of sandy material which is up to 2 km thick in places near Vaalwater. These sediments accumulated over a long period of time in a slowly subsiding basin that extended southwestwards towards the present-day Kalahari (Wadley, 2009). The characteristic reddish colour of the Waterberg sediments is due to the presence of iron oxides, which in turn could only have been formed in the presence of free oxygen. The Waterberg Group rests unconformably on top of the rocks of the Transvaal Supergroup and also above the igneous rocks of the Bushveld Complex (Figure 16).

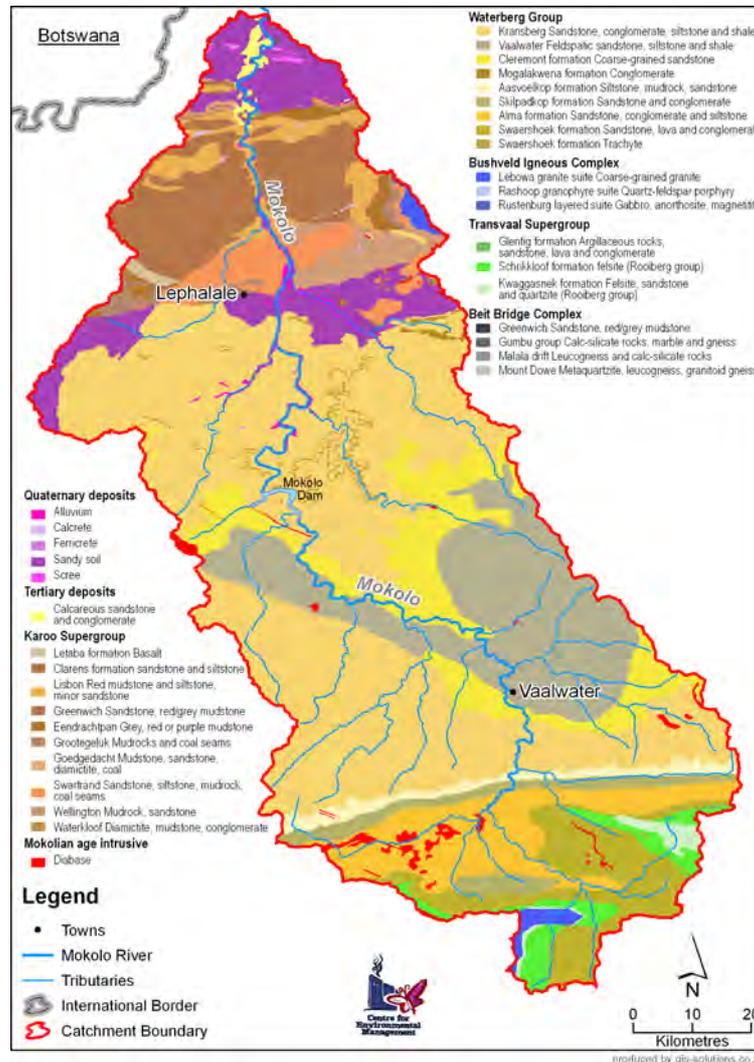


Figure 16. Lithostratigraphy of the Mokolo River catchment

The northern section of the study area is heavily faulted. It is composed of sediments of the Karoo Sequence and forms a graben structure, bounded in the north by the Zoetfontein fault and in the south by the Eenzaamheid fault (Figure 17). The Daarby fault subdivides the coalfield into the shallow opencastable western part and the deeper northeastern part of the coalfield (a displacement of some 400 m). The Zoetfontein fault resulted from pre-/during-Karoo depositional tectonism, whilst the Eenzaamheid and Daarby faults resulted from post-Karoo depositional tectonism. All the units of the Karoo Sequence are present, and the subdivision of the Karoo Sequence is mainly based on lithological boundaries consisting, from top to bottom, of the Stormberg Group (Letaba Formation), followed by the Beaufort Group, the Eccca Group and the Dwyka Group. Within the Waterberg, coal

occurs in both the Vryheid and Grootegeluk Formation, (which are equivalent to the Volksrust Formation) of the Karoo Supergroup (Figure 17) (Vermeulen and Bester, 2009).

Along most of the northern margin, the Waterberg rocks are bounded by the Eenzaamheid fault. The Daarby fault connects the Eenzaamheid and Zoetfontein faults. The main Waterberg basin is a fault-bounded depository which was influenced by the Thabazimbi-Murchison fault zone along its southern edge and bounded by the Zoetfontein and Melinda faults in the north. Diabase intrusions are plentiful in the Waterberg formation. The sills occur predominantly in the Aasvoëlkop formation and the dykes in the Mokgalakwena formation (Figure 16). The most prominent trends for the dykes are west-northwest. A few dykes strike east-northeast parallel to the Zoetfontein and Melinda faults (Brandl, 1996).

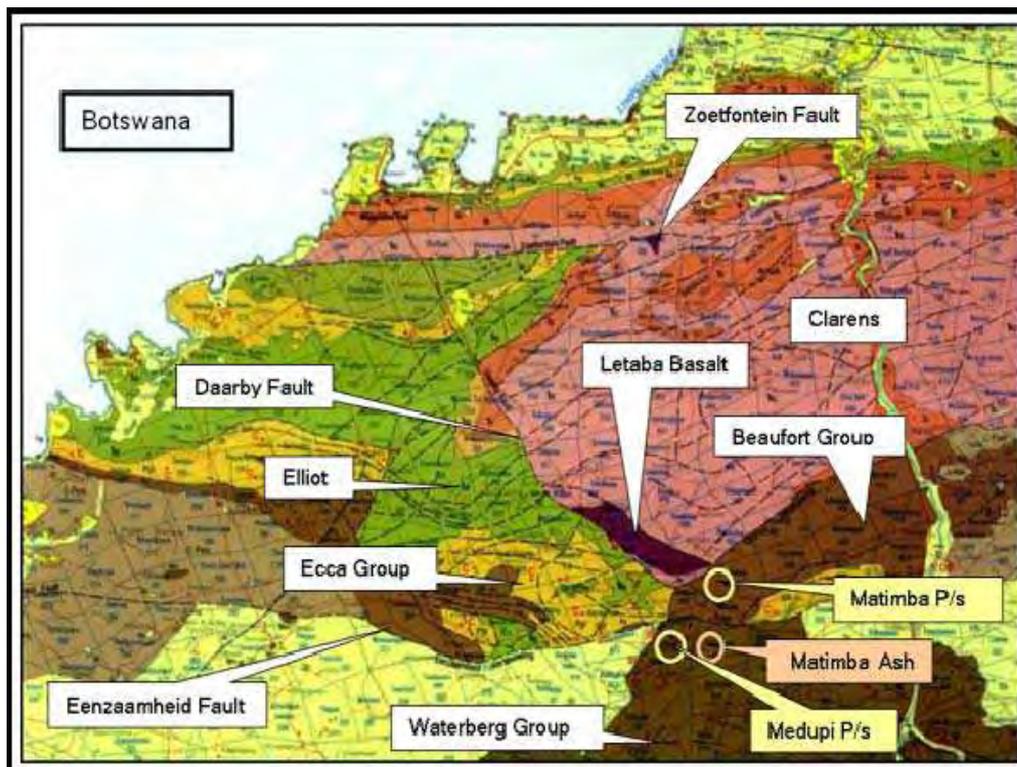


Figure 17. Simplified geological map of the Lephalale coalfield indicating faults present. (Department of Mineral and Energy Affairs Geological map Series: Ellisras taken from Vermeulen and Bester, 2009)

5.3.1.1.3 Geomorphology

Geomorphic provinces:

The Mokolo River flows through two geomorphic provinces namely The Waterberg geomorphic province in the south and the Western Limpopo Flats in the north (Partridge et al., 2010) (Figure 18).

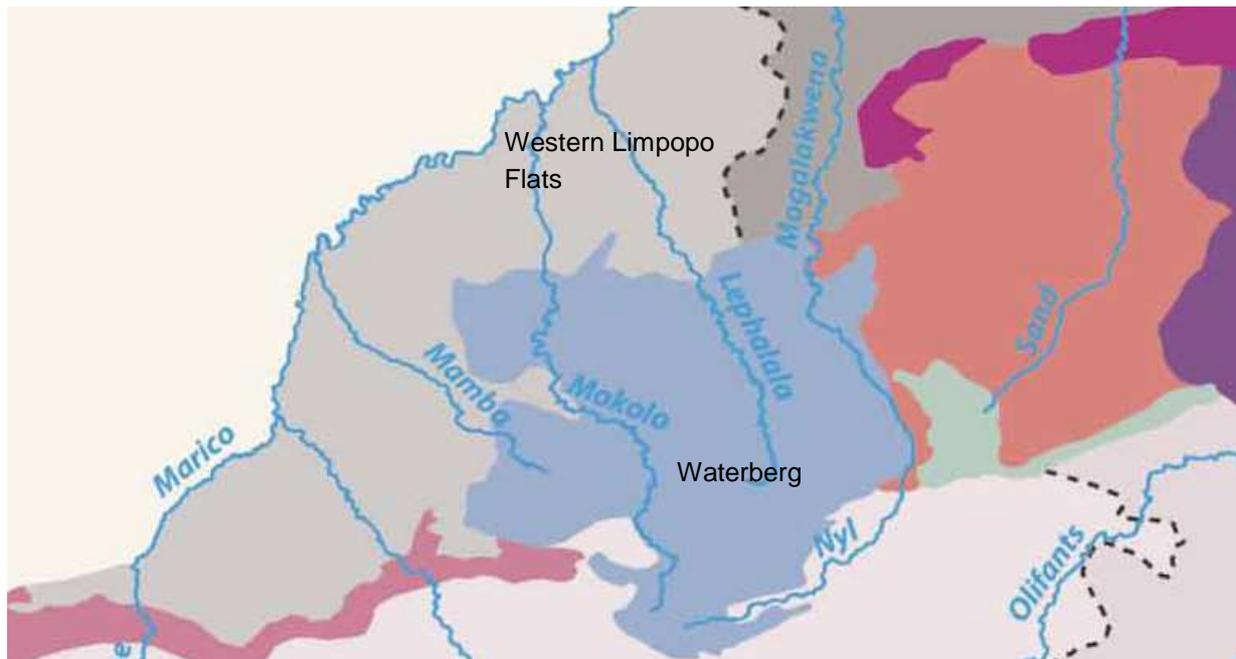


Figure 18. Geomorphic provinces in Mokolo River district (Taken from Partridge et al., 2010)

- Waterberg

This province is underlain almost exclusively by resistant Waterberg sandstones and conglomerates (and a few softer shale beds). Some of the Mokolo River occupies narrow gorges but most has a broad valley cross-sectional profile and a flatter longitudinal slope, so that the sediment storage surrogate descriptor is BS (Broad steep = medium storage of sediment). The storage of sediment is related to the assumption that rivers with steep slopes and narrow valleys have limited storage capacity and rivers with flat slopes and wider valleys have more storage capacity (Partridge et al., 2010).

- Limpopo Flats

Sub-province Western Limpopo Flats: The Mokolo River in this sub-province is underlain mainly by granite-gneiss in the Limpopo Flats area, flowing predominantly northwest into the Limpopo River. Sediment surrogate descriptor is BS (Broad steep) which indicates medium storage of sediment and WF (high storage of sediment). The profile of the river is average concave. The Mokolo River in this section of the Limpopo Flats mostly has a wider valley cross-sectional profile and flatter slopes than the section in the Waterberg Province (Partridge et al., 2010).

Geomorphological zones:

The zonation of rivers in South Africa reflects regional geology, tectonic events and the long-term fluvial action. Channel characteristics recorded during site visits at several rivers in South Africa were linked to channel gradients measured off 1:50000 topographic maps (Rowntree et al., 2000). Geomorphological zones are based on an *a priori* assumption, that is, for a particular range of slopes, you will get a certain 'geomorphological zone' or 'type' of river – e.g. foothills. This means that any river length that falls within a slope category of say 0.002 to 0.0035 m/m falls within zone Lower Foothills (pers. comm. E. Dollar October 2010) (see Table 10).

The main stem of the Mokolo River upstream of the Mokolo Dam falls in the Lower foothills river zone with some Upper foothills, Mountain stream and Transitional zones in the tributaries. The Mokolo River downstream of the Mokolo Dam falls mostly in the Lowland river zone with some small areas of Upper foothills (Table 10 and Figure 19).

Table 10. Geomorphological zonation of river channels (after Rowntree et al., 1996 and Rowntree et al., 2000, with acknowledgements to Rosgen, 1996, Harrison and Elsworth, 1958, Oliff, 1960 and Chutter, 1967).

Zone	Zone class	Gradient class	Characteristic channel features
A. Zonation associated with a 'normal' profile			
Source zone	S	not specified	Low gradient, upland plateau or upland basin able to store water. Spongy or peaty hydromorphic soils.
Mountain head water stream	A	> 0.1	A very steep gradient stream dominated by vertical flow over bedrock with waterfalls and plunge pools. Normally first or second order. Reach types include bedrock fall and cascades.
Mountain stream	B	0.04 - 0.099	Steep gradient stream dominated by bedrock and boulders, locally cobble or coarse gravels in pools. Reach types include cascades, bedrock fall, step-pool. Approximate equal distribution of 'vertical' and 'horizontal' flow components.
Transitional	C	0.02 - 0.039	Moderately steep stream dominated by bedrock or boulder. Reach types include plane bed, pool-rapid or pool riffle. Confined or semi-confined valley floor with limited flood plain development.
Upper Foothills	D	0.005 - 0.019	Moderately steep, cobble-bed or mixed bedrock-cobble bed channel, with plane bed, pool-riffle or pool-rapid reach types. Length of pools and riffles/rapids similar. Narrow flood plain of sand, gravel or cobble often present.
Lower Foothills	E	0.001 - 0.005	Lower gradient mixed bed alluvial channel with sand and gravel dominating the bed, locally may be bedrock controlled. Reach types typically include pool-riffle or pool-rapid, sand bars common in pools. Pools of significantly greater extent than rapids or riffles. Flood plain often present.
Lowland river	F	0.0001 - 0.0009	Low gradient alluvial fine bed channel, typically regime reach type. May be confined, but fully developed meandering pattern within a distinct flood plain develops in unconfined reaches where there is an increased silt content in bed or banks.
B. Additional zones associated with a rejuvenated profile			
Rejuvenated bedrock fall / cascades	Ar, Br or Cr	>0.02	Moderate to steep gradient, confined channel (gorge) resulting from uplift in the middle to lower reaches of the long profile, limited lateral development of alluvial features, reach types include bedrock fall, cascades and pool-rapid.
Rejuvenated foothills:	Dr or Er	0.001 - 0.019	Steepened section within middle reaches of the river caused by uplift, often within or downstream of gorge; characteristics similar to foothills (gravel/cobble bed rivers with pool-riffle/ pool-rapid morphology) but of a higher order. A compound channel is often present with an active channel contained within a macro channel activated only during infrequent flood events. A limited flood plain may be present between the active and macro-channel.
Upland flood plain	Fr	< 0.005	An upland low gradient channel, often associated with uplifted plateau areas as occur beneath the eastern escarpment.

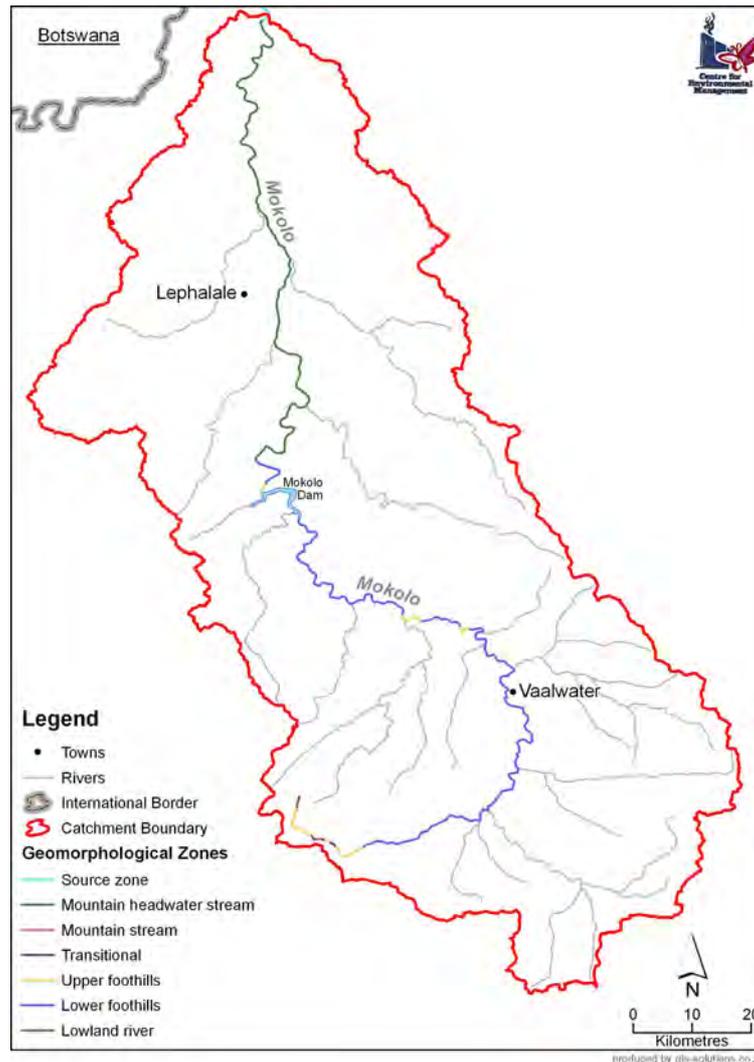


Figure 19. Geomorphological zones in the main stem of the Mokolo River

Macro-reach analysis:

The original macro-reach analysis is a method developed by Dollar et al. (2006) where a statistically repeatable approach called the Worsely Likelihood Ratio Test (WLRT) is used for splitting the long profile of the river into different reaches based on statistically significant changes in slope. These were not determined (in advance) based on an assumed category (as in geomorphological zones), but on where the statistically significant breaks were (using the WLRT method). Hence, the macro-reach approach does not say macro-reach 1 is a ‘foothill’ for example, but simply characterises the reach between two significant breakpoints using various descriptors. This approach was applied to 99 rivers in SA – and hence divided all the rivers using the same approach without categorising them. This allowed the authors of the macro-reach analysis method to look at patterns, etc. and also contributed to defining the geomorphic provinces (personal communication E. Dollar, October 2010).

For this study van der Waal and Rowntree (2010) created a long profile of the Mokolo River using ArcGIS and 1:50 000 topographical data. The distance, following the river course, between each contour was measured and plotted against elevation. The macro reaches were then identified based on slope as described by Rowntree and Wadeson (1999) and Rowntree et al. (2000). A new reach would begin where the river slope changes significantly. These delineated reaches were compared to valley form (confined, semi-confined and unconfined) and the geology of the surrounding area. The

delineated reaches were adjusted so that the resultant macro reaches would each consist of a similar slope, valley form and geology by using information from 1:50000 maps, backed up with aerial survey video and Google Earth images. The macro-reaches only relate to the main stem and not the tributaries (van der Waal and Rowntree, 2010).

Eight (A-H) macro reaches were identified in the Mokolo River ranging from a confined valley form (A) in the upper reaches to an unconfined valley form (H) downstream (Figure 20, Figure 21 and Table 11). The characteristics of each reach are provided in Table 11.

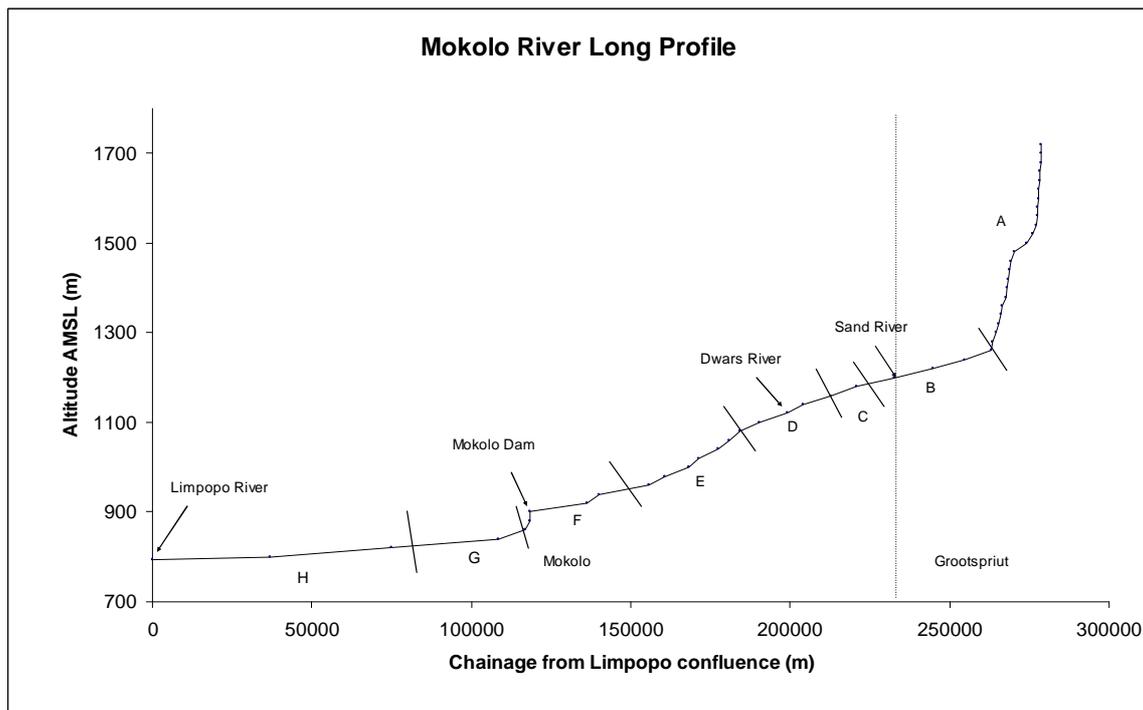


Figure 20. Mokolo River Longitudinal Profile

Table 11. Mokolo River Macro Reach Analysis

Section	Top			Bottom			Length (m)	Gradient m/m	Description		
	Lat (S)	Long (E)	Height AMSL (m)	Lat (S)	Long (E)	Height AMSL (m)			Valley form	Dominant channel	Notes
A	24.4687	27.7538	1815	24.5116	27.8861	1260	15648	0.0354	Confined	Single thread	Poor resolution
B	24.5116	27.8861	1260	24.407	28.1095	1190	30253	0.0023	Unconfined, flat valley floor	Single thread	Pools of varying length, artificially constricted by agriculture, lined with reeds, impoundments, islands, wetlands with dense reed covering, possible incised channel
C	24.407	28.1095	1190	24.332	28.1249	1160	20004	0.0015	Partially confined	Wandering	Natural channel, alluvial, pools, reeds lining pools, sandbars, weirs, islands, meandering channel
D	24.332	28.1249	1160	24.1922	28.0533	1080	28698	0.0028	Partially confined	Bedrock controlled, multi channel	Islands, pools, bedrock, weirs

Section	Top			Bottom			Length (m)	Gradient m/m	Description		
	Lat (S)	Long (E)	Height AMSL (m)	Lat (S)	Long (E)	Height AMSL (m)			Valley form	Dominant channel	Notes
E	24.1922	28.0533	1080	24.075	27.7839	950	28530	0.0046	Partially confined, narrowing valley	Bedrock controlled, single channel pools, multi channel	Islands, reeds lining pools, boulders, bedrock, weirs form pools
F	24.075	27.7839	950	23.9184	27.7334	860	38786	0.0023	Partially confined, narrowing valley	Wandering	Alluvial, pools, boulders, large impoundment, Bedrock, pool-rapid, sand bar, islands, vegetated bars below dam (reduced flooding)
G	23.9184	27.7334	860	23.7307	27.7444	824	41904	0.0009	Partially confined	Wandering	Pools, alluvial, sand bars, reeds lining pools, single thread, islands
H	23.7307	27.7444	824	23.2302	27.7199	792	74865	0.0004	Unconfined	Wandering	Pools, alluvial, sand bars, reeds lining pools, single thread, islands

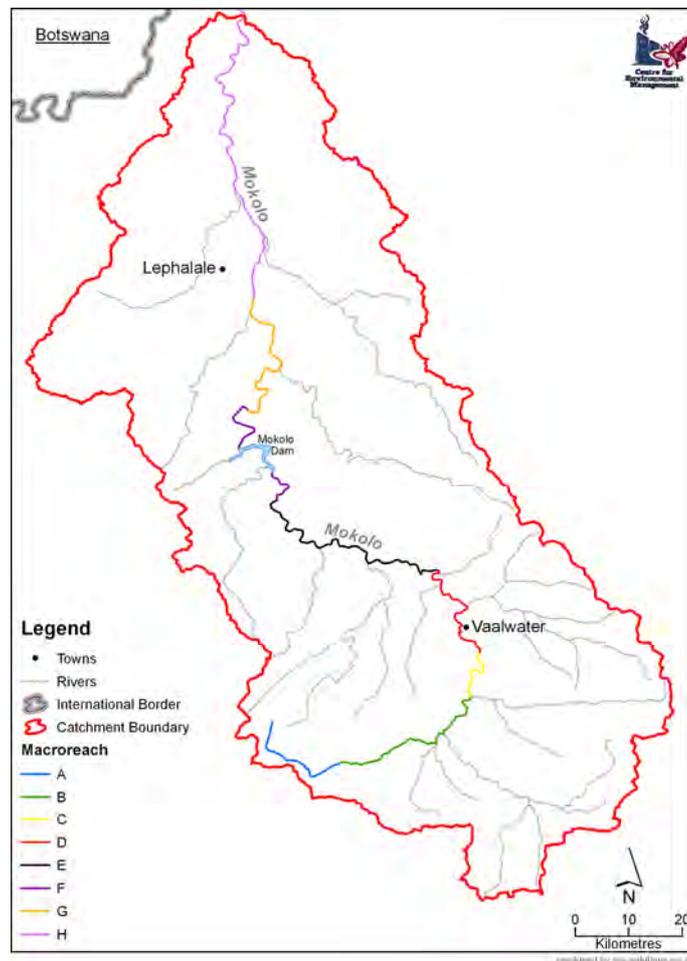


Figure 21. Macro-reaches of the Mokolo River main stem

5.3.1.2 Soil

A Land type unit is a unique combination of soil pattern, terrain and macroclimate, the classification of which is used to determine the potential agricultural value of soils in an area (Bolweki Environmental, 2006). Landtypes occurring in the Mokolo catchment include (Figure 22):

- **Red-Yellow apedal, freely drained soils (Ac- Ah).** Red and yellow soils without water tables and belonging in one or more of the following soil forms – Inanda, Kranskop, Magwa, Hutton, Griffin and Clovely (LTSS, 1989).
- **Plintic catena: Upland duplex and marginalitic soils rare (Ba-Bd).** Includes Hutton, Bainsvlei, Avalon and Longlands forms. Plintic soils are more than 10% of area in Ba-Bd (LTSS, 1989).
- **Plintic catena: Upland duplex and/or marginalitic soils common (Ca).** Margalitic and/or duplex soils cover more than 10% of area.
- **Glenrosa and/or Mispah forms (Fa-Fc).** Young landscapes that are not predominately rock and not predominately alluvial or Aeolian – soil forming process was predominantly rock weathering. Soil forms are mostly Mispah and Glenrosa (LTSS, 1989).
- **Miscellaneous landclasses (Ia-Ib).** Soil pattern difficult to accommodate elsewhere – at least 60% is pedologically youthful, deep unconsolidated deposits. Common soil forms are Dundee and Oakleaf. Landtypes with exposed rock covering 60-80% of area are included here.

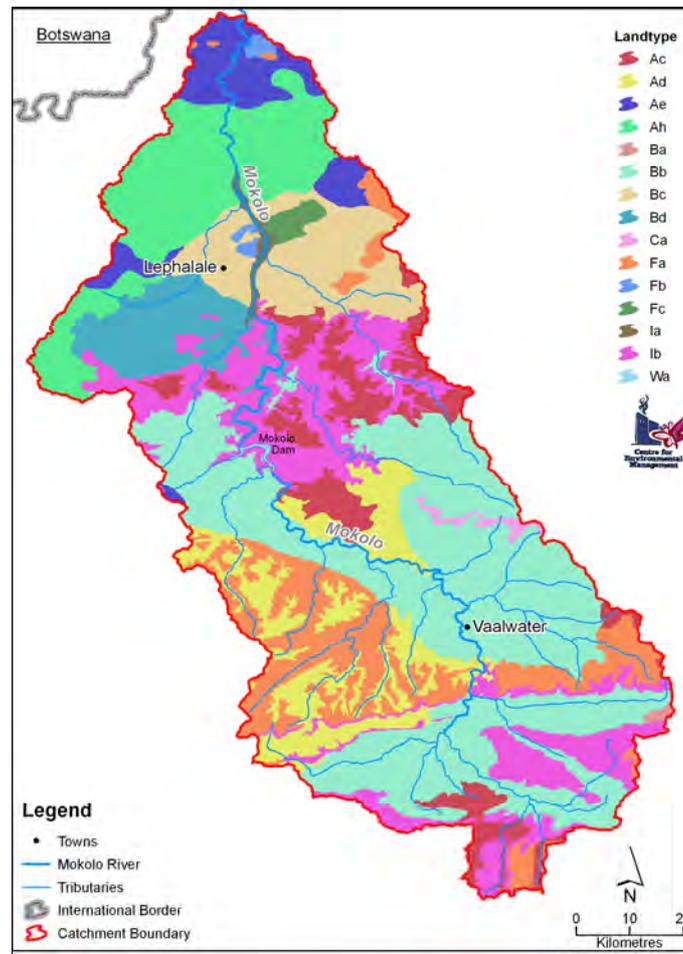


Figure 22. Landtypes in the Mokolo River catchment

In spite of variation in soil distribution patterns (as shown by the land types (Figure 22) in the catchment) the largest part (>80%) of the Mokolo River catchment topsoil is sand to loamy sand

(6-15% clay) and the balance is pure sand (<6% clay) (Figure 23). This range in soil texture tends to have high infiltration rates when not crusting. However, most South African soils form crusts and this parameter should be determined rather than being interpreted from the texture class. Sandy soils hold little water but store rain water deeper in the profile with increased rainfall, effectively resulting in denser vegetative base cover, higher vegetative production and often different species composition selection.

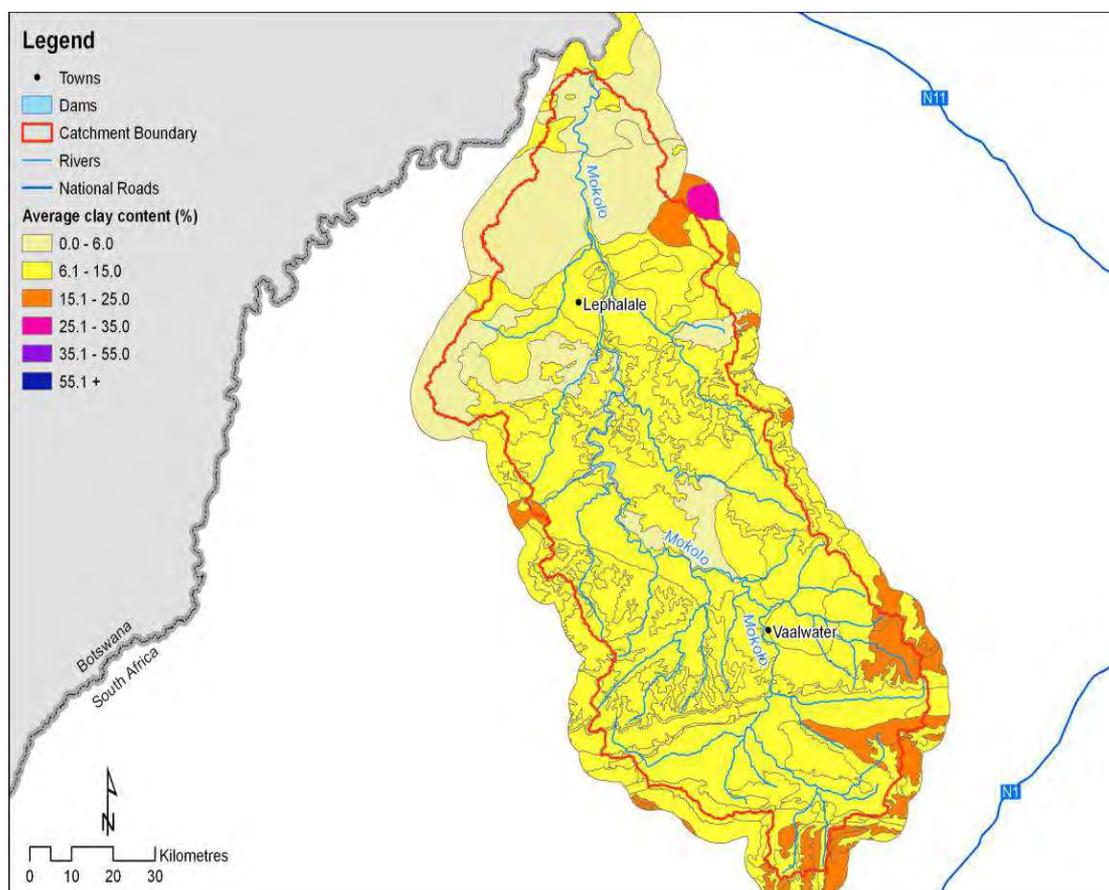


Figure 23. Percentage clay content in the Mokolo catchment

5.3.1.3 Precipitation and evaporation

Rainfall in the catchment is largely summer rain (October to March) and ranges from 400 to 700 mm per annum (Figure 24a and Table 12) with most rain falling in the southern section of the catchment.

Table 12. Quaternary catchment hydrological information for the Mokolo River

Quaternary catchment	Name	Catchment Area ⁽¹⁾ (km ²)	MAP ⁽²⁾ (mm)	MAR ⁽³⁾ (mm)	MAR as % of MAP	CV ⁽⁴⁾	BFI ⁽⁵⁾	HI
A42A	Sand	573	650	44	6.8%	0.86		
A42B	Grootspruit	522	666	53	8.0%	0.86		
A42C	Mokolo u/s A4H002	698	660	54	8.1%	0.86	0.633	3.178
A42D	Sterkstroom	497	674	87	13.0%	0.88	0.229	6.504
A42E	Mokolo d/s A42A to D	1007	598	44	7.3%	1.26	0.312	6.47
A42F	Mokolo u/s Mokolo Dam	1022	570	34	6.0%	1.26	0.169	22.385
A42G	Mokolo d/s Mokolo Dam	1207	545	28	5.2%	1.51	0.162	22.177
A42H	Tamboitie	1009	515	27	5.2%	1.42	0.165	21.056
A42J	Mokolo u/s Limpopo	1515	427	10	2.4	1.72	0.148	47.41

- Notes (1) excludes catchment areas that drains into pans and do not contribute to surface flows. Determined from 1:50000 topographical maps
 (2) Mean annual precipitation (MAP) from Seago et al. (2005)
 (3) Mean annual runoff (MAR)
 (4) Coefficient of variation (CV)
 (5) Base flow Index (BFI)
 (6) Hydrological Index from Hughes and Hannart (2003)

The mean annual potential evaporation (PET) is more than twice the amount of rainfall over most of the area. It varies across the Mokolo Catchment from about 2200 mm/a in the south to about 2450 mm/a in the north (Figure 24b) (DWA, 2010). The mean annual precipitation (“MAP”) in the catchment increases with elevation where the MAP is greater than 50% in the higher, southern A42D catchment compared to the northernmost A42J catchment. The reverse is true for Potential Evapotranspiration (PET), which is about 11% lower in catchment A42D than in A42J, due to the higher elevation. As a result, more rain falls on the higher, southern catchments and has a lower chance of being lost through evapotranspiration than in the northern, lower catchments, probably due to increased average air temperatures at lower elevations and towards the north.

Hail occurs on average 3 days per year in Modimolle (Nylstroom) area and 1 day per year in Lephalale area. Average temperature ranges from 14 to 20°C with the low lying areas in the north having the highest temperatures.

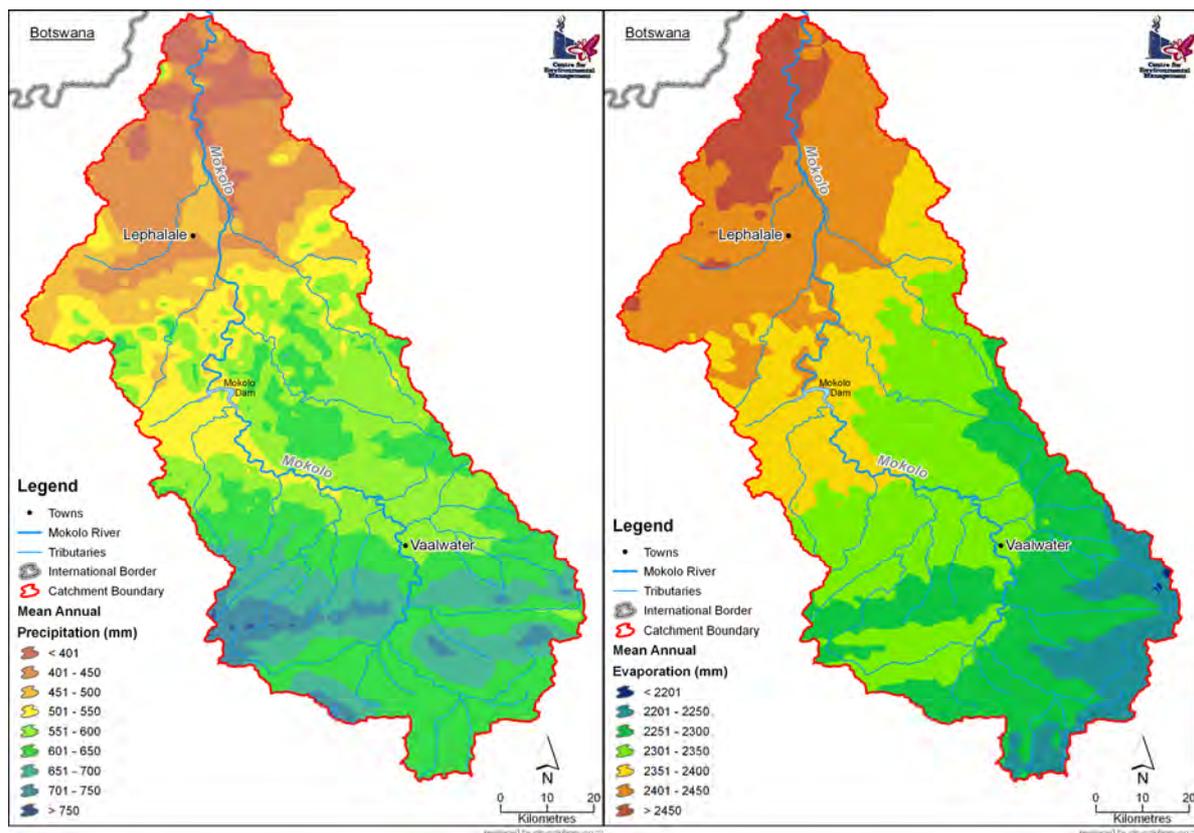


Figure 24. Left (a): Mean Annual precipitation and Right (b): Mean Annual evaporation in the Mokolo River Catchment

Mean baseflow is indicated as a percentage of the total flow in the river and it is observed that the baseflow contributes more to the total flow in the upstream section of the Mokolo River than in the downstream section of the river. Quaternary A42J has very low mean annual runoff and low baseflow

contribution (baseflow index (BFI) of 0.9 indicates a permeable catchment with stable flow and 0.15-0.2 an impermeable catchment with flashy flows (Institute of Hydrology, 1980)). The Hydrological Index (HI) also indicates the flow is more variable in this quaternary catchment when compared to upstream (Hughes and Hannart, 2003) therefore moving closer to being non-perennial in the lower reaches of the river (Table 12).

5.3.1.4 Vegetation

The Mokolo catchment falls within the Savanna Biome with a small section, mostly surrounding the Sandriver Mountains, in the Grassland biome (Figure 25a). The biomes in the catchment are divided into bioregions but in the case of the Mokolo River catchment they correspond almost exactly. Two bioregions namely the Central Bushveld bioregion and the Mesic Highveld grassland bioregion are present (Figure 25b). Some areas of azonal vegetation are present in the catchment mostly in the floodplain areas surrounding the Tambotie tributary.

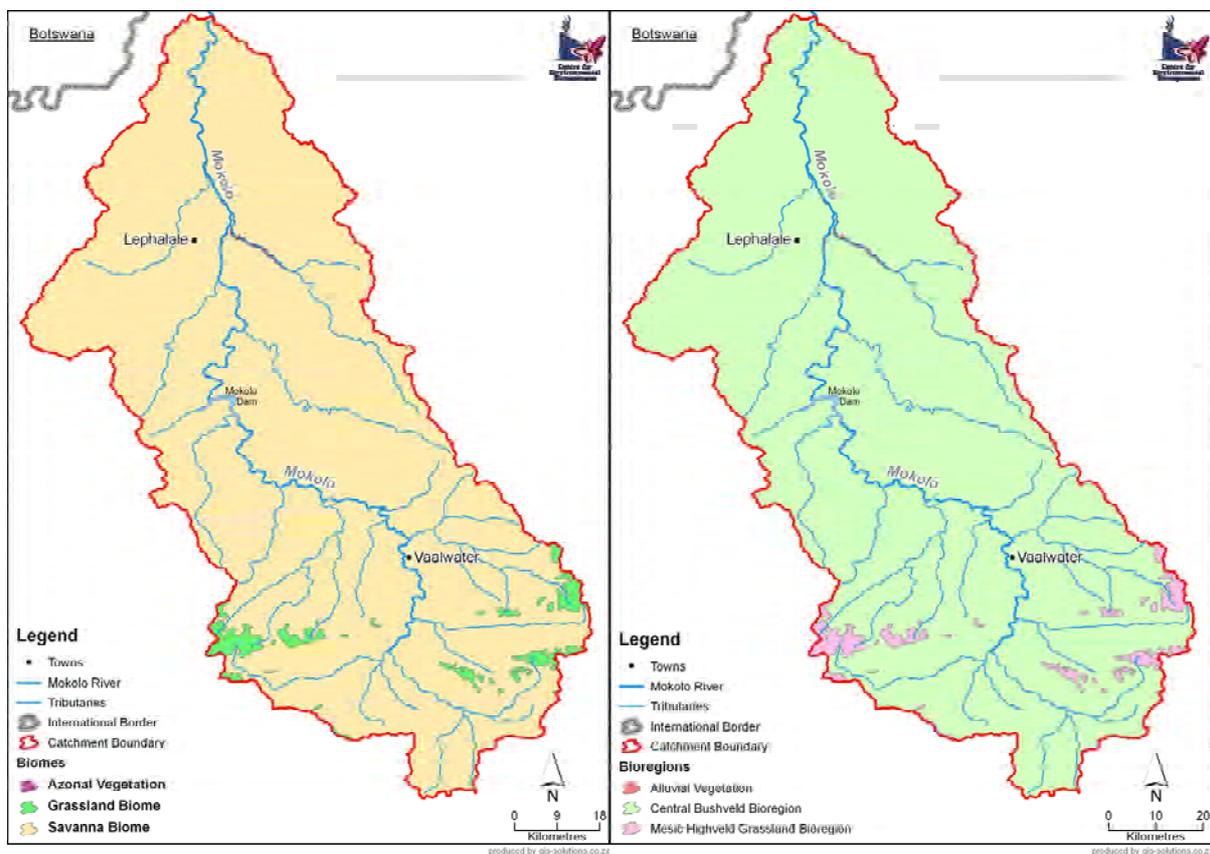


Figure 25. Left (a): Map of the biomes and Right (b): bioregions in the Mokolo River catchment

The bioregions are divided into vegetation units and a total of seven vegetation units are located in this catchment (Figure 26).

In the southern and central section of the Mokolo catchment upstream of the Mokolo Dam Central Sandy Bushveld, Waterberg Mountain Bushveld, Waterberg Magalies Summit Sourveld and Western Sandy Bushveld is present.

- **SVcb12 Central Sandy Bushveld**

Plant groups are associated with the soil types in the region with tall, deciduous *Terminalia sericea* and *Burkea africana* woodland on deep sandy soils, low, broadleaved *Combretum* woodland on shallow rocky or gravelly soils and species of *Acacia*, *Ziziphus* and *Euclea* on flats and lower slopes on eutrophic and less sandy soils. Some areas in valleys are dominated by *A. tortilis* and grass-dominated herbaceous layer is present on dystrophic soils (Mucina and Rutherford, 2006).

- **SVcb17 Waterberg Mountain Bushveld**

A moderately to well-developed grass layer is present. Vegetation on mountains mostly *Faurea saligna-Protea caffra* bushveld through to broadleaved deciduous bushveld on the rocky mid- and footslopes. *Burkea africana-Terminalia sericea* savanna is mostly present in the lower valleys and on deeper sands in the plateau (Mucina and Rutherford, 2006).

- **GM 29 Waterberg Magalies Summit Sourveld**

Grassland mostly covering the higher slopes and summit including crests, steep rocky scarps and cliff faces and dominated by wiry tussock grasses. There are areas of open *Protea caffra* and open shrubland with *Englerophytum magalismontanum* as well as *Landolphia capensis* (Mucina and Rutherford, 2006).

- **SVcb16 Western Sandy Bushveld**

Acacia erubescens dominates the flat areas and *Combretum apiculatum* is found on the shallow soils. *Terminalia sericea* is present on deep sands. The vegetation varies from tall open woodland to low woodland with broadleaved as well as microphyllous tree species present (Mucina and Rutherford, 2006).

Downstream of the Mokolo Dam some areas of Central Sandy Bushveld, Western Sandy Bushveld, Waterberg Mountain Bushveld are also present. The Limpopo Flats in the north are mostly covered with Limpopo Sweet Bushveld and a small area of Roodeberg Bushveld is found to the east.

- **SVcb19 Limpopo Sweet Bushveld**

Situated in the northern section of the Mokolo catchment this unit consists of short open woodland and in disturbed areas *Acacia erubescens*, *A. mellifera* and *Dicrostachys cinerea* are present in large numbers (Mucina and Rutherford, 2006).

- **SVcb18 Roodeberg Bushveld**

Mostly short closed woodland to tall open woodland and grass cover is scarce (Mucina and Rutherford, 2006).

The floodplain of the Tambotie tributary is mostly covered with Subtropical Alluvial Vegetation

- **AZa7 Subtropical Alluvial Vegetation**

The vegetation is found in the flat alluvial riverine terraces which contain macrophytes, marginal reed belts and extensive flooded grasslands as well as ephemeral herb lands and riverine thickets (Mucina and Rutherford, 2006).

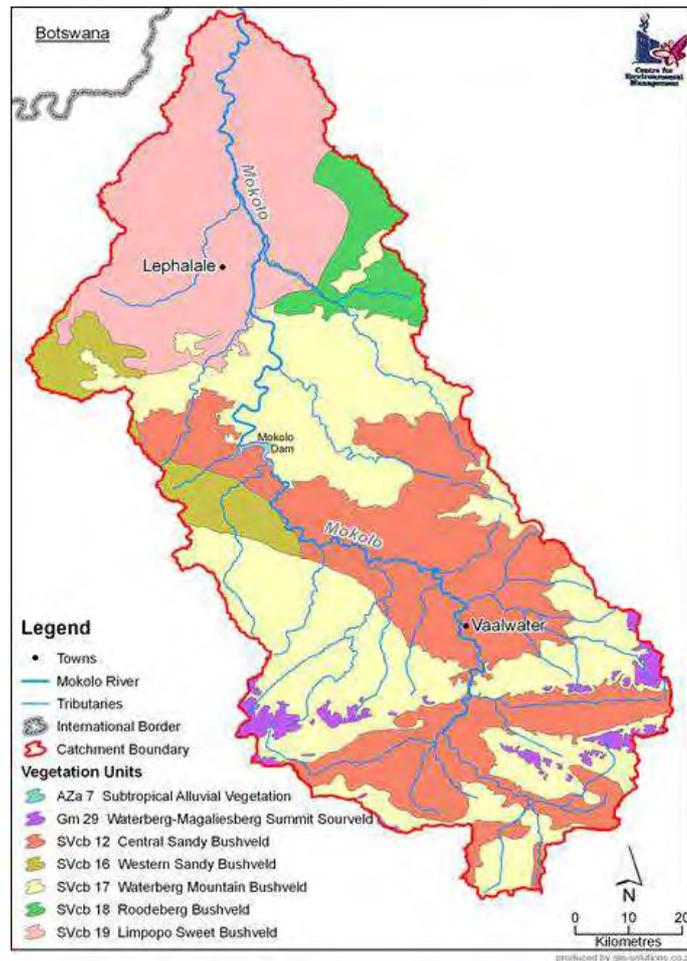


Figure 26. Map of the Vegetation Units in the Mokolo River Catchment (Mucina and Rutherford (2006), modified and prepared by Frank Sokolic in 2010

5.3.1.5 Landcover and Landuse

Most of the catchment is covered by Woodland with some Grassland as well as Thicket and Bushland in the upper reaches and a large area of Thicket and Bushland in the lower reaches. Commercial cultivated farmland is found along the upper and middle reaches of the river (Figure 27).

The following land cover information is taken from the Delineation Report for the Intermediate Reserve study (DWA, 2008b), and describes the land cover within the 500m buffer zone alongside the river (See Figure 13 for location of quaternary catchments).

- A42A (upper catchment): Dominated by natural thicket, bushland and bush clumps, with the second most predominant land use consisting of cultivated temporary commercial dryland. Land-use is extensively agricultural, with vegetable and fruit farming predominating.
- A42B and A42C: Dominated by natural woodland, degraded forest and woodland, natural thicket, bushland and bush clumps, woodland as well as cultivated temporary commercial dryland.
- A42D: This quaternary catchment is still in a minimally modified condition, with the predominant land use feature consisting of natural thicket, bushland and bush clumps as well as woodland.
- A42E: Land cover consists primarily of natural thicket, bushland, bush clumps and woodland, as well as degraded forest and woodland.
- Quaternary catchments A42F, A42G, A42H and A42J are still in a minimally modified condition, with the predominant land use feature consisting of natural thicket, bushland and bush clumps as

well as woodland with modified land use consisting predominantly of cultivated temporary commercial dryland.

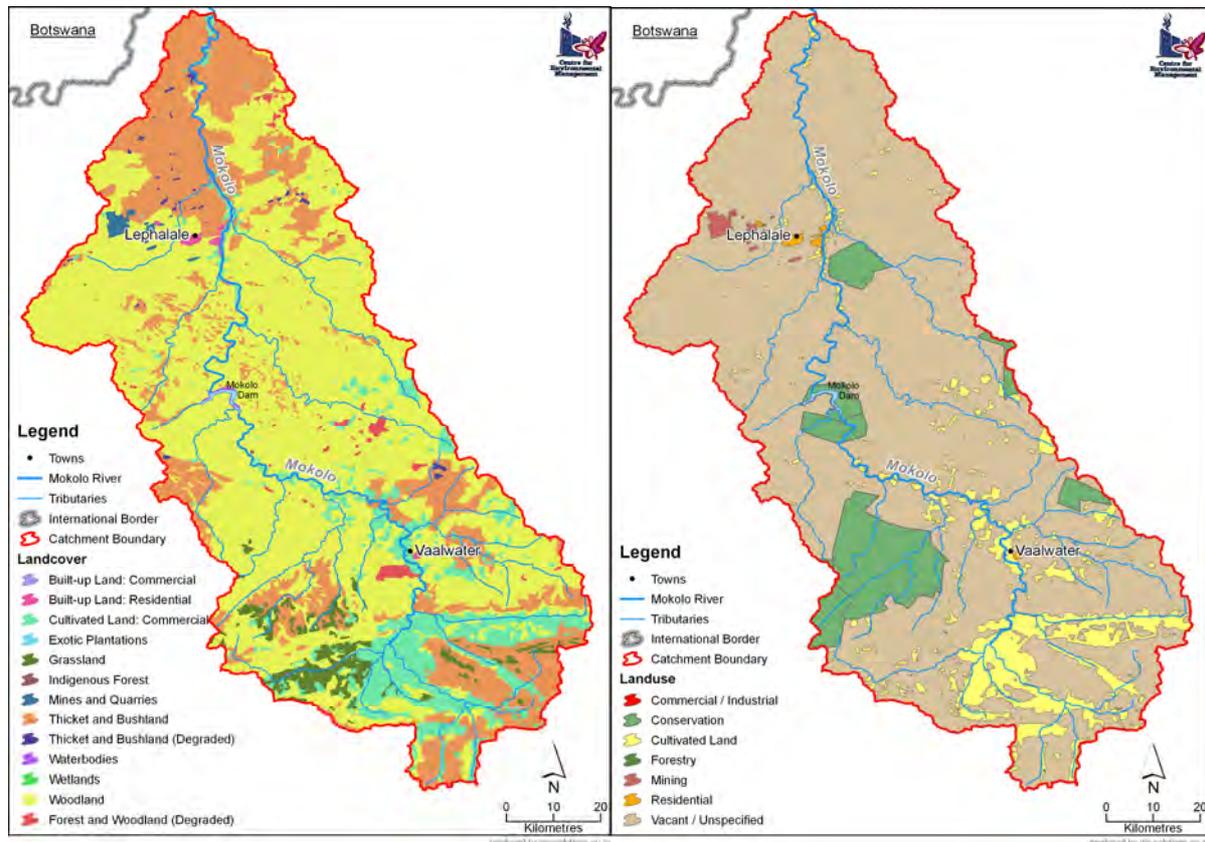


Figure 27. Left: Landcover and Right: Landuse in the Mokolo River Catchment

Some 661 farms (2516 subdivisions) are located within the catchment of which 272 farms are riparian to public streams. The actual use of water for irrigation decreased by some 35 million m³/a between mid-1980s and 1998/99 probably due to the fact that assurance of supply was affected by the increase in water use. Higher agricultural input costs also contributed and this led to a marked change in the agricultural practices in the catchment where farmers converted from irrigation farms to cattle ranches or game farming (DWA, 2007).

5.3.1.6 Ecological classification

Level I Ecoregions are determined using various attributes such as terrain morphology, vegetation types, altitude, precipitation, temperature, simulated runoff. These Level I ecoregions are then refined into Level II ecoregions using the same typing attributes but in more detail (Kleynhans et al., 2004).

Four Level I Ecoregions are present in the Mokolo River catchment namely Limpopo Plains (1), Waterberg (6), Western Bankenveld (7) and Bushveld Basin (8) and these include seven Level II Ecoregions in the catchment from north to south namely 1.02, 1.03, 6.01, 6.02, 7.02, 7.03 and 8.05 (Figure 28). For details on the Ecoregion attributes please see Appendix A.



Figure 28. Level II Ecoregions of the Mokolo River Catchment

5.3.2 Activity 6: Runoff potential Units (RPUs)

The method described in section 4.1.3 under Activity 6 was followed to delineate the RPUs for the Mokolo River catchment.

The Mokolo is a fifth-order (Strahler's ordering) catchment with 48 third-order catchments forming the RPUs. The highest potential runoff will occur mostly in the southern and eastern part of the catchment as the result of low cover steeper slopes and higher rainfall intensity. Figure 29 indicates the RPUs for soil (Clay content C_p), cover (C_v), slope (C_s) and rainfall intensity (C_i).

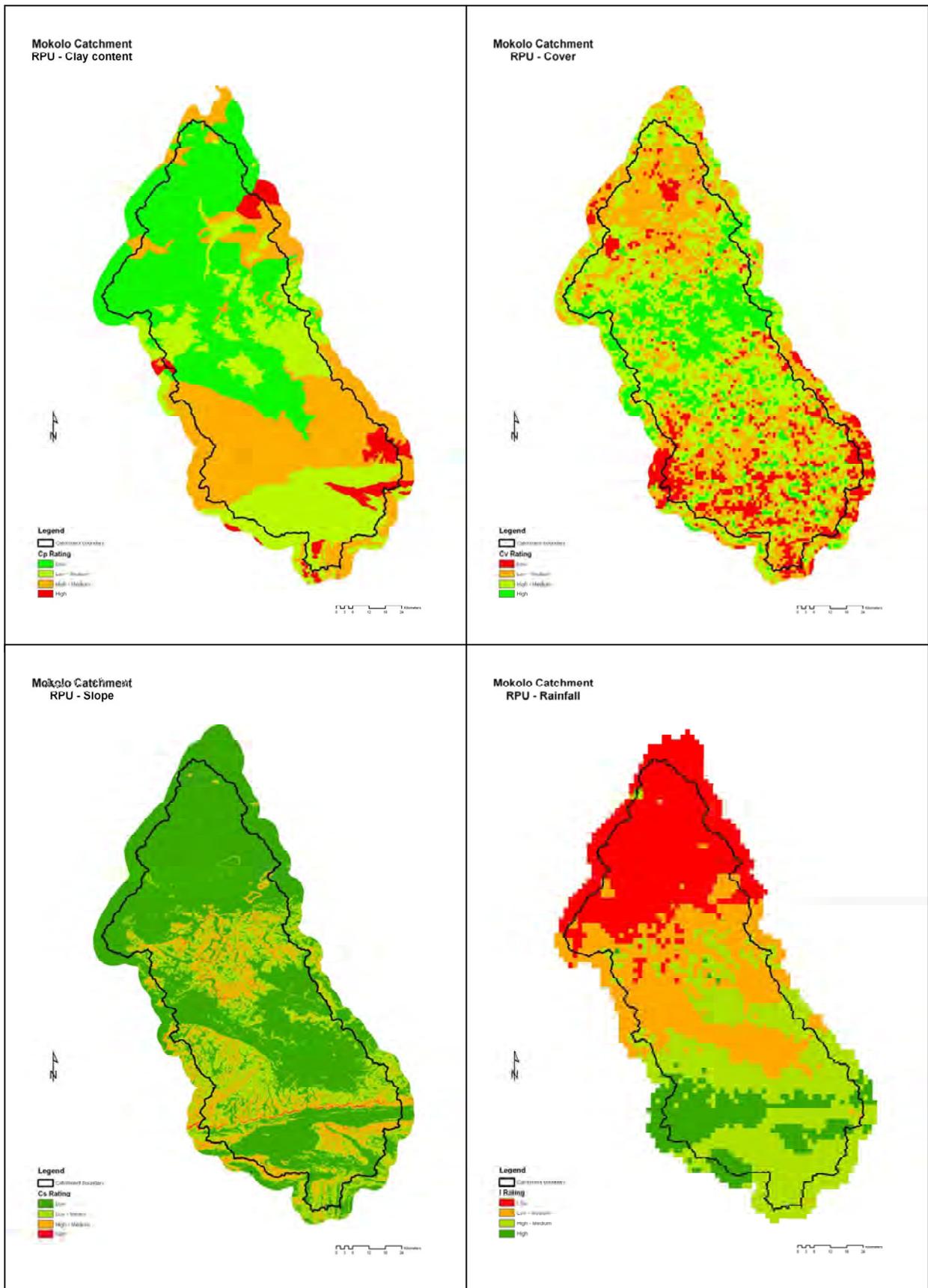


Figure 29 Top left: Runoff potential for Clay content (Cp), Top right: Runoff potential for cover (Cv), Bottom left: Runoff potential for slope (Cs) and Bottom right: Runoff potential for rainfall intensity (Ci)

The RPU are rated from Low to High in Figure 30. It is assumed that areas of high runoff potential (RPU) would probably result in higher instream flow downstream of these areas.

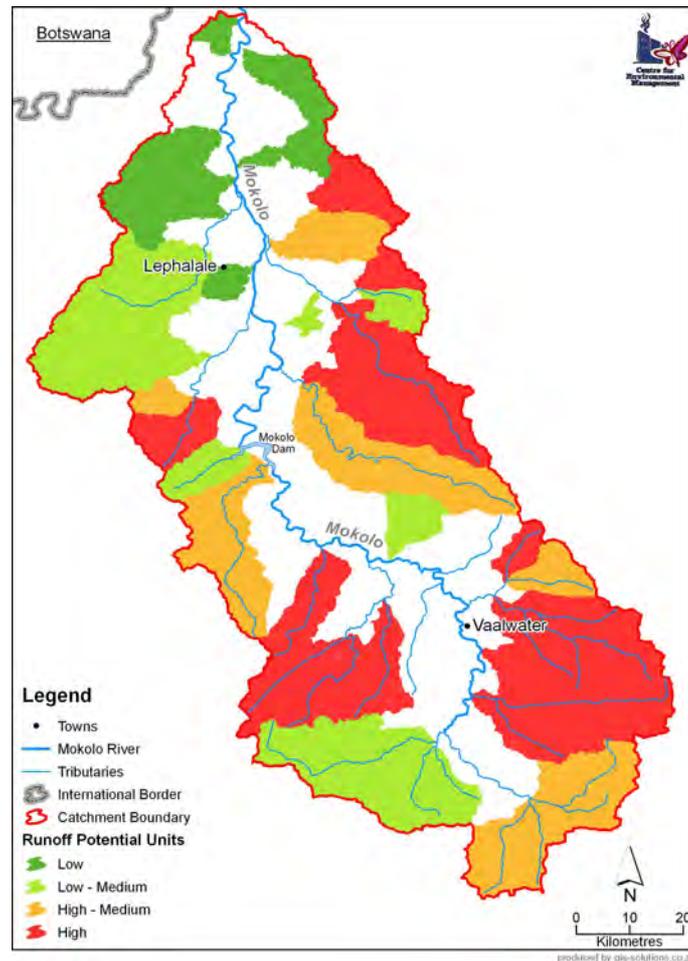


Figure 30. RPU in the Mokolo catchment

5.3.3 Activity 7: Catchment hydrology and delineation of homogenous groundwater and surface water Units

Flows appear to be mostly perennial along the Mokolo River, though for some extended periods (i.e. a decade) over the past 60 years, the river and its tributaries, where gauged, have stopped flowing during the dry period. It is difficult to say whether all of the tributaries respond the same way mainly because of the complex faulted/dike-intruded geology, though the few that are gauged suggest they are subject to the same periods of no flow during the dry seasons. Unfortunately, flows in the lower basin area were not gauged until only the last few years, which do not cover the decade of dry periods. So it is not possible to determine whether the lower portion of the Mokolo River basin system has experienced non-perennial conditions using gauging weir data but the HI indicates that flow is highly variable in this area and farmers have also indicated that there are periods of no-flow.

A dam and substantial development of both surface water and groundwater resources, primarily for agricultural irrigation, impact the current flows in the river and complicate its analysis. A portion of the infiltrating precipitation that is otherwise not lost as evapotranspiration, surface runoff, or diverted for agriculture, recharges groundwater. After recharge mainly during the rainy period of the year, groundwater levels rise everywhere, adding to groundwater storage.

Groundwater then generally moves downgradient, from uphill areas to nearby stream areas. Groundwater levels decline following rainy period recharge. This causes groundwater in storage to deplete over time. Groundwater flow towards streams is complicated by faulting and the presence of dikes. These are believed to impede flows perpendicular to them, but could enhance flow parallel to these planar features via possible permeable zones. As uphill groundwater flow reaches rivers, it flows into the river if stage levels are lower than the underlying groundwater levels. If river levels are higher than underlying groundwater levels (typically during rainy periods when river flows pick up, and stage likewise increases), flow in the rivers flows into the groundwater system beneath the river. Regardless of whether groundwater flows into or out of the river and tributaries within the basin, it also flows in a downstream direction, beneath the rivers as 'underflow/subsurface channel flow'

5.3.3.1 Surface water

A description of the hydrology of the catchment is based on a desktop analysis of historical and recent information on the catchment. Information from the Intermediate Reserve completed on the Mokolo River by the DWA (DWA, 2008a) is included here.

The upper Mokolo (upstream of Mokolo Dam) was a perennial river under natural conditions. The lower Mokolo River (downstream of Mokolo Dam) is presumed to have been near-perennial; only drying up during drought periods. Present day flow modifications to the lower Mokolo River have significantly increased the frequency and duration of low and zero flow periods (DWA, 2010a).

The Mokolo Dam, situated on the Mokolo River is by far the largest dam in the WMA. It has a full supply capacity of about 146 million m³, with the natural MAR at the dam site estimated at 240 million m³/a (Midgley et al., 1994). The dam was constructed in the late 1970s primarily to supply water to the Matimba power station but the dam also supplies water to the town of Lephalale as well as for irrigation downstream of the dam. At the time of constructing the dam, the yield of the dam was given as 39 million m³/a (RSA, 1970). Subsequent to the construction of the Mokolo Dam, there was rapid and extensive irrigation development upstream of the dam, supplied from farm dams as well as from run-of-river. As a result of this, the yield of the Mokolo Dam dropped dramatically to an estimated 23 million m³/a (DWA, 1992). The Mokolo Dam is currently used to supply water to the Matimba Power station (7.3 million m³/a); Iscor coal mine (9.9 million m³/a); Lephalale (1.0 million m³/a) and Irrigation (downstream of dam – 10.4 million m³/a) (DWA, 2001). Although the allocation to irrigators downstream of the dam is at a low assurance, the dam is fully allocated (DWA, 2004).

Five sites were studied in the Mokolo River catchment as part of the Intermediate Reserve (DWA, 2008) namely EWR1a, EWR1b, EWR2, EWR3, EWR4 (Figure 31). The MAR at the sites sampled varied from 28.58% of natural MAR at site EWR1a (upstream) to 12% of natural MAR at site EWR4 (downstream). This implies that the system has changed from a naturally perennial to a non-perennial river as it stops flowing under present conditions. Baseflow conditions have decreased from natural as a result of irrigation utilising the baseflow almost completely at all the sites upstream of the Mokolo Dam. Downstream of the Mokolo Dam water is released sporadically for irrigation but this is less than natural baseflow. The Mokolo Dam has also had an influence on the small to moderate floods which have been reduced in frequency. The timing of onset of the floods has also been influenced resulting in a later onset compared to natural. Moderate to large floods have not been influenced with regard to frequency and seasonality upstream of the Mokolo Dam (DWA, 2008).

Impacts on surface hydrology: The most important impacts on the hydrology of the catchment are abstraction for irrigation especially upstream of the Mokolo Dam and abstractions for power station and mine in the Lephalale area downstream of the Mokolo Dam (DWA, 2008).

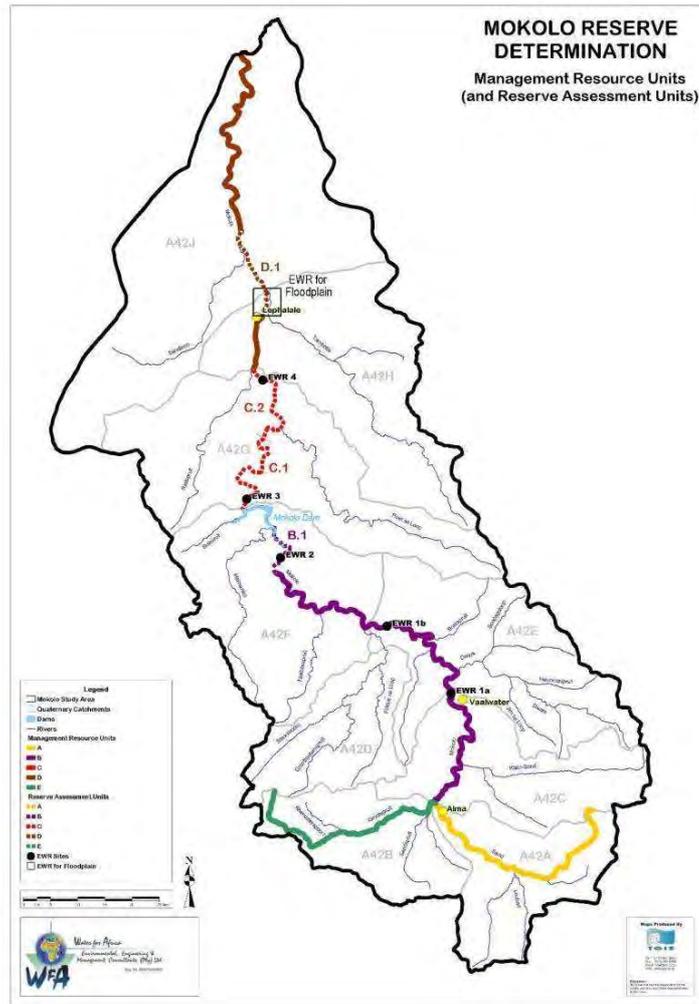


Figure 31. Sites sampled in the Mokolo River as part of the Intermediate Reserve (Taken from DWA, 2008)

5.3.3.1.1 Homogenous surface water units identified in the Mokolo River catchment

Each specialist in the team was asked to identify homogenous units in the Mokolo River catchment which were unique in terms of the specific field of study, i.e. which areas could be identified where surface water hydrology is expected to be homogenous. All available historical data and information on the catchment was used to identify units. Five surface water units (Figure 32) were identified and they correspond closely to the precipitation in the catchment.

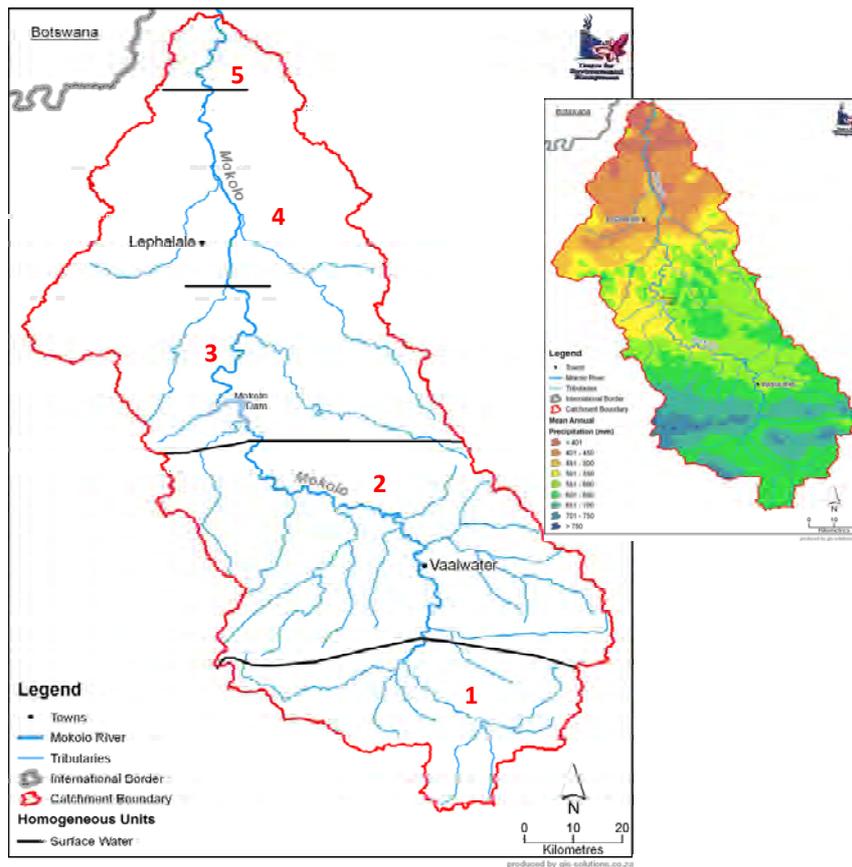


Figure 32. Homogenous surface water units identified in the Mokolo River Catchment. Insert is the precipitation in the catchment

Motivation for surface water units identified (Figure 32):

Surface water units identified corresponds with the precipitation pattern (see insert in Figure 32) in the catchment. The Mokolo Dam plays a large role in the surface water upstream and downstream.

The units were delineated using the following information:

- Ecoregions
- Geomorphic zones
- Land cover
- Presence of dams and other operational aspects
- The physical nature of the river (reaches, characteristics of river bed, etc.).

The summary of these units are:

Unit 1: Mountainous area of the Waterberg, with high rainfall. Many of the streams in this area are considered to be seasonal under present flow conditions (RHP, 2006). The main tributaries to the Mokolo River include the Sand River, Klein Sand River, Sandspruit, Loubadspruit and Grootspruit. Nearly all of this area is under agriculture. The streams of this area vary in gradient and are classified from mountain streams to upper and lower foothill streams. Plainbed, pool-riffle or pool-rapid reach habitat types predominate. Very little alluvium present as the Mokolo River passes through a steep gorge as a single thread channel. There are a large number of bridges, weirs, dams, pumps and off-channel storage reservoirs. River banks are impacted by vegetation removal and cattle tracks. There is bank instability as a result of alien vegetation. The area is characterised by Waterberg Moist

Mountain Bushveld and Mixed Bushveld. Altitude varies between 1200 m and 1600 m and mean annual rainfall varies between 400 and 700 mm.

Unit 2: Mountainous area of the Waterberg, moderate recharge is expected (5-9 mm/a). The Mokolo has a mixed channel section with bed material consisting predominantly of large, moderately embedded cobbles. This reach is classified as pool-riffle and numerous sand or gravel bars are present. Flood plains are often present. Bank stability is considered to be moderate. The Dwars River and Jim-se-loop have lower gradient mixed bed alluvial channels with sand and gravel dominating the bed (RHP, 2006). A large number of farm dams, weirs, bridges and crossing points are located in the area. Mountain streams have stopped flowing during severe droughts.

Unit 3: This reach is in the foothills of the Waterberg. Throughout this area, the Mokolo River has a steep gradient. The area is characterized with alluvium, pools, boulders, large impoundment. There are a large amount of sandbars. Vegetated bars below dam reduce flooding. There is some irrigation and numerous game reserves The Mokolo Dam is found in this unit. The dam supplies water to downstream irrigation farms, the town of Lephalale, Matimba Power Station and some coal mines. Impacts within the area are dominated by irregular water releases from Mokolo Dam to the lower section of the river.

Unit 4: This section of river has several oxbows and isolated off-channel pools. A wide floodplain borders the river for much of this section. Both of the larger seasonal tributaries, the Sandloop and the Tambotie, were dry. The river channel is dominated by pools and reeds. The river flow highly regulated from the Mokolo Dam with sporadic flows being released for the farming community. There are five major road bridges in this area. A number of farm dams are located in the Mokolo River close to the Limpopo confluence. Sand mining is widespread. Sand is being mined from the river and in the process riparian vegetation is being removed. This results in the river banks becoming unstable resulting in increased erosion (RHP, 2006).

Unit 5: Low land underlain by mainly the Karoo and Basement Formations. The lower river does not usually flow close to its confluence with the Limpopo River and consists of many large sandy pools. This section of river has several oxbows and isolated off-channel pools. A wide floodplain borders the river for much of this section. Reeds are common in the area (RHP. 2006).

5.3.3.2 Groundwater

Groundwater levels are on average 28 m below the surface. At the extreme, the water levels range from artesian boreholes to as deep as 154 m below the surface. The water levels in the study area vary greatly; the artesian boreholes predominantly occur near the Mokolo River, where the groundwater level and the surface topography intersect, while deeper water levels occur near the centre and northern section of the study area (Figure 33a), due to a rise in elevation. Another reason for the increase in water level depth is the high level of abstraction for watering livestock in certain areas. The groundwater recharge is between 1.5-1.9% of the mean annual precipitation. Higher recharge occurs in the South eastern and Northwest sections of the catchment with a moderate recharge in the middle sections (Figure 33b) (pers. comm. Dr. Ingrid Dennis, February 2010).

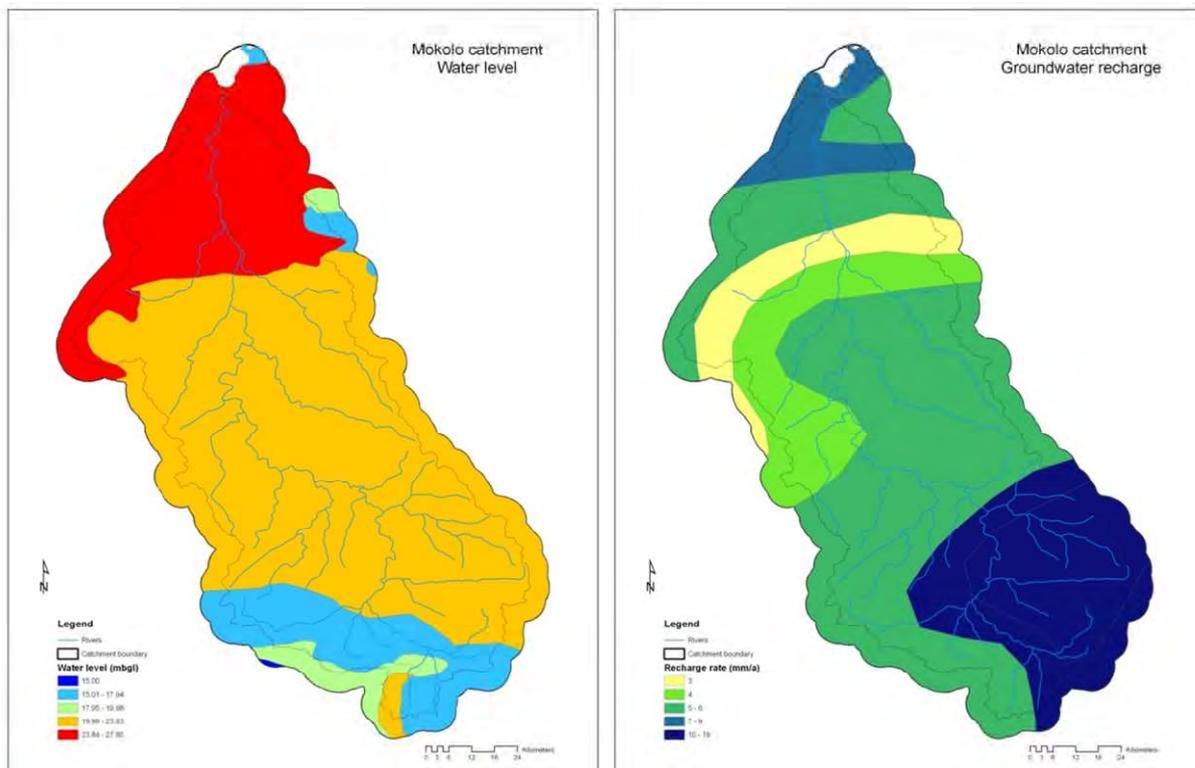


Figure 33. Left (a): Groundwater level and Right (b): Groundwater recharge in the Mokolo River Catchment

The main aquifer type in the Mokolo River catchment is an alluvial aquifer which is recharged mostly by high flow (after high rainfall events) and discharges from the Mokolo Dam. The aquifer is in direct contact with the river and is generally unconfined. The regional aquifers in the catchment are in limited contact with the alluvial aquifer and show marginal gradients towards the river. The depth and hydraulic conductivity of the alluvial aquifer decreases in a downstream direction (DWA, 2010).

Groundwater is underutilized in the catchment (DWAF, 2004). Most of the groundwater is used by agriculture but abstraction for domestic use is increasing in the south of the Mokolo Catchment. An increase in use of groundwater was also observed for game ranching and eco-tourism in the Waterberg Wilderness area (middle sections of the Mokolo catchment (Busari, 2008).

5.3.3.2.1 Homogenous groundwater units

Five groundwater units (Figure 34) were identified in the catchment using historical data and data from recent groundwater reports.

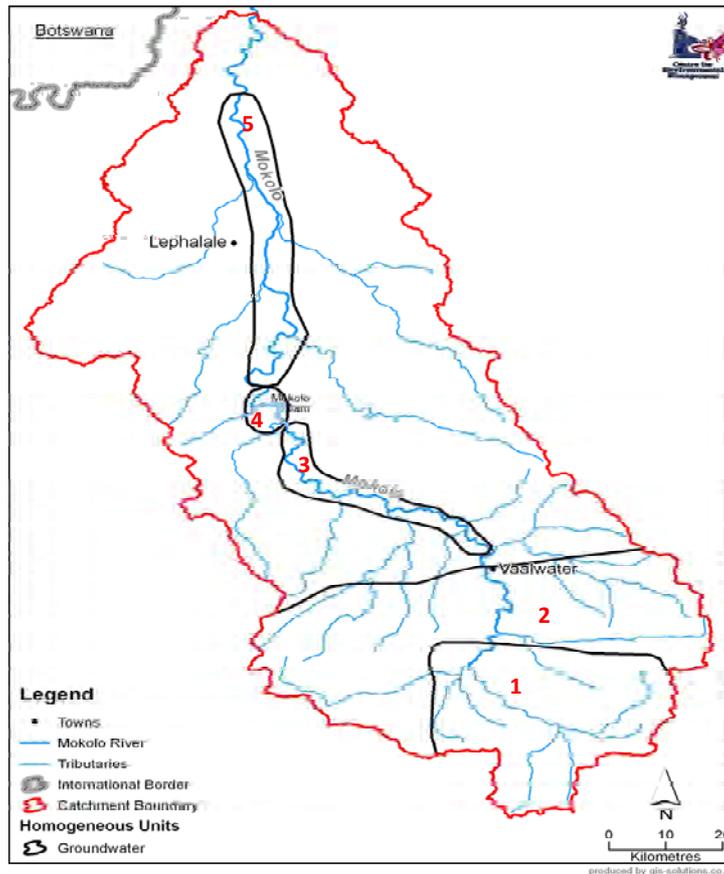


Figure 34. Homogenous groundwater units identified in the Mokolo River Catchment

Motivation for Groundwater Units chosen:

Unit 1: Recharge zone where mountains are – high groundwater recharge. Groundwater would probably flow towards the river in this region

Unit 2: Based on geology and cut off of area near Vaalwater.

Unit 3: Connection of surface and groundwater is important and this area upstream of the dam is needed to determine the interaction.

Unit 4: Mokolo Dam artificial recharge point – dam separate because it is a recharge zone (Unnatural)

Unit 5: Area all the way from the Mokolo Dam up to where the geology changes – in this area surface water use is more and this would influence groundwater.

5.3.4 Activity 8: Habitat integrity

The Mokolo River was not surveyed as part of the current project as a Habitat Integrity study had been completed as part of the Intermediate Reserve Determination. Results of the Habitat Integrity Assessment of the Mokolo River are taken from the report by DWA (2008a).

5.3.4.1 Instream Habitat Integrity:

Results from an Intermediate Reserve Determination study by DWA (2008a) indicated that the largest impact on the Instream habitat integrity of the Mokolo River is due to changes in hydrology. There are periods of no flow and increased abstraction (farm dams) for irrigation purposes which have led to a loss in connectivity. Unseasonal releases from the Mokolo Dam have also impacted on the instream habitat. The Instream habitat integrity improves from upstream (Class: D/E – large to serious modification) to downstream (Class C – moderately modified) (Figure 35a)

5.3.4.2 Riparian Habitat Integrity:

Impacts on the Riparian Habitat Integrity are a result of no flow periods, changes in flooding regime due to the presence of dams in the system, vegetation removal and exposure for irrigated lands as well as increased presence of exotic vegetation due to catchment disturbance. The Riparian Habitat Integrity is also influenced by changes in the flooding regime due to Mokolo Dam (DWA, 2008a). The Riparian Habitat Integrity improves from upstream (Class D – largely modified) to downstream (Class B/C – small to moderate modification) (Figure 35b). The lower section of the Mokolo River was not assessed by DWA (2008a).

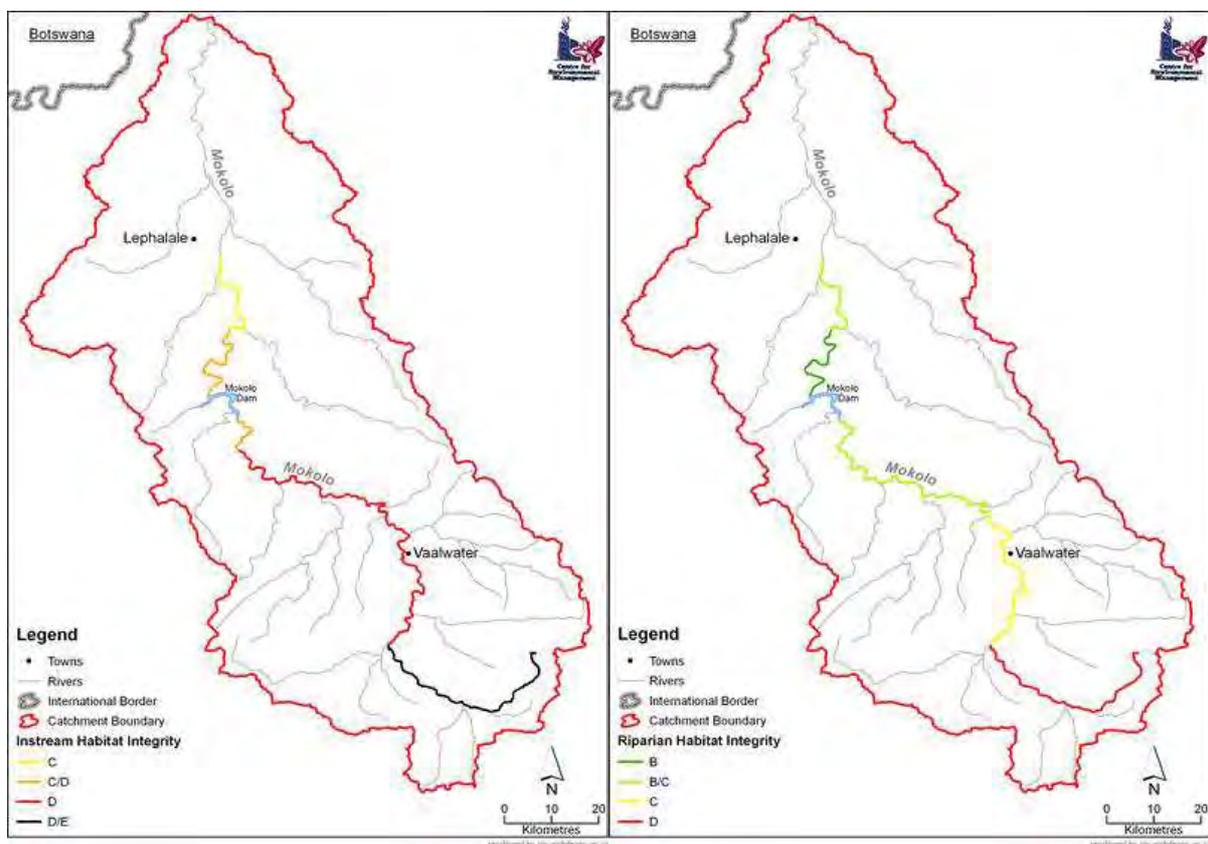


Figure 35. Delineation of Habitat Integrity units in the Mokolo River Catchment (Adjusted using data from DWA, 2008a). Left (a): Instream Habitat Integrity, Right (b): Riparian Habitat Integrity

5.3.5 Activity 9: Delineation of Natural Response Units (NRUs), Management Response Units (MRUs) and Combined Response Units (CRUs)

The Combined Response Units (CRUs), which are homogenous units in the catchment in terms of natural and management characteristics, were delineated using the method described in Section 4.1.3 Activity 9.

5.3.5.1 Delineation of Natural Response Units (equivalent to the Natural Resource Units in DWA, 2008b)

In the current project an overlay (Figure 36a) of geomorphological zones (Figure 19), macro-reaches (Figure 21), level II ecoregions (Figure 28), and Runoff potential Units (RPUs; Figure 30) was used to produce **Natural Response Units (NRUs)** (Figure 36b).

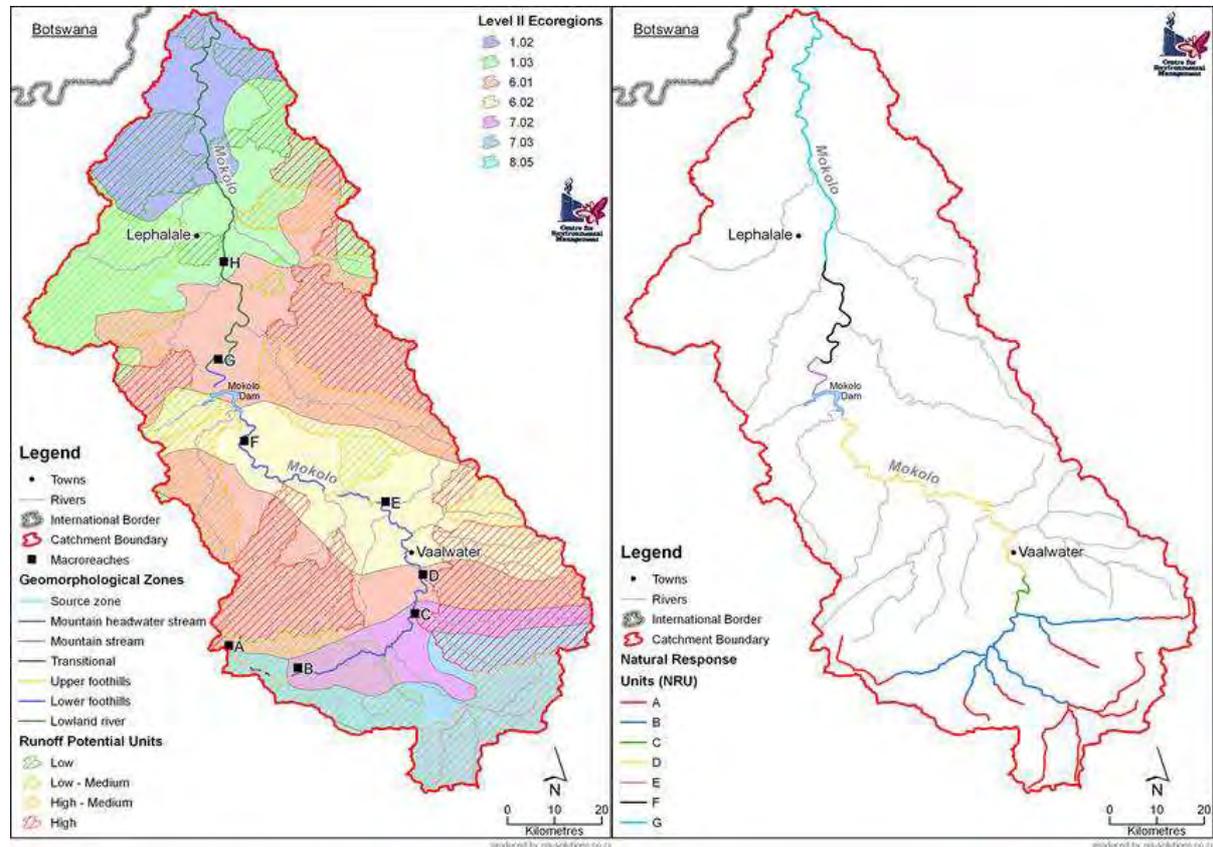


Figure 36. Left (a): Overlay of Geomorphological Zones, Macroreaches, level II Ecoregions and Runoff Potential Units (RPUs) to identify Right (b): Natural Response Units (NRUs) of the Mokolo River

Each NRU should represent a homogenous unit where the natural characteristics of the river are similar. The attributes of each NRU is provided in Table 13.

Table 13. Natural Response Units (NRUs) identified in the Mokolo River

NRU	Delineation	Macroreach	Geomorphological Zone	Ecoregion Level II	RPU
A	All the Upper tributaries (Sand, Sandspruit, Klein-Sand and Grootspruit including upper foothills, mountain headwaters and transitional zones	A – Height AMSL = 1260-1815, gradient = 0.0354 m/m, confined valley form, single thread channel.	Upper foothills, mountain stream and transitional zone	7.03 small part of 7.02	Medium to high

NRU	Delineation	Macroreach	Geomorphological Zone	Ecoregion Level II	RPU
B	Lower foothill sections of Sand, Sandspruit, Klein-Sand and Grootspuit tributaries up to confluence with Mokolo River	B- Height AMSL = 1190-1260, gradient = 0.0023 m/m, unconfined, flat valley floor, single thread channel, pools, channel artificially constrained by agriculture, reeds, impoundments, islands, wetlands dense reed covering, possible incised channel	Lower foothills	7.02	Low to high
C	From confluence of Klein-Sand to end of Ecoregion level II 6.01 as well as complete Macroreach C	C- Height AMSL = 1160-1190, gradient = 0.0015 m/m, partially confined valley form, , wandering channel, Natural channel, alluvial, pools, reeds lining pools, sandbars, weirs, islands, meandering channel	Lower foothills	6.01	High
D	From start of Macroreach D (24.332S, 28.1249E) and ecoregion level II 6.02 to upstream of Mokolo Dam	D and E. Height AMSL= 1160-950, gradient = 0.0028-0.0046 m/m. Partially confined, narrowing valley, bedrock controlled multi-channel to bedrock controlled single channel pools. Islands, pools, boulders and bedrock, weirs form pools and reeds lining pools.	Lower foothills with small areas of upper foothills	6.02 with small section of 6.01	Mostly high and some medium to high with a small section of low runoff
E	From upstream of Mokolo Dam to end of Macroreach F (23.9184S, 27.7334E).	F Height AMSL= 860-950. Gradient = 0.0023 m/m, partially confined narrowing valley and wandering channel. Alluvial, pools, boulders, large impoundment, Bedrock, pool-rapid, sand bar, islands, and vegetated bars below dam (reduced flooding). Mokolo Dam.	Lower foothills with small area of upper foothills and lowland river.	6.01 with small section of 6.02.	Medium to high with small section of low runoff
F	From end of Macroreach F (23.9184S, 27.7334E) to just downstream of Rietspruit confluence.	G Height AMSL = 824-860. Gradient = 0.0009 m/m, partially confined valley form with wandering channel. Pools, alluvial, sand bars, reeds lining pools, single thread, islands	Lowland River	6.01 with small section of 1.03	High to medium
G	From just downstream of confluence with Rietspruit to confluence with Limpopo River	H Height AMSL= 792-824. Gradient = 0.0004 m/m, unconfined valley form with wandering channel and Pools, alluvial, sand bars, reeds lining pools, single thread, islands	Lowland River	1.03 and 1.02	Mostly low runoff

5.3.5.2 Delineation of Management Response Units (MRUs) (equivalent to Management Resource Units delineation in DWA 2008b):

Management Response Units (MRU) were identified by overlaying information from Water Quality Response Units (WQRUs), Socio-Economic Response Units (SRUs) and Habitat Integrity (Figure 35a and b) results.

A combination of the three maps provides an understanding of the catchment in relation to the impacts and future developments planned for the catchment. Knowledge from a desktop catchment hydrology assessment can be used to augment understanding and delineation of Management Response Units (MRUs).

5.3.5.2.1 Water Quality Response Units (WQRUs)

Water Quality Response Units (WQRU) are areas that are expected to have a homogenous water quality. The water quality in most catchments in South Africa has been impacted on and it was therefore decided that the WQRU would reflect the impacted state (human management influences) and not the natural WQ status of the river.

There are many factors that influence the surface water quality. The geology and climate of a region, the land use activities such as agriculture, towns and their associated infrastructure and effluents, informal settlements, game farming, etc. groundcover and the groundwater contribution to the surface water and dams in the river, all influence water quality. When delineating WQRUs, all the above factors need to be taken into account, starting with the geology of the region. Similar geological areas are expected to have similar water quality. All other activities and features further impact on the water quality.

For the Mokolo River the WQRUs were delineated using the following components:

- GIS maps: geology, land cover, ecoregion (Level 1) classification, topography and rainfall, land use and quaternary catchments. These maps were overlain and areas that were expected to have similar water quality were grouped together.

Once the WQRUS were delineated, using the GIS maps, they were compared to the results from the Intermediate Reserve Determination Study (DWA, 2008 a and b).

Motivation for units identified in Figure 37:

Five WQRUs were identified based mainly on the activities in and around the mainstem of the Mokolo River.

WRQU 1: Contains the Grootspruit, Sandspruit and Sand Rivers. This WQRU is similar in geology and there is a natural ridge that separates this unit from the next as the river has to flow through a gorge/poort. This unit represents the upper portion of the Mokolo River and the whole unit falls within one Level 1 Ecoregion (Western Bankenveld).

WRQU2: The WQRU is from where the river exits the gorge/poort up to the upper reaches of the Mokolo Dam. The dam is seen as having a major influence on the water quality of the river. Upstream and downstream of the dam is therefore seen as separate WQRUs, although the geology is very similar.

WRQU3: This WQRU stretches from downstream of the Mokolo Dam to just after the confluence of the Rietspruit with the Mokolo River, upstream of the influences from the Lephalale built-up area.

WRQU4: The fourth WQRU is from the confluence of the Rietspruit with the Mokolo River to where the geology changes incorporating the influence from the Lephalale built up area.

WRQU5: The last WQRU is from the break in the geology up to the Mokolo and Limpopo River confluence.

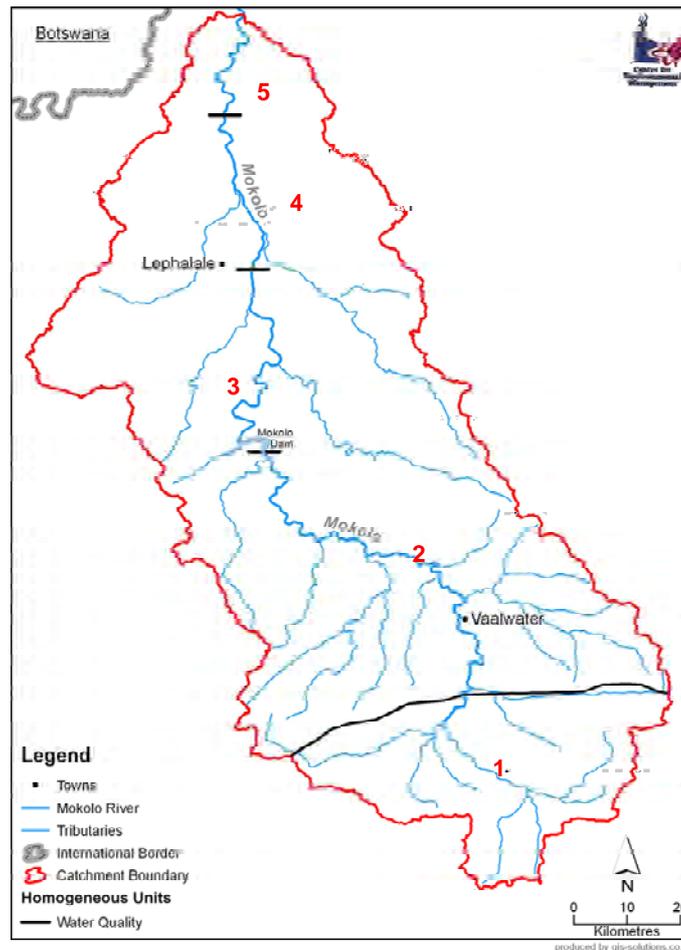


Figure 37. Homogenous Water Quality Response Units (WQRUs) in the Mokolo River

5.3.5.2.2 Socio-economic Response units (SRUs)

Socio-economic background of the Mokolo River Catchment

The Mokolo River is also called the Mogul or Mogolo River and the catchment falls within the municipal boundaries of the Waterberg District Municipality (DC36). Four local municipalities, namely Lephalele (NP 362), Modimolle (NP 365), Thabazimbi (NP 361) and Bela Bela (NP 366) have a share in this river catchment. The largest part of the catchment falls within the boundaries of the Lephalele (NP 362) and Modimolle (NP 365) local municipalities.

The Mokolo River is one of several main catchments in the Limpopo Water Management Area (RHP, 2006; DWAF, 2004). According to DWAF (2004a) the catchments in the Limpopo WMA are mostly independent of each other and therefore require separate and largely independent water management strategies. However, the catchments all feed into the Limpopo River which is shared between South Africa and neighbouring Botswana, Zimbabwe and Mozambique. Therefore, water management decisions in the Mokolo catchment need to be taken with the larger Limpopo River Basin included and more specifically how it relates to international cooperation between the riparians of the Limpopo River.

There is no catchment management agency (CMA) functioning in the Mokolo River Basin and this has been pointed out as a concern by some of the stakeholders. The Mogul Irrigation Board is the main institutional body that mediates between stakeholders in the agricultural sector and the DWA.

Currently, some 200 farmers fall under the management of the board and the board manages the yearly fees that are transferred to the DWA for water rights. The Mogul Irrigation Board only serves the farmers downstream of the Mokolo Dam. Upstream of the dam, there is no functioning irrigation board, or WUA. Only a few farmers in the catchment currently have water licenses as required by the Water Act and many still have old order water rights.

The current status of water availability and requirements for the different sectors are summarised in Table 14. From this data it appears that the water use in the catchment is currently balanced. However, the Mokolo River catchment is the most developed catchment in the Limpopo WMA and there is little room for additional allocations of water (DWAF, 2004). Given current and projected changes in the demographic profile of the population and the increasing economic development in the catchment, it can be expected that the water demand will increase and that the social impacts on the river will become more extensive, widespread and complex.

Table 14. Water requirements in the Mokolo Catchment (at 1:50 year assurance) in 2003 (DWAF, 2004)

User sector	Water requirements/ impacts on yield (million m ³ /a)
Irrigation	68
Urban	2
Rural	2
Industrial	0
Mining	4
Power generation	7
Afforestation	0
Total local requirements	83
Transfer out	0
Total	83

Population in the Mokolo River basin is estimated at 137 305 people, while population density in the catchment is between 56-154 people per km² (Demarcation Board, 2006; RHP, 2006). Lephalale (formerly Ellisras), the largest town in the catchment, has a population density of around 180 people per km² (African Development Bank, 2009). The age structure of the population in the catchment corresponds almost completely with that of the South African population as a whole, with 33% of the population under 15 years of age, and 5% older than 64 years in both the catchment and in South Africa as a whole (Demarcation Board, 2006; PRB, 2007). There is no specific data on population growth rates for the Mokolo Catchment available. However, between 2001 and 2008 the population growth rate for the Limpopo Province was 1.03% and for the period 2001-2021 it is expected to be 1.05%.

Urbanisation is one of the key features of demographic change in today's society. The catchment is experiencing unprecedented urban growth in Lephalale as a result of economic developments surrounding this town. The local municipality of Lephalale, which includes surrounding rural areas, has a population of approximately 96 000 people (South African Municipalities, 2010). Lephalale is currently a major economic growth point in the catchment due to the current and future industrial developments around the town. As a result of these economic developments, particularly the expansion of the Grootegeluk Colliery and the building of the Medupi power station, the population of the town in particular and of the catchment in general may increase over the next few years.

Eskom and Exxaro have both bought houses in a housing development on the western Mokolo River bank in Lephalale to supply their workers with houses. These new houses required that land next to

the river be converted for urban use and this translates into decreased ecosystem sustainability in this riverine ecosystem as the riverine habitat becomes fragmented and built up; as more water is extracted from the river, and as more pollution eventually ends up in the river. Currently a large number of temporary workers and contractors are residing in Lephalale to work on the building of Medupi power station and on the expansion of the mine. An estimated 8 500 contractors are reportedly currently working on the Medupi power station and will stay until the completion of the project. However, once the power station is completed, only an additional 800 permanent employment opportunities will have been created by the developments.

Apart from Lephalale, smaller towns are also found along the river. These include Alma, Bulge River, and Vaalwater. These towns are mainly service centres for the agricultural sector with relatively small populations. Vaalwater has a population of around 37 000 people, of which 36 000 reside in the former township. The town is separated from the Mokolo River by farmland. A small agricultural village (the Agrivillage) is situated on the banks of the Sandspruit near Alma. This village is home to some farm workers in the area.

The health of the population in the region is poor, particularly among the urban inhabitants. Malnutrition is rife and water-borne diseases are common, although not necessarily more so than in the rest of South Africa. With regards to water-related health indicators, it is particularly the incidence of diarrhoea in the under five year age category that serves as an indicator of the overall health status of the population. The incidence of diarrhoea under children has increased markedly over the past years for the Limpopo province as a whole, as well as in the Waterberg Municipality (SAIRR, 2009). Another health issue related to water quality, at least in part, is the high incidence of pesticide poisoning, particularly in the Waterberg district (DOH, 2008). While the reported cases only reflect the incidences where poisoning was severe enough to warrant reporting it, it is worth considering the impact that agricultural run-off into the Mokolo River may have on the health of the populations dependent on this river.

The main economic activities in the catchment are centred on commercial farming and industry. Both these sectors, agriculture and industry, are significant users of water and also modify the natural environment to the extent that it impacts on the ecological functioning of the river. Agriculture accounts for the use of around 87% of water in the catchment while 13% is used for industry, mining, power generation and domestic water supply (DWA, 2008a). Each of these sectors will be discussed in turn.

- **Agriculture**

Commercial agriculture is one of the key economic activities along the Mokolo River. Game farming takes place on a lesser scale and is mostly linked to tourism rather than to farming. A number of informants have reiterated that the land use along the river comprises almost exclusively of commercial farming and there are no subsistence farming activities along the river (Google Earth, 2010; personal communications, field observations).

The main crops grown in the Mokolo catchment include maize, citrus fruit, tropical fruit and vegetables. More specifically downstream from the dam, water melons, potatoes, onions, tomatoes, green peppers and pumpkins are among the crops grown. Crops are watered mainly through irrigation from the river, although in some instances groundwater is also used. According to the spokesperson for AgriLimpopo around 1000 hectares of land is under irrigation in the Mokolo Catchment. Some dryland farming is also practiced, particularly upstream from the Mokolo Dam. The Mokolo Dam serves as a divide between the agricultural practices and interactions with the river between farmers upstream and downstream from the dam. Upstream from the dam crops grown

include tobacco, seed crops like maize, and some fruit crops such as lemons and oranges. Irrigation is widely practiced, although farmers have indicated that the possibilities of irrigation are limited by the natural downward slope of the river, which means that the water does not stay in the river long. As a result of the unpredictability of water supplied by the river in the upstream area, many farmers have built farm dams to store water from where water is pumped for irrigation. Some of these dams are quite large in terms of storage capacity. Farmers downstream from the Mokolo Dam benefit from the supply of water from the dam for irrigation and thus have a greater assurance of supply. However according to the Mogul Irrigation Board the releases from the dam sometimes run off too quickly to be used productively for irrigation. To address this problem, the board, in collaboration with DWAF (now DWA) has built two smaller dams downstream of the Mokolo Dam in order to better manage the water supply to the downstream farmers.

Conversion of crop producing farms to game farms

In recent years many farms have been converted from crop producing farms to game farms. There is definite potential for tourism development in the area, but that is reliant on the preservation of the ecosystem surrounding the river. Especially around Vaalwater, there are some large and impressive game farms, while some smaller operations also exist. A number of private game farms and lodges, as well as a nature reserve, the Mokolo Dam Nature Reserve, are found along the river. Some tourist locations include Pitse Lodge, Welgevonden Private Game Reserve and Kamonade Game Farm.

• **Industry**

Significant industrial land use in the catchment includes the Grootegeluk Coal Mine and the Matimba Power Station outside Lephalale.

The Grootegeluk coal mine

Grootegeluk Coal Mine, owned by Exxaro Mining Company is the largest coal mine in the country (DWA, 2008a). The allocated amount of water to the mine is 9.9 million m³/year although the total water requirements for the mine at the moment are 4 million m³/a (DWAF, 2004). The mine is therefore presently not using their full allocation of water. With the building of the Medupi Power station there is an increased demand for coal. Therefore the mine is in the process of expanding its operation by developing two new plants at the mine. Even with this expansion the mine does not envision that it will need an additional allocation of water, but they will possibly then use their full allocation to provide the additional plants with water (Pers. comm. Mine Environmental Office, 2010). The mine will, however, build more dams at the mine to store water, but these water resource developments will still fall under their existing license as a bulk water user. The current water requirements of the mine is positive for farmers downstream of the dam, since they currently enjoy a higher assurance of supply than would have been the case if the mine used their full allocation of water (DWAF, 2004). With the planned expansion of the mine, their assurance of supply will be affected.

Grootegeluk mine is well aware of the risk of polluting water resources, particularly groundwater resources. Advantageously the geology of the area seems to be helping in isolating any potential pollution of water resources from the mine. As a result of the Daarby geological fault that runs through the area, the coal pit is separated from what happens in the rest of the plant. Therefore, polluted mine water can be contained so that it does not significantly affect the groundwater, according to the mine spokesperson. The mine operates on a closed system, where a volume of 2000-3000 m³ of water enters the mine a day, but where no polluted or used water leave the site again. The mine has dams in which the used water is contained and therefore no used water is pumped back into the Mokolo River again. The mine is also working on a system to reticulate the process water at the mine so that this water can be used in the mining operations again.

Further mining developments

Some 45% of South Africa's coal reserves are found in the Lephalale and Mokolo River Basins (DWAf, 2004). These coal reserves are currently still largely unexploited, but there are planned mining developments by SASOL and Anglo Holdings (Pers. comm. Mine Environmental Office, 2010). Additionally, some smaller mining companies are currently exploring the possibilities of starting operations in the area. All these future developments could increase the demand for water in the catchment considerably.

Sand mining

Individual farmers as well as the Lephalale Farmers' Association indicated that sand mining along the river has huge implications on the water. Sand mining operators alter the flow of the river, impact on the riparian vegetation and degrade the natural ecosystem. These mining operations create weirs to keep water back in order to mine the sand. Farmers downstream are affected because when the water is prevented from flowing, these farmers get less water from the river. The sand in the river also acts like a sponge that retains the water, even after the water has run off and the river is dry. Some pools are left behind and some water is left in the sand beneath the pool. As the pools dry up, the farmers can still access the water that is retained in the sand layer. This makes it possible to still irrigate to an extent, since there is still water trapped in the sand. When the sand is removed it interrupts this function that the river serves for farmers in drier periods.

Matimba and Medupi power stations

Matimba power station is the world's largest dry cooling power station (DWA, 2008a). This power station currently uses its total allocation of 7.3 million m³/a of water (DWAf, 2004). Another power station is currently being built near the existing Matimba power station and the mine, namely Medupi. It is unclear what the future impacts on water availability will be once the Medupi Power Station is functioning.

• **Subsistence uses of the Mokolo River**

The energy use pattern of people in the catchment is consistent with communities living in poverty. More than half of households (53%) rely on wood for cooking. When natural resources such as wood are being depleted, land degradation and a loss of biodiversity may also contribute to habitat degradation of river ecosystems through increased erosion and siltation of rivers.

Although a large proportion of the population is poor, there is a low reliance on food obtained from the river. Some of the population in the catchment do catch fish from the river, but the fish does not constitute a major proportion of the food intake of the population. There are also no indications that the population use reeds from the river as a main source of building material. Near Vaalwater there are two plots on which poorer urban dwellers practice some small-scale subsistence farming, but it is largely dryland agriculture and a few heads of cattle. Thus, there is no significant interaction with the river from subsistence users and therefore, changes with regard to the flow or the ecosystem of the river will not significantly affect the livelihoods of poorer households.

• **Water quality**

All farmers along the river have indicated that water quality is a main issue affecting agricultural production in the basin. One of the key issues pointed out by farmers is that they have until recently had access to good quality water and see the deteriorating water quality as a major concern. A citrus farmer near Vaalwater indicated that he regularly monitors the water quality because he exports his produce and finds that he cannot use water from the river for irrigating his export crops. As a result, he has to make use of groundwater. The sewage works in Vaalwater is situated close to the river and there are concerns that because it is not well managed by the municipality that the river is polluted by

untreated sewage. Lephalale receives its water from the Mokolo Dam, thus the domestic water supply to this town is affected by what happens upstream from the dam.

A possible water-transfer scheme from the Crocodile River (DWAF, 2004) would also adversely affect the water quality in the Mokolo River.

- **Assurance of Supply**

DWAF (2004) state that the implementation of the ecological Reserve will 'almost certainly' result in a deficit situation at the Mokolo Dam. Implementation of the Reserve will require a reallocation from the Mokolo Dam.

A concern is that Eskom will need more water for Medupi once the power station is in operation and then the water in the Mokolo Dam could fall below 50%.

Socio-economic Response units (SRUs)

The socio-economist identified homogenous units which reflect the different human activities such as agriculture, game ranching, mining, informal settlements, built-up areas, etc. in the region of the Mokolo River using historic data.

Motivation for units identified (Figure 38):

SRU 1: This area is dominated by agriculture with land use mainly comprised of crop growing. There is a small town in this area (Alma) and there are also some informal settlements.

SRU 2: In this area land use is also dominated by agriculture, but with large areas of land under irrigation. Some game farming is practiced. The town of Vaalwater is a significant urban settlement in this area and there are some informal settlements around the town.

SRU 3: This area is dominated by game farming, although some irrigation farming is also practiced. The Mokolo Dam and the Mokolo Dam Nature Reserve are situated in this area.

SRU 4: The area around Lephalale is dominated by industrial activities. There is a coal mine as well as a power station close to Lephalale that indicates different interactions between society and the environment than in the other areas. This is also a fairly large urban settlement that depends on water from the Mokolo via the Mokolo Dam for urban water supply.

SRU 5: Some agriculture and game farming takes place in this area.

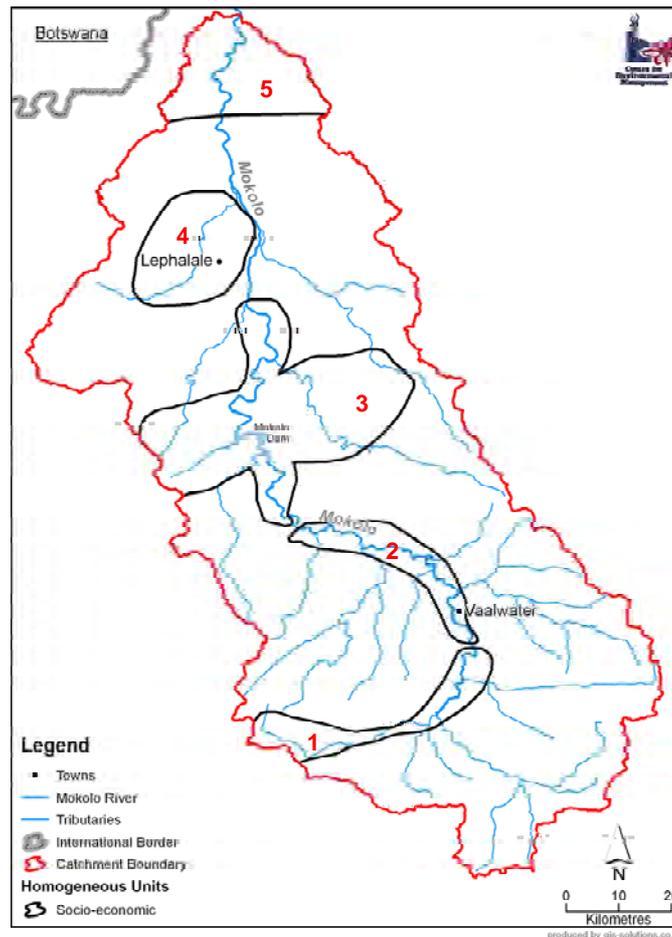


Figure 38. Homogenous Socio-economic Response Units (SRUs) in the Mokolo River

5.3.5.2.3 Management Response Units (MRUs)

An overlay of the Water Quality units (Figure 37), Socio-economic units (Figure 38) and Habitat Integrity units (Figure 35) was completed to produce the Management Response Units (MRUs) for the Mokolo River (Figure 39a & b).

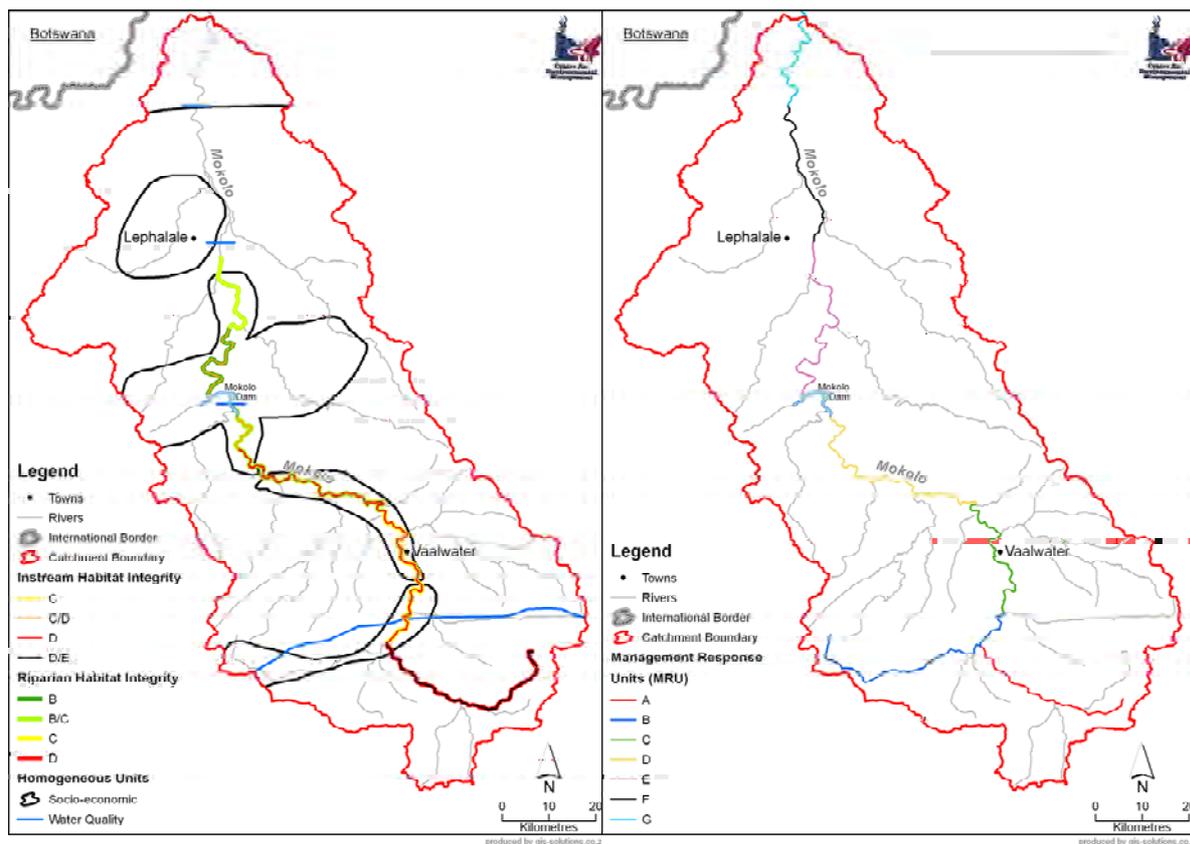


Figure 39. Left (a): Overlay of Water Quality Response Units (WQRUs), Socio-economic Response units (SRUs) and Habitat Integrity Units, Right (b): Management Response Units (A-G) identified in the Mokolo River

Each MRU should represent a homogenous unit where the human impact (management) on the river is similar. The attributes of the MRUs chosen are provided in Table 15.

Table 15. Management Response Units (MRUs) identified in the Mokolo River

MRU	Delineation	Water Quality Unit	Socio-Economic Unit	Habitat Integrity Unit	
				Instream	Riparian
A	Source of Sand River to confluence with Grootspuit	WQRU 1 – This WQRU is in a similar geological area and there is a natural ridge that separates this unit from the next as the river has to flow through a poort. This unit represents the upper portion of the Mokolo River	Not defined but agriculture (cultivated lands) is dominant in this area. There is a small town in this area (Alma) and there are also some informal settlements.	D/E – very poor	D – poor
B	Source of Grootspuit to confluence of Klein- Sand and Mokolo River	WQRU 1 – This WQRU is in a similar geological area and there is a natural ridge that separates this unit from the next as the river has to flow through a poort. This unit represents the upper portion of the Mokolo River	Unit 1 – Mostly dominated by natural bush (Grootspuit) with some agriculture. Land use mainly comprised of crop growing.	E – (very poor)- D –(poor) Several dams resulting in flow regulation in area	D/E (poor to very poor) – D (poor)

MRU	Delineation	Water Quality Unit	Socio-Economic Unit	Habitat Integrity Unit	
				Instream	Riparian
C	Mokolo River from Klein Sand tributary to confluence with Brakspruit.	Upper part of WQRU 2 – The total WQRU is from where the river exits the poort up to the upper reaches of the Mokolo Dam.	Part of Unit 2 – In this area land use is also dominated by agriculture, but with large areas of land under irrigation. Some game farming is practiced. The town of Vaalwater is a significant urban settlement in this area and there are some informal settlements around the town.	D (poor)	C (fair) Habitat integrity differs from section upstream and downstream
D	From confluence with Brakspruit to upper reaches of Mokolo Dam	Lower section of WQRU 2 – The WQRU is from where the river exits the poort up to the upper reaches of the Mokolo Dam.	Part of unit 2 and part of unit 3 In this area land use is also dominated by agriculture, but with large areas of land under irrigation. Unit 3 This area is dominated by game farming, although some irrigation farming is also practiced.	D (poor) to C/D (poor to fair)	B/C (good to fair) Riparian Habitat Integrity good – probably due to mostly game farming in area
E	From upstream of Mokolo Dam to upstream of Lephale (upstream of Tambotie confluence)	WQRU 3 – downstream of the Mokolo Dam and up to just after the confluence of the Rietspruit with the Mokolo River.	Unit 3 – This area is dominated by game farming, although some irrigation farming is also practiced. The Mokolo Dam and the Mokolo Dam Nature Reserve are situated in this area.	C/D(Poor to Fair) – C (fair)	B (good) – B/C (fair to good)
F	From downstream of Lephale to where geology changes to where the lithology changes from Arenite and Shale to Gneiss	WQRU 4 – from the confluence of the Rietspruit with the Mokolo River to where the lithology changes from Arenite and Shale to Gneiss	Unit 4 – The area around Lephale is dominated by industrial activities. There is a coal mine as well as a power station close to Lephale that indicates different interactions between society and environment than in the other areas. This is also a fairly large urban settlement that depends on water from the Mokolo via the Mokolo Dam for urban water supply.	None done	None done
G	From where lithology changes from Shale and Arenite to Gneiss	The last WQRU is from that break in the geology up to the Mokolo and Limpopo confluence.	Unit 5 – Some agriculture and game farming takes place in this area.	None done	None done

5.3.5.3 Delineation of CRUs identified in the Mokolo River (equivalent to Integrated Units of Analysis produced by the DWA's Water Resource Classification System (Dollar et al., 2007), and the Reserve Assessment Units (RAUs) of Kleynhans and Louw (2007a)

The **Combined Response Units (CRUs)** are delineated by overlaying the NRUs (Figure 36b) and MRUs (Figure 39b) and using any other relevant information such as desktop surface and groundwater hydrology and units/areas identified by specialists as being critical to their specialist field (e.g. critical habitat available to fish, etc.). Nine CRUs (Figure 40) were identified which represents units in the Mokolo River which are homogenous with regards to natural attributes and management impacts.

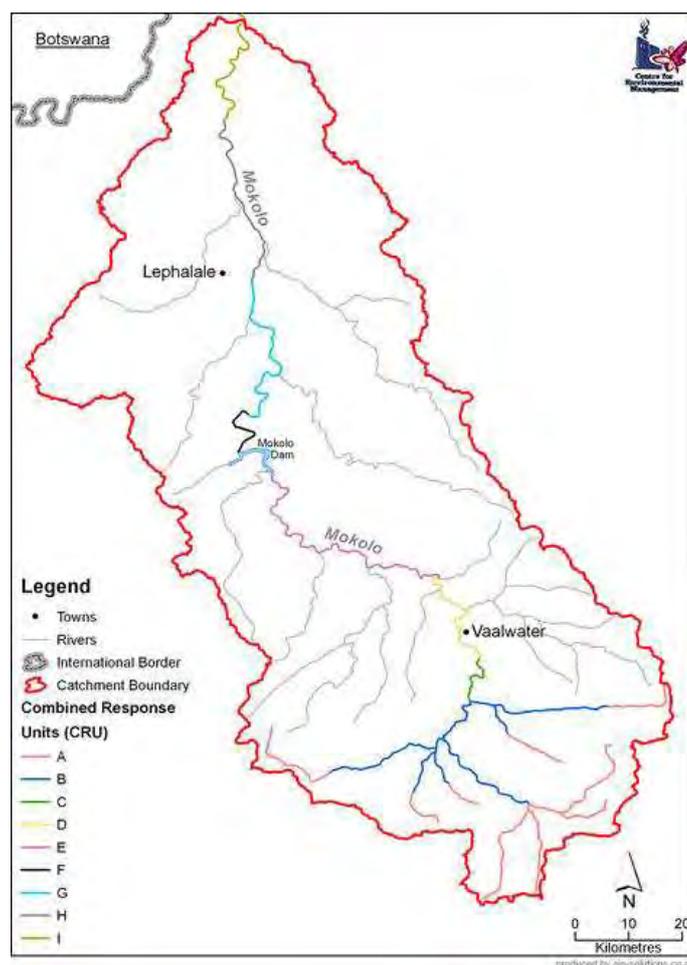


Figure 40. Combined Response Units (CRUs) identified in the Mokolo River

The attributes of each CRU are provided in Table 16.

Table 16. Attributes of Combined Response Units (CRUs) identified in the Mokolo River

CRU	Delineation	NRU	MRU
A	All the Upper tributaries (Sand, Sandspruit, Klein-Sand and Grootspuit including upper foothills, mountain headwaters and transitional zones	NRU A Upper tributaries – upper foothills and mountain headwaters Confined valley form, single thread channel	Part of MRU A+B agriculture and natural bush
B	Lower foothill sections of Sand, Sandspruit, Klein-Sand and Grootspuit tributaries up to confluence with Mokolo River	NRU B Lower foothills. unconfined, flat valley floor, single thread channel, pools, channel artificially constrained by agriculture, reeds, impoundments, islands, wetlands dense reed covering, possible incised channel	Part of MRU A+B
C	From confluence of Klein-Sand to end of Ecoregion level II 6.01 as well as complete Macro-reach C	NRU C different channel and slope from rest of river – meandering channel	Part of MRU B irrigation and agriculture
D	From start of Macro-reach D (24.332S, 28.1249E) and ecoregion level II 6.02 to confluence with Brakspruit	Part of NRU D Partially confined, narrowing valley, bedrock controlled multi channel to bedrock controlled single channel pools. Islands, pools, boulders and bedrock, weirs form pools and reeds lining pools.	MRU C agriculture and influence of Vaalwater
E	From confluence with Brakspruit to Upstream of Mokolo Dam	Part of NRU D Partially confined, narrowing valley, bedrock controlled multi channel to bedrock controlled single channel pools. Islands, pools, boulders and bedrock, weirs form pools and reeds lining pools.	MRU D agriculture and game farming

CRU	Delineation	NRU	MRU
F	From upstream of Mokolo Dam to end of Macro-reach F (23.9184S, 27.7334E).	NRU E Dam and gorge downstream Partially confined narrowing valley and wandering channel. Alluvial, pools, boulders, large impoundment, Bedrock, pool-rapid, sand bar, islands, and vegetated bars below dam (reduced flooding). Mokolo Dam	Part of MRU E mostly game farming
G	From end of Macro-reach F (23.9184S, 27.7334E) to Upstream of Lephale.	NRU F Upstream of Lephale and influence of dam. Partially confined valley form, wandering channel. Pools, alluvial, sand bars, reeds lining pools, single thread, islands	Part of MRU E mostly game farming
H	Downstream of Lephale to downstream of Sandloop confluence (where lithology changes from Shale and Arenite to Gneiss).	Part of NRU G change to unconfined valley form, lower runoff,	MRU F Lephale influence and mostly mining, etc.
I	From end of CRU I to confluence with the Limpopo River	PART G low runoff, different geology, mostly dry	MRU G water quality different plus influence of everything upstream

5.3.5.4 Ranking CRUs in terms of importance

CRUs are units in the river that are homogenous in terms of natural as well as management aspects. Once the CRUs are chosen, sites need to be identified that would represent the CRU. The number of sites to be sampled is determined by the complexity of the river, the budget available and the level of EWR to be done.

The CRUs that have been identified by the team and delineated using GIS (see section 5.3.5.3) are sent to the specialists who are required to rank/rate each of the CRUs according to importance (ranging from 1- 9 (depending on the number of units identified where 1 is important and 9 (maximum number of CRUs identified in study) is least important) with a motivation for each decision.

The results from each specialist in the Mokolo River study are discussed below.

5.3.5.4.1 Soil Response Units and CRU ranking (Pieter le Roux, Johan van Tol and Leon van Rensburg):

Six homogenous units (Figure 41) were identified by specialists in the Mokolo River catchment, according to soil characteristics.

Unit 1: Shallow responsive soils with shallow recharge

Unit 2: Shallow recharge soils

Unit 3: Deep Interflow soils

Unit 4: Shallow responsive soils

Unit 5: Deep interflow (Soil/bedrock interface)

Unit 6: Deep recharge alluvial sands.

Motivation for units identified (Figure 41):

Deep interflow: Soils show indications of saturation on the soil bedrock interface. Water drains vertically through the soil until it reaches the bedrock and then flows laterally on the bedrock.

Recharge: No indications of saturation in the soil profile, indicating that the vertical drainage through the soil is dominant and recharge of groundwater is assumed. (The difference between deep and shallow recharge soils is the depth of the soil profile).

Responsive soils: These soils respond immediately to rain events, either because they are shallow (with relative impermeable rock) or saturated. In both cases the greater part of precipitation can't infiltrate the pedon but will flow as overland flow.

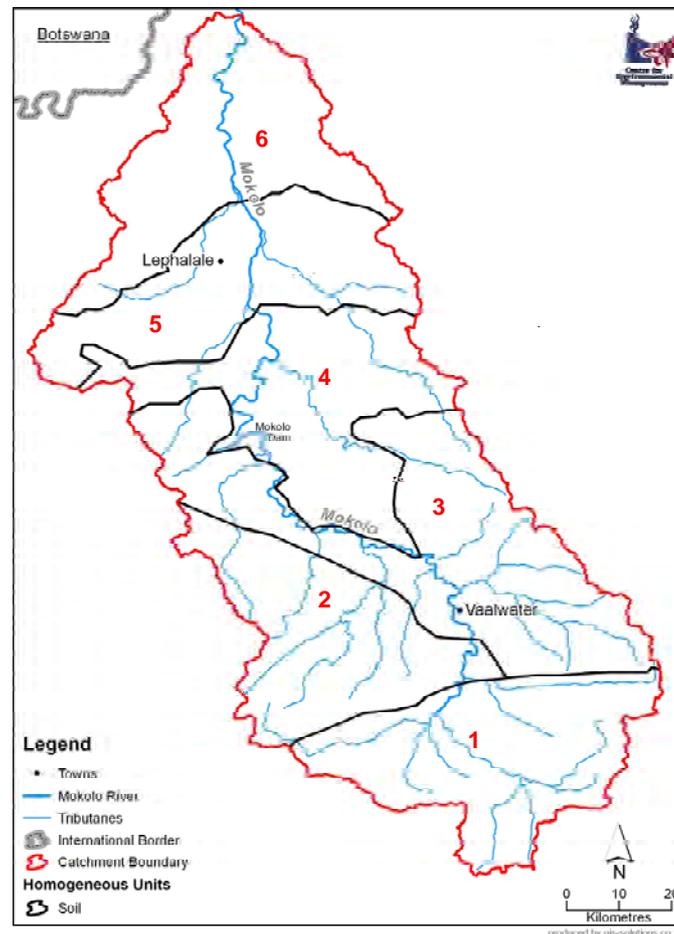


Figure 41. Homogenous units identified according to soil types in the Mokolo River

CRUs identified by the team (Figure 40) were ranked (from 1=important to 9 =not important) in terms of soil properties using information from Homogenous units (Figure 41) (see Table 17).

Table 17. Importance ranking of soil units with motivation for each CRU identified

Specialist Field Criteria chosen		Soil
CRU	Ranking	Motivation
A	9	Lack of soil and agricultural activities
B	9	Lack of soil and agricultural activities
C	9	Lack of soil and agricultural activities
D	1	Land use change can affect water regime
E	3	Land use change can affect water regime
F	3	Land use change can affect water regime
G	3	Land use change can affect water regime
H	1	Land use change can affect water regime
I	1	Land use change can affect water regime

5.3.5.4.2 Vegetation Response Units and CRU ranking (Marthie Kemp):

Five homogenous units were identified by the riparian vegetation specialist (Figure 42).

Motivation for units identified (Figure 42).

Vegetation is a function of the environment in which a particular vegetation type occurs. The underlying geology, the soil type and the climate will play a role in characterizing a particular vegetation type. The general vegetation descriptions of the catchment from literature, does not necessarily represent the riparian zone, since the scale of VEGMAP (Mucina et al., 2005) is on a 1:000 000 and phytosociological data are mostly broad descriptions of the vegetation occurring in the catchment.

It was decided that although seven different vegetation types occur on the catchment, the proposed units should meet the following criteria:

- The vegetation type should border the Mokolo River
- The vegetation type should cover a larger area of the catchment

Topography, climate and soil characterises are captured by Land Type maps (Figure 22). The land types and vegetation types (Figure 26), bordering the Mokolo River, were indicated on each of the maps and these maps were overlaid to give five potential units as indicated in Figure 43. The different vegetation types and landtypes are listed below:

- Unit 1: Bb Landtype, Central Sandy Bushveld
- Unit 2: Bb Landtype, Central Sandy Bushveld
- Unit 3: Ib Landtype, Western and Central sandy bushveld
- Unit 4: Bc Landtype, Waterberg Mountain Bushveld
- Unit 5: Ah Landtype, Limpopo Sweet Bushveld

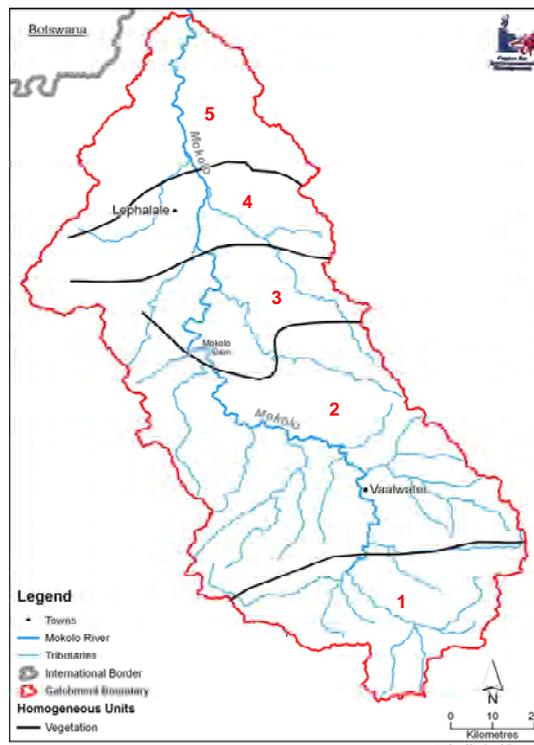


Figure 42. Homogenous vegetation units identified in the Mokolo River Catchment

Using the information on homogenous units (Figure 42), the CRUs identified by the team (Figure 40) were ranked in terms of the importance for sampling vegetation (Table 18).

Table 18. Importance ranking of Vegetation with motivation for each CRU identified

Specialist Field		Riparian Vegetation
Criteria chosen		<ul style="list-style-type: none"> High number of people Major development
CRU	Ranking	Motivation
A	7	Not many influences
B	6	Not many influences
C	5	Not many influences
D	2	Agricultural impact
E	1	Population and agriculture impact
F	2	Just below the dam, agricultural impact
G	2	All the combined influences upstream should be reflected
H	2	All the combined influences upstream should be reflected
I	3	All the combined influences upstream should be reflected

5.3.5.4.3 Macro-invertebrate Response Units and CRU ranking (Marie Watson)

All available historical data and information on the catchment was used to identify units (Table 19).

Table 19. A list of literature resources consulted during the identification of Macro-invertebrate units in the Mokolo River

Document	Author
Macro-invertebrate specialist report for Intermediate Reserve Determination study on the Mokolo	Thirion and Uys, 2008 (personal communication)
Reference frequency of occurrence of macro-invertebrate species in South Africa	Thirion, unpublished data
State-of-the-Mokolo River Report	RHP (River Health Programme), 2006
Mokolo River biomonitoring results (2002)	Angliss (unpublished data)
A Level II River Ecoregion classification System for South Africa, Lesotho and Swaziland	Kleynhans et al., 2007b
Macroreach analysis	Rowntree and van der Waal, 2010.
Geomorphological Zonation of River Channels	Rowntree and Wadeson, 1999
Runoff Potential Units	Barker, 2010

Six macro-invertebrate units were identified (Figure 43).

Motivation for units identified (Figure 43)

Unit 1: Contains all Upper foothills, Transitional Zone, Mountain Streams and Mountain headwater stream where the macro-invertebrate community structure is different from the Lower foothills, Lowland River and source zones. There appears to be a larger split in invertebrate community structure between the Upper foothill Unit (1) and the Lower foothill Units (2-6). One could still split these groups up into smaller groups but then it becomes too complex. Most of this unit consists of tributaries and the habitat is more diverse in these tributaries than in the main stream.

Unit 2 Lower foothills zone (Rowntree and Wadeson, 1999) in Ecoregion level II (Western Bankenveld 7.02) which has Plains with moderate relief (Kleynhans et al., 2007b) and medium to high runoff potential (RPU) (Barker, 2010). This unit consists of the Lower Foothill zone of the Sand River, Grootspuit and Sandspruit at the origin of the Mokolo River and differs from unit 3 in terms of the lower slope. Plain bed, pool-riffle or pool-rapid reach habitat types predominate. Habitat diversity is moderate and marginal vegetation cover is good. Throughout this area there are a large number of bridges, weirs, dams, pumps and off-channel storage reservoirs (RHP, 2006).

Unit 3: Lower foothills zone (Rowntree and Wadeson, 1999) in Ecoregion level II (Waterberg 6.01) which has Table-lands with moderate and high relief (Kleynhans et al., 2007b). This area is dominated by slow deep water with many weirs and habitat is poor for macro-invertebrates (Angliss, Unpublished data). Macroreach analysis results state that the reach is dominated by pools of varying length which are artificially constricted by agriculture and lined with reeds. Dense reed beds are present (Van der Waal and Rowntree, 2010).

Unit 4: Lower foothills zone (Rowntree and Wadeson, 1999) in Ecoregion Waterberg (6.01 and 6.02) with Table-lands; moderate and high relief and Plains; low relief (limited) (Kleynhans et al., 2007b). The river is naturally perennial through most years in this unit and habitat diversity is high. Good quality benthic, the dominant bed material being cobble and boulders, and marginal habitat is available. Sensitive macro-invertebrates are expected (stoneflies, etc.) (RHP, 2006).

Unit 5: Lowland River (Rowntree and Wadeson, 1999) in Ecoregion Waterberg (6.01) with Table-lands; moderate and high relief (Kleynhans et al., 2007b). Low to High RPUs (Barker, 2010). Mostly low runoff into river channel in this unit. Lowland River which implies low gradient alluvial fine bed channel and a distinct floodplain (Rowntree and Wadeson, 1999). This unit falls downstream of the Mokolo Dam and periodic pulses of flow are expected. Good quality habitat is available. Sandy runs and deep pools are present and rocky habitat is absent. Sensitive invertebrates such as stoneflies are absent (RHP, 2006).

Unit 6: Lowland River (Rowntree and Wadeson, 1999) in Ecoregion Limpopo Plains (1.03 and 1.02) with Plains; low relief (Kleynhans et al., 2007b) and low runoff (RPUs) (Barker, 2010). Lowland River which implies low gradient alluvial fine bed channel and a distinct floodplain (Rowntree and Wadeson, 1999). This unit has seasonal flow and is often dry. Wetland areas are present. Species typical of lowland alluvial system are expected. Poor habitat diversity accounts for an invertebrate assemblage that is dominated by hardy families associated with marginal vegetation and sand (RHP, 2006).

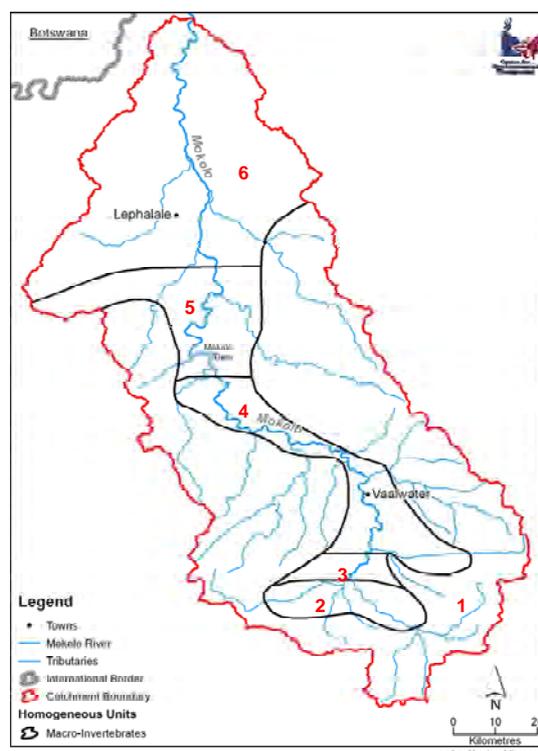


Figure 43. Homogenous macro-invertebrate units identified in Mokolo River catchment

Using the information on homogenous units (Figure 43), the CRUs identified by the team (Figure 40) were ranked in terms of the importance for sampling macro-invertebrates (Table 20).

Table 20. Importance ranking of CRUs for sampling macro-invertebrates

Specialist Field		Macro-invertebrates
Criteria chosen 3, 5, 6		<ul style="list-style-type: none"> Major development Sensitive habitat and species Zones sensitive to manipulation
CRU	Ranking	Motivation
A	5	Sensitive area for invertebrates as it includes mountain headwaters and upper foothills which are not represented in the rest of the CRUs
B	6	Impact of agriculture – abstractions from river could increase – increase in nutrients as a result of runoff into river from irrigated lands – change in invertebrate community structure
C	7	Different habitat available to invertebrates than in the rest of the river and possibly a different community structure present. Also includes impacts from agriculture.
D	2	Influence of Vaalwater and possible increase in population or impacts from the sewage effluent from the town.
E	8	Impacts from all upstream activities would be reflected here upstream of the Dam and also still has sensitive invertebrates which are already absent downstream of the Dam
F	9	Dam and just downstream of the Dam would reflect the direct impacts of the Dam but invertebrates can recover downstream and this would be picked up in CRU G
G	3	Influence of Dam which could have added abstraction as a result of the new power station which is going to be supplied from the Dam – decreased flow downstream of the Dam and influence on invertebrates
H	1	Influence of Dam and other developments at Lephale which would impact on flow and therefore on the invertebrates present
I	4	Accumulation of all impacts on the river – perhaps this site is not a possible Macro-invertebrate site as it is mostly dry according to literature

5.3.5.4.4 Fish Response Units and CRU ranking (Marinda Avenant)

Six units were identified where habitat available to fish should be homogenous (Figure 44).

Motivation for units identified (Figure 44):

Six “fish” units have been identified for the Mokolo River. The selection of these units was based on information obtained from available literature resources on the fish communities of the catchment (see Table 21 for a list) and not on personal observation and/or practical experience acquired in the river and its tributaries. Motivations in support of this division, is provided below (also see Table 23).

Table 21. A list of literature resources consulted during the desktop study

Document	Author
Fish specialist report for Intermediate Reserve Determination study on the Mokolo	Kotze, 2008
Reference frequency of occurrence of fish species in South Africa	Kleynhans et al., 2008a
State-of-the-Mokolo River Report	River Health Programme, 2006
D.Sc. dissertation	Kleynhans, 1984
Ph.D. dissertation	Gaigher, 1969

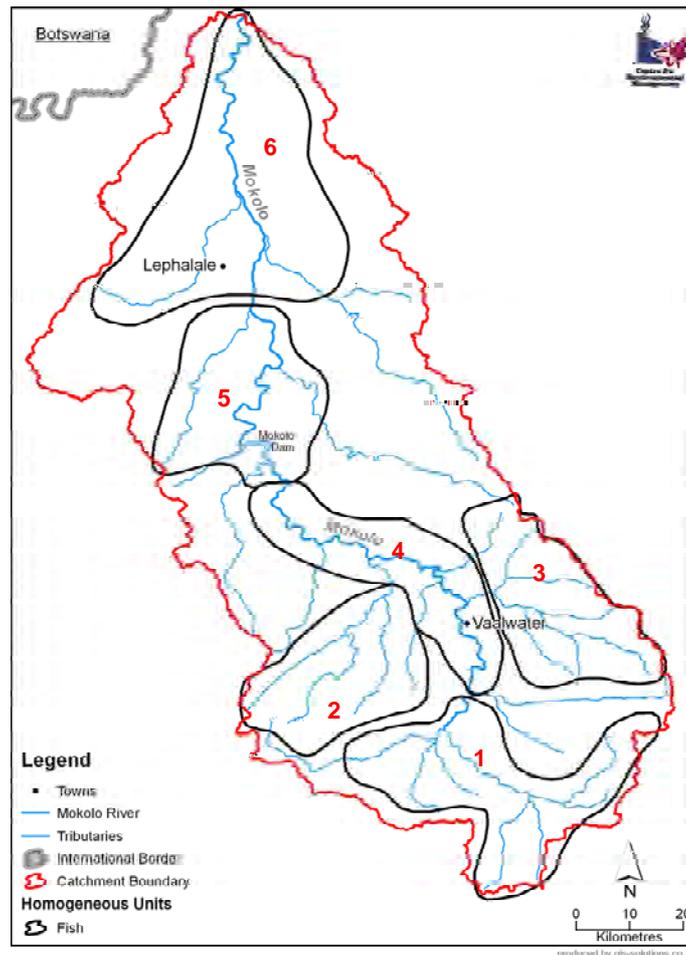


Figure 44. Homogenous fish units identified in the Mokolo River catchment

Fish unit 1 comprises mainly the Sand and the Klein Sand Rivers and their tributaries. The unit is the only part of the Mokolo catchment that falls within Ecoregions 7.03 and 7.02 (Western Bankenveld). The upper sections of the tributaries are classified as geomorphological zone class D (Upper foothills) and the lower sections as class E (Lower foothills). Although the streams vary in gradient, the predominant habitat-types are plain-bed, pool-riffle or pool-rapid (RHP, 2006). The streams are at present flowing seasonally (RHP, 2006). Based on the available fish data, the fish assemblage in this unit is different from that of unit 2 in the following respects:

- 18-19 species were previously recorded in this part of the catchment,
- none of the species requires to migrate at a catchment scale, and
- the fish assemblage is dominated by species that has a strong preference for fast-shallow and slow-shallow habitat.

There was not sufficient data to determine if there were differences between the fish assemblages of Ecoregions 7.01 and 7.02.

Fish unit 2 comprises the three tributaries Sterkstroom, Grootfonteinstream and Frikkie se Loop. These tributaries were historically perennial mountain streams that have only stopped flowing during severe droughts (RHP, 2006) and four rheophilic species have been recorded in these streams (Kleynhans, 2008a). Deep well-oxygenated pools provide refuge to these species during periods of drought (RHP, 2006). The unit falls into the 6.01 Ecoregion (Waterberg). The upper reaches comprise

geomorphological zone classes B (Mountain stream) and C (Transitional), while the middle and lower reaches of these streams comprise class D (Upper foothills). The habitat in this unit is different from unit 1 in that the flow is more perennial in nature and the stream gradients are steeper. The fish assemblage is different from that of units 1 and 3 in that:

- 20 to 24 species have been recorded,
- 4 rheophilic species occur,
- 1 of the recorded species is known to migrate at a catchment scale, and
- the majority of species prefers slow-deep habitat.

Fish Unit 3 consists mainly of the following tributaries: Jim-se-Loop, Dwars River, Heuningspruit and Sondagsloop. According to RHP (2006), these tributaries have a lower gradient with mixed bed alluvial channels. Sand and gravel dominated the stream beds. It also falls within the 6.02 Ecoregion.

The recorded fish assemblage is different from that of units 2 and 3 in that flow dependant species are mostly absent. It appears, however, that this is “unnatural” and that some of these streams only recently lost their perennality as a result of flow regulation, increased dam storage and increased loss of wetland (RHP, 2006).

Fish Unit 4 stretches from downstream of the confluence of the Klein-Sand and Mokolo Rivers up to the dam. The downstream ends of the tributaries were also included in this unit, but the dam was excluded. Due to the artificial nature of the dam it was uncertain if it should be included or not.

In this unit the river flows through a relatively flat area until it enters the Mokolo Dam. This part of the catchment falls within the 6.02 Ecoregion (Waterberg) and the lower foothills geomorphic region (Class E). In this section the river has a mixed channel section with bed material consisting of large cobbles (RHP, 2006). The reach comprises a combination of pools and riffles with sand/gravel bars and flood plains also being present (RHP, 2006). The fish assemblage in this section is different from that of unit 1 with the respect to the following:

- 22-23 species have previously been recorded in this reach (compared to the 19 of unit 1),
- 1 species is known to migrate at a catchment level (compared to none in unit 1),
- The fish assemblage is dominated by species with a high preference for slow-deep habitat (compared to predominantly shallow habitat for unit 1).

Fish Unit 5 starts downstream of the Mokolo Dam, through the gorge area up to the relatively flat area located downstream of the Rietspruit’s confluence with the Mokolo River. The river has a steep gradient in the upper section of the unit below the dam. Here the river falls into the lower foothills geomorphic class (class E), compared to the downstream section which falls into the lowland river geomorphic class (class F). Unit 5 is situated within the 6.01 Ecoregion (Waterberg). The fish assemblage is characterized by the following:

- 28 species have been recorded in this unit,
- only 1 rheophilic species occurs in this section,
- the majority of species prefer shallow habitat,
- the majority of species are associated with overhanging vegetation and substrate cover, and
- 2 of the species are expected to migrate at a catchment level

Fish Unit 6 comprises the flat sandy plain downstream starting downstream of the Rietspruit-Mokolo confluence up to the point where the Mokolo joins the Limpopo River. In this unit the river flows mainly through a flat plain with a low gradient (RHP, 2006). The river has several oxbows and isolated off-channel pools and the river channel itself is dominated by sandy runs and pools. The area falls within the 1.02 and 1.03 Ecoregions (Limpopo Plain) and the river channel corresponds with a lowland river

(geomorphic zone class F). The main tributaries, Sandloop and Tambotie, are seasonal streams. The fish assemblage in this unit is very different from the upstream assemblages in that it is dominated by hardy, pool-dwelling species and that no rheophilic species occur here (RHP, 2006).

Using the information on homogenous units (Figure 44), the CRUs, identified by the team (Figure 40), were ranked in terms of the importance for sampling fish (Table 22).

Table 22. Importance ranking of Fish for each CRU identified

Specialist Field Criteria chosen		Fish
		<ul style="list-style-type: none"> • Sensitive species and habitat • Presence of refuge pools/areas • Major developments and landuse
CRU	Ranking	Motivation
A	9	No species that migrate on catchment scale; no rheophilic species present; mostly agricultural impacts.
B	1	Four rheophilic species present in this section; important refuge pools present.
C	2	Sensitive species and species that need to migrate at a catchment scale; water abstraction for irrigation farming.
D	3	Sensitive species and species that need to migrate at a catchment scale; water abstraction for irrigation farming.
E	7	Fish community similar to that of CRU D; riparian habitat in good condition; mainly game farming
F	8	Fish community similar to that of CRU G; sampling preferred in CRU G due to downstream effects of Mokolo Dam.
G	4	Natural flow regime altered by dam; important refuge pools.
H	5	Natural flow regime altered by dam; influence from Lephale; important refuge pools; accumulation of impacts from upstream.
I	6	Natural flow regime altered by dam; accumulation of all upstream impacts; refuge pools.

Table 23. Characteristics of the fish assemblages expected for the various fish Units (based on the classification of Kleynhans (2008a))

FD, fast-deep; FS, fast-shallow; SD, slow-deep; SS, slow-shallow; WQ, water quality; OV, overhanging vegetation cover; BU, bank undercut cover; SUB, substrate cover; AM, aquatic macrophyte cover; WC, water column cover. Migration: 1, species with requirement for movement within river reaches; 3, species with requirement for movement between river reaches; 5, species with requirement for catchment scale migrations. The velocity-depth and fish-cover classes taken from Kleynhans (1999a, 2003 & 2008a).

	Quat. catchment	Geomorphic zones	Eco-region	FD	FS	SD	SS	Flow intolerant sp.	WQ Intolerant sp.	Migration 5	3	1	OV	BU	SUB	AM	WC	Sp. Richness
				%	%	%	%	% (N)	% (N)	%	%	%	%	%	%	%	%	N
<i>Tributaries</i>																		
Sand (Unit 1)	A42A	Lower foothill	7.02	17	29	41	52	17 (3)	17 (3)	0	64	35	41	11	29	0	11	19
Sterkstroom (Unit 2)	A42D	Upper foothill	6.01	17	26	48	43	17 (4)	17 (4)	4	69	26	43	21	30	4	17	24
Frikkie se loop (Unit 2)	A42D	Upper foothill	6.01	20	30	50	35	20 (4)	20 (4)	5	65	20	35	25	35	0	15	20
Rietspruit (Unit 5)	A42G	Upper foothill	6.01	4	13	65	43	4 (1)	4 (1)	4	78	17	47	17	21	4	21	24
<i>Mainstem</i>																		
Unit 1 (Proposed site 1)	A42C	Lower foothill	7.02	17	35	29	35	23(4)	17 (3)	0	70.5	29.5	35	11	35	0	6	18
Unit 3 (Proposed site 2)	A42E	Lower foothill	6.02	13	21	43	39	13 (3)	13 (3)	4	70	26	39	21	30	30	4	23
Unit 3 (Proposed site 3)	A42F	Lower foothill	6.02	9	18	55	36	4 (1)	4 (1)	4	68	23	27	23	27	4	18	22
(Unit 4) Proposed site 4	A42G	Lowland river	6.01	14	18	64	39	3.5 (1)	3.5 (1)	7	75	14						28
Unit 6 (Proposed site 5)	A42J	Lowland river	1.02	7	11	59	40	0	0	3	74	15			22			27

5.3.5.4.5 Socio-economic Response Units and CRU ranking (Nola Redelinghuys)

Using the information on Response Units (see section 5.3.5.2.2 and Figure 38) the CRUs identified by the team (Figure 40) were ranked in terms of the importance for socio-economic issues (Table 24).

Table 24. Importance ranking of Socio-economic issues for each CRU identified

Specialist Field: Social		Social
Criteria chosen:		<ul style="list-style-type: none"> • areas with high numbers of people dependent on the river • areas in which major water-resource developments are planned or possible
CRU	Ranking	Motivation
A	5	Extensive agricultural activity
B	4	Extensive agricultural activity
C	3	Extensive agricultural activity
D	2	Extensive agricultural activity
E	7	
F	6	Possible future increase in dam's capacity
G	8	
H	1	High human dependence on the river due to current and proposed future industrial and urban developments – town of Lephalale, Matimba Power Station, and Grootgeluk Colliery
I	9	

5.3.5.4.6 Final ranking of CRUs

The ranking of CRUs by each specialist (see section 5.3.5.4) was combined to determine the final ranking for the Mokolo catchment. Different CRUs could have the same ranking and it was therefore necessary to standardise the ranking from each specialist to produce the same total throughout. CRUs were ranked from 1 (important) to 9 (not important) as there were 9 CRUs identified by the team in the Mokolo River. The total of 1+2+3+4+.....9 = 45 and therefore each specialists ranking was standardised to a total of 45 (Table 25). The ranking for each CRU was then totalled and arranged from lowest to highest. The lowest result would indicate the most critical/important CRU. CRU H is the most critical CRU in the example (Table 25).

Table 25. Combined and Standardised Combined specialist CRU ranking in the Mokolo River in terms of importance for sampling

CRU	Water Quality		Soil		Fish		Macro-invertebrates		Vegetation		Fluvial Geomorphology		Catchment Geomorphology		Socio-economic		Ranking		Final Rank	
	O	S	O	S	O	S	O	S	O	S	O	S	O	S	O	S	O	S	O	S
H	2	6	1	2	5	5	1	1	2	3.5	1	1	5	5	1	1	18	24.5	1	1
D	2	6	1	2	3	3	2	2	2	3.5	5	5	6	7.5	2	2	23	31	2	2
G	1	2.5	3	5	4	4	3	3	2	3.5	4	4	5	5	8	8	30	35	3	3
B	1	2.5	9	8	1	1	6	6	6	8	7	7	2	1	4	4	36	37.5	6	4
E	1	2.5	3	5	7	7	8	8	1	1	3	3	6	7.5	7	7	36	41	5	5
C	2	6	9	8	2	2	7	7	5	7	2	2	7	9	3	3	35	44	4	6
F	1	2.5	3	5	8	8	9	9	2	3.5	9	9	3	2.5	6	6	41	45.5	8	7
I	4	8.5	1	2	6	6	4	4	3	6	6	6	5	5	9	9	38	46.5	7	8
A	4	8.5	9	8	9	9	5	5	7	9	8	8	3	2.5	5	5	50	55	9	9
TOT	45		45		45		45		45		45		45		45					

O=Original Specialist Ranking, S=Standardised Ranking

5.4 PHASE 5: Site selection in CRUs

Once the important CRUs are chosen by the specialists the sites are selected. For a detailed discussion on site selection see 4.1.5.

The location of the sites in each of the five most important CRUs (H, D, G, B and E see Table 25) was determined by using data on existing sites already sampled as part of the River Health Programme (DWA 2010a), routine fish sampling sites (Kleynhans et al., 2008a) and Intermediate Reserve (EWR) sites (DWA, 2008b). See Figure 45 for the position of all existing sites on the Mokolo River. Criteria mentioned in the site selection method (see 4.1.5), Google images and historic information on the catchment were also taken into consideration when sites were selected.



Figure 45. Position of existing River Health Programme sites (DWA, 2010a), Intermediate Reserve (EWR) sites (DWA, 2008b) and fish sites on the Mokolo River (Kleynhans et al., 2008a)

The chosen sites were then groundtruthed in April 2010 and the final location of the sites is indicated in Table 26 and Figure 46.

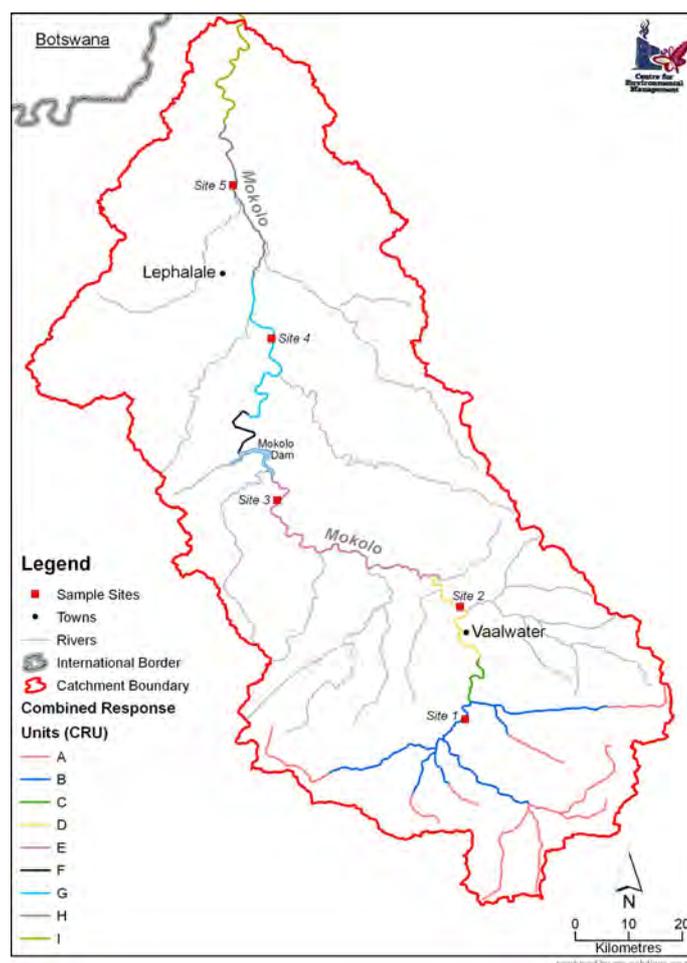


Figure 46. Map indicating sites chosen in the Mokolo River in each of the five most important CRUs (see Table 25)

A summary of the site characteristics of the sites chosen in the Mokolo River are provided in Table 26.

Table 26. Summary of the sites chosen in the Mokolo River indicating specific characteristics

Site Code	1	2	3	4	5
River:	Mokolo	Mokolo	Mokolo	Mokolo	Mokolo
WMA:	Limpopo	Limpopo	Limpopo	Limpopo	Limpopo
Catchment	A42C	A42E	A42F	A42G	A42J
Latitude:	-24.437	-24.2467	-24.0654	-23.7911	-23.5318
Longitude	28.1014	28.0927	27.7849	27.775	27.7108
Altitude (m)	1118	1111	932	806	814
Ecoregion	Western Bankenveld 7.02.	Waterberg 6.02	Waterberg 6.02	Waterberg 6.01	Limpopo Plains 1.02
Location	Mooiwater landgoed	Leeuwdrift	Ka'ingo Lodge	Vygeboomspoort	Die End/Ons Hoop
Site description	Situated upstream of RHP site A4MOKO-TWEEF	Situated downstream of RHP site A4MOKO-VAALW and downstream of Vaalwater town.	Situated upstream of RHP site A4MOKO-MOKOL and Intermediate Reserve Site EWR2 on a nature reserve	Situated upstream of Intermediate Reserve Site EWR4	Situated downstream of Intermediate Reserve Site EWR5 and A4MOKO-SHOTB.
Geology	Waterberg Group (Aasvoel Formation)	Waterberg Group (Vaalwater Formation)	Waterberg Group Situated on divide between Cleremont and Mogalakwena Formation	Waterberg Group: Mogalakwena Formation	Karoo Supergroup: Clarens Formation

Site Code	1	2	3	4	5
Vegetation Type	Central sandy bushveld	Central sandy bushveld -	Western and Central sandy bushveld	Waterberg Mountain Bushveld	Limpopo Sweet Bushveld
Hydrological Index	3.178 (Hughes and Hannart, 2003)	6.47 (Hughes and Hannart, 2003)	22.385 (Hughes and Hannart, 2003)	22.177 (Hughes and Hannart, 2003)	47.41 (Hughes and Hannart, 2003)
Macroreach	B	D	F	G	H
Geomorphological Zone	Lower foothills	Lower foothills	Lower foothills	Lowland River	Lowland River
Instream Habitat Integrity	D (Poor)	D (Poor)	C/D (Fair to Poor)	C (Fair)	Not done
Riparian Habitat Integrity	C (Fair)	C (Fair)	B/C (Good to Fair)	B/C (Good to Fair)	Not done
NRU	B	D	D	F	G
MRU	A+B	C	D	E	F
CRU:	B	D	E	G	H
Equivalent existing RHP and EWR sites	A4MOKO-TWEEF	A4MOKO-VAALW and EWR 1a & EWR 1b	A4MOKO-WITFO; A4MOKO-MOKOL; A4MOKO-ABDAM and EWR 2	A4MOKO-BEDAM; A4MOKO-WITKO and EWR 4	A4MOKO-SHOTB

5.4.1 Site descriptions

Five sampling sites were selected on the Mokolo River (Figure 46 and Table 26). Sites 1, 2 and 3 are situated upstream of the Mokolo Dam and sites 4 and 5 downstream. The location and physical characteristics of the sites are described below.

Site 1 (see: Appendix B: Plate 1).

Site 1 is situated in the Limpopo Water Management Area in quaternary catchment A42C at altitude 1118 m. The site is situated on the mainstem of the Mokolo River on the farm "Mooiwater Landgoed" owned, at the time of sampling, by farmer Attie Snyman. It falls in the Western Bankenveld (7.02) ecoregion and has a hydrological index of 3.178 (Hughes and Hannart, 2003) indicating low flow variability. The river was naturally/historically perennial at this site. The farmer (Attie Snyman pers. comm.) indicated that the river mostly starts flowing after high rainfall in February to March and also after early rain in November. It usually stops flowing in July. According to the farmer this area had been flooded 7 times in 28 years or on average once in 4 years. The most recent flood event of this magnitude had occurred as recently as March/April 2010.

The site is situated in the lower foothills geomorphological zone (Rowntree and Wadeson, 1999) and the surrounding area has a medium to high runoff potential (Barker, 2010). The river at the site is a single thread, slightly incised within a broad valley floor that is said to be composed of sands reaching a depth of 8 m (Attie Snyman pers. comm.). A narrow flood plain (20-50 m) could be seen on one or both sides of the channel. The main channel was colonized by reed growth that was dense in places. Long stretches of open water could be seen on Google Earth, indicating pools. Plain bed, pool-riffle or pool-rapid reach habitat types predominate. Pools of up to 8 m deep are present when river has no flow and some of these pools are fed by fountains (Attie Snyman pers. comm.). Frequent farm dams in the catchment would have had a moderate impact on hillslope-channel connectivity. There were also infrequent instream weirs and a small upstream dam. These would have had a small to moderate impact on longitudinal connectivity. There was judged to be limited erosion in the catchment, with dirt roads noted as a possible source of any increase in sediment. Without historic information it is difficult to judge changes to stabilizing effects of marginal and riparian vegetation, but it is likely that nutrient rich irrigation return flow has increased reed growth due to greater availability of both water and nutrients (Rowntree and van der Waal, 2012).

The Central sandy bushveld is the dominant vegetation type at the site. The Aquatic zone contains huge tufts of *Sporobolus fimbriatus*. These grasses were much higher than normal, but *Sporobolus* does not normally occur in the Aquatic zone as such. It could be explained by the high water level, since good rains had fallen just before the field trip. The Marginal zone contained mainly grasses with *Cynodon dactylon* being the most dominant. Patches of *Phragmites* also occurred. Medium (2.5 m) to high (6 m) trees occurred in the Marginal zone and no exotic species could be seen. The Lower bank was dominated by trees and grass of which *Terminalia sericea* and *Rhus (Searsia?) pentheri* were the most dominant species present. The Flood zone was dominated by the shrub, *Seriphium vulgare*, previously known as *Stoebe vulgare*. *S. vulgare* is adapted to dry conditions and its dominance is normally seen as an indication of overgrazing (Kemp, 2012).

The main impact on the river is farming and small dams which lead to an increase in zero flow period and loss of connectivity (longitudinal) (DWA, 2008).

Site 2 (See Appendix B: Plate 2).

Site 2 is in the Limpopo Water Management Area in quaternary catchment A42E at altitude 1111 m downstream of the RHP site A4MOKO-VAALW and downstream of the town Vaalwater. The site is situated on the mainstem of the Mokolo River on the farm "Leeuwdrift" managed, at the time of sampling, by Charles Newton. It falls in the Waterberg (6.02) ecoregion and has a hydrological index of 6.47 (Hughes and Hannart, 2003) indicating a low flow variability. The system has changed from being naturally perennial to seasonal as it stops flowing often under present conditions.

The site is in the lower foothills geomorphological zone (Rowntree and Wadson, 1999) and the surrounding area mostly has a high runoff potential (Barker, 2010). Site 2 is a more confined site (compared to site 1) with direct hillslope-channel coupling on the north bank, but some evidence of a floodplain on the less accessible south bank. The width of the channel that was flooded at the time of the field visit was around 100 m in places. In its flooded state the channel splits into two main channels around reed islands. Sand is the dominant material on the banks and probably also the bed. Although bedrock was not evident, it may have been present, possibly forming the core of reed islands. Plain bed, pool-riffle or pool-rapid reach habitat types predominate. Numerous weirs within the macro-reach were judged to negatively affect longitudinal connectivity; there was a broken weir immediately below the site. Roads in the catchment cause a small increase in connectivity between the channel and hillslopes. A small to moderate increase in sediment inputs was assumed due to catchment land use and roads. As at Site 1, irrigation return flow with a high nutrient load is likely to have caused increased reed growth (Rowntree and van der Waal, 2012).

The surrounding environment at the site was dominated by a grass layer (veld) and scattered trees. *Eucalyptus* trees were also present in the area, although not at the site. *Phragmites* occurred in the Aquatic zone with a mixture of grass (mainly *Panicum coloratum*) and trees (mainly *Combretum erythrophyllum*) being present in the Marginal zone. The Lower bank was mainly covered with grass, shrubs, smaller trees and herbs and typical terrestrial grasses occurred on the Upper zone with the tree canopy cover being much lower than in the Lower zone (Kemp, 2012).

The main impact on the river at the site is farming and small dams which lead to an increase in zero flow period and loss of connectivity (longitudinal) (DWA, 2008). Land use is dominated by agriculture, with large areas of land under irrigation. Some game farming is practiced. The town of Vaalwater is a significant urban settlement in this area and there are some informal settlements around the town.

Site 3: (see Appendix B: Plate 3)

Site 3 is situated in the Limpopo Water Management Area in quaternary catchment A42F at altitude 932 m, upstream of the RHP site, A4MOKO-MOKOL and the Intermediate Reserve Site, EWR2 on a nature reserve. The site is on the mainstem of the Mokolo River on the farm “Laurel 159”, business name “Ka’ingo Lodge” owned by Mac van der Merwe at the time of sampling. It falls in the Waterberg (6.02) ecoregion and has a hydrological index of 22.385 (Hughes and Hannart, 2003) indicating a higher flow variability than the upstream sites. The river is naturally perennial at this site but the system has changed from being perennial to seasonal as it stops flowing often under present conditions.

The river at Site 3 has a single thread channel within a confined reach with vertical cliffs or steep hillslopes on either side of the river channel. This site had the steepest gradient of all the sites sampled. It falls on the boundary between lower foothills and upper foothills geomorphological zone due to steep gradient and the surrounding area mostly has a high runoff potential (Barker, 2010; Rowntree and van der Waal, 2012). Pools with a well-developed rapid section with large boulders downstream were the main habitat types present at the site. The banks of the channel adjacent to the pool were composed of sand, but the bed of the channel included areas of exposed bedrock. The extent of these could not be judged due to the high flow levels. Dense reeds lined the edge of the main channel but were sparser on the flood benches. There was no high level flood plain; high floods washed directly over the hillslopes as was evident from flood debris (Rowntree and van der Waal, 2012).

The area is characteristic of the Bushveld vegetation that consists of more trees and less grass. The site itself was very different in terms of the two river banks. Three plant species occurred in the Aquatic zone namely *Phragmites mauritanicum*, *Cyperus sp.* and *Pennisetum macrohrum*. The Marginal zone consisted mostly of a flat area that gradually merged into the river with grass dominating (*Cynodon dactylon* being the dominant species) and some *Mariscus congestus*, *P mauritanicum* and a *Cyperus species* also present. One tree, *Combretum molle*, occurred in the Marginal zone. The Lower bank was characterised by sparse trees and grasses with the Upper bank being dominated by tree and shrub species *Peltophorum africanum*, *Ochna natalitia*, *Mimusops zeyheri*, and *Burkea Africana* (Kemp, 2012).

Roads in the steep landscape were the major observed local catchment impact, increasing hillslope-channel connectivity and providing a source of sediment. Weirs in upstream macro-reaches and irrigation return flow would continue to have a small impact on longitudinal connectivity and water quality respectively (Rowntree and van der Waal, 2012).

Site 4 (see Appendix B: Plate 4)

Site 4 is situated in the Limpopo Water Management Area in quaternary catchment A42G at altitude 806 m. The site is on the mainstem of the Mokolo River on the farm “Vygeboomspoor” owned by Jan Eckardt at the time of sampling. It falls in the Waterberg (6.01) ecoregion and has a hydrological index of 22.177 (Hughes and Hannart, 2003) indicating a slightly lower flow variability than the upstream site.

It is in a confined section 36 km downstream of the Mokolo Dam and the river at this point is significantly wider (than upstream of the dam) with a wandering low flow channel pattern within a straighter macro-channel. There was no floodplain at the site. A rocky bluff formed the left hand bank of the channel, with steep slopes coming down to the channel edge. A shallow gradient alluvial fan formed the right hand bank. Upstream and downstream terraces that may have been flooded during extreme events bound the channel (Rowntree and van der Waal, 2012).

According to Rowntree and Wadeson (1999) this site is situated in a lowland river geomorphological zone with a low gradient, alluvial fine bed channel. The surrounding area mostly has a medium to high runoff potential (Barker, 2010). Pools, alluvial, sand bars, reeds lining pools, single thread, and islands are present (van der Waal and Rowntree, 2010).

The main impact at this site is the Mokolo Dam, which is judged to have a large impact on the magnitude and frequency of flood events and on the sediment load. Increased low flow releases would have the effect of encouraging reed growth and enhancing channel stability. Historic aerial photographs would allow an assessment of the extent of change due to the dam. This bed of this river reach is clearly highly mobile and the course of the wandering channel is liable to change from one flood event to the next.

The Marginal zone at this site is very narrow (50-80 cm) and is dominated by *Phragmites* and *Cynodon dactylon* (dominant grass species). The Lower Bank has a steep slope with large boulders in some areas and is mostly dominated by trees and shrubs. The Upper bank is distinguished from the terrestrial zone by structure. It has almost the same species composition, but trees in the Upper bank are larger than those in the terrestrial zone (Kemp, 2012).

Site 5 (see Appendix B: Plate 5).

Site 5 is situated some 70 km downstream of the Mokolo Dam in an open plains-type landscape (Limpopo Plains (1.02) ecoregion) and downstream of the Intermediate Reserve Site EWR5 and the RHP site A4MOKO-SHOTB. It falls in the Limpopo Water Management Area in quaternary catchment A42J at altitude 814 m. The site is on the mainstem of the Mokolo River on the farm "Die End/Ons Hoop" rented by Koos Combrink at the time of sampling. It has a hydrological index of 47.41 (Hughes and Hannart, 2003) indicating a much higher flow variability than upstream sites. The surrounding area mostly has a low runoff potential (Barker, 2010) and the river is seasonal at this site with periods of no-flow.

This section of the river is in a lowland river geomorphological zone with a low gradient, alluvial fine bed channel (Rowntree and Wadeson, 1999). The river course is close to 500 m wide at this point, consisting of a wandering or braided sand bed low flow channel within a straight macro-channel. There is no clear floodplain evident beyond the confines of the macro-channel. Low wooded islands formed relief features within the macro-channel. At the time of the visit the entire macro-channel was flooded up to the edge of the wooded islands (Rowntree and van der Waal, 2012).

It was difficult to define the vegetation zones at this site as it was flooded during sampling but it appears as if the vegetation present is more characteristic of a terrestrial ecosystem. The Marginal zone could not be defined due to the flooding. The Lower and Upper zones were dominated by *Acacia mellifera*, which were mostly at least 1.8m high with taller trees further from the river. The main impacts at this site are the Mokolo Dam and extensive sand mining. Together these would decrease available sediment in the river. The dam would also impact on the magnitude and frequency of flood events. The effect of the dam at this site would be less than at Site 4. No habitat integrity was done in this area (as part of the Intermediate Reserve study; DWA, 2008a) but it was stated that there was riparian vegetation removal and some alien vegetation present at site A4MOKO-SHOTB which is just upstream of this site (Kemp, 2012).

5.5 PHASE 5: Indicator selection

Each specialist was requested to identify indicators in their specific disciplines as well as links between their indicators and other disciplines' indicators. The specialists first drew up a list of preliminary indicators before fieldwork using historic information, recent data and expert opinion. This

list was then refined in consultation with the project advisor (Jackie King) and project modeller (Alison Joubert) during and after fieldwork in April 2010. For detail on process followed see section 4.1.5.

Indicators were divided into driving indicators: Hydrological, Hydraulic, Geomorphological, and responding indicators: Water Quality, Vegetation, Macro-invertebrates, Fish and Socio-economic. Detail on indicators chosen is included in separate specialist reports (available on CD). A summary of indicators and links is presented in Table 27

Table 27. All indicators and their linked indicators as defined for the Mokolo River

Group	Code	Indicator	Links						
Flow indicators	H1	Total annual volume of surface flow (MAR)							
	H2a	Depth of water table, channel, dry							
	H2b	Depth of water table, channel, wet							
	H3a	Perc contribution of groundwater to surface flow, dry							
	H3b	Perc contribution of groundwater to surface flow, wet							
	H5	Onset of surface flow after period of dry river bed							
	H6	Onset of hydro wet season after a period of wet river bed							
	H7	No of floods per year that cover FZ1							
	H8	No of floods per year that cover FZ2							
	H9	Longest duration of inundation of FZ2							
	H10	No of floods per year that enter FZ3							
	H11	Flood greater than PD 1.3 magnitude							
	H12	Peak flow discharge							
	H13	Surface flow duration							
	H14	No surface flow onset							
	H15	No surface flow duration							
H16	Channel subsurface flow, dry								
Hydraulic indicators	Hy1	Height of max flood per year							
	Hy2	Length flow LT 0.3							
	Hy3	Length flow GT 0.3							
	Hy4	Average depth dry season							
	Hy5	Average depth wet season							
Scenario indicators	P1	Pollution							
	S1	Ratio fine to coarse							
	Sc1	Hectares of cultivated land							
	Sc2	Hectares of game farms							
	Sc3	Power produced by power plants							
Geomorphology	G1	Percent of fines (sand and smaller) on bed	H8	S1					
	G2	Width of low flow channel	H8	H12	S1	V2			
	G3	Low flow channel depth	H8	H12	S1				
	G4	Geomorphic pool depth	H8	H12	S1	V3			
	G5	Length of pools	H8	H12	V2				
	G6	Area of Flood Zone 1	G2						
	G7	Area of Flood Zone 2	G2	V3					
	G8	Area of Flood Zone 3	H12						
	G9	Number of low flow channels	S1	V2					
	G10	Geomorphic number of floods covering FZ3	G3						
Water Quality	WQ1	Conductivity (flowing state)	H3a	H3b	H10	H13	P1		
	WQ2	pH (flowing state)	H3a	H3b	H10	H13	P1		
	WQ3	Nutrients (flowing state)	H3a	H3b	H10	H13	P1		
	WQ5	Algae/ Chlorophyll a (flowing state)	H3a	H3b	H10	H13	P1		
	WQ6	Conductivity (isolated pools)	H3a	H3b	H10	H16	P1		
	WQ7	pH (isolated pools)	H3a	H3b	H10	H16	P1		
	WQ8	Nutrients (isolated pools)	H3a	H3b	H10	H16	P1		
	WQ10	Algae/ Chlorophyll a (isolated pools)	H3a	H3b	H10	H13	P1		
	WQ11	Microbiological pollution. E. Coli, cholera, etc.	H3a	H3b	H10	H13	P1		

Group	Code	Indicator	Links						
Vegetation	V1	Aquatic veg	H5	H6	H13	Hy5	WQ8		
	V2	Marginal veg	H2a	H12	H15	Hy5	S1		
	V3	Lower bank veg	H2a	H8	H15	S1			
	V4	Upper bank veg	H2a	H10	S1				
	V5	Floodplain veg (switched off at Site 4)	H2a	H2b	H8	H10	S1		
Macro-invertebrates	I1	Riffle / rapid families (incl. rocky interpools)	H5	H13	H14	H15	Hy5	Hy2	Hy3
	I2	Pool and open sandy beds families	H15	H16	Hy4	G1	WQ6	WQ10	
	I3	Aquatic and marginal vegetation families	WQ5	WQ10	V1	V2			
Fish	F1	Rapid/riffle-dwelling fish species	H5	H9	H13	H14	Hy4	G1	WQ5
	F2	Deep pool-dwelling species	H8	H15	Hy5	G1	WQ6	WQ10	V2
	F3	Shallow pool-dwelling species	H9	H15	Hy4	G7	WQ10	V1	V2
Socio-economics	SE1	Employment	Sc1	Sc2	Sc3				
	SE2	Household income	Sc1	Sc2	Sc3				
	SE3	Tourist numbers	Sc2	WQ11	Ecosystem integrity				
	SE4	Incidence of diarrhoea in under 5 yr olds	P1	WQ11					
	SE5	Pesticide poisoning	P1	Sc1	Ecosystem integrity				
	SE6	Impacts of floods and droughts	WQ5	WQ5	WQ11				

5.6 PHASE 6: Specialist studies

A multidisciplinary team of specialists (excluding the socio-economic and catchment geomorphology specialists) attended a weeklong fieldtrip on the Mokolo River from 26 April to 2 May 2010. They included specialists in surface and groundwater hydrology, soils, fluvial geomorphology, water quality and algae, vegetation, macro-invertebrates and fish. The team was instructed to collect data in their disciplines that would assist them with data for the specific indicators they chose and also in drawing Response Curves for each indicator and link. The data needed to be discipline specific and linked to flow and habitat available in the river. The socio-economic specialist also collected data using qualitative and quantitative methods during a separate fieldtrip in May 2010.

Data were collected at the five sites (Figure 46) chosen on the Mokolo River which was in flood during fieldwork and this hampered data collection.

Only a summary of the methods used and data collected will be presented here. A detailed account of the data collected and results are available in specialist reports (available on CD).

5.6.1 Activity 15: Collect data

At present, no formal method has been developed for the collection of data on non-perennial rivers in the different disciplines. As the Mokolo River is close to perennial it was possible for most specialists to use the methods designed for perennial rivers for data collection.

A summary of data collection methods for each discipline follows.

5.6.1.1 Surface and Groundwater Hydrology

Dr. Ingrid Dennis accompanied the team on the field trip where she collected basic surface and groundwater data to be used in conjunction with available data from the Intermediate Reserve (DWA, 2008) and the DWA for modelling the groundwater and surface water interaction in the catchment. This data were subsequently used by DHI in the MIKE SHE model setup (Chapter 6). Dr. Dennis

worked together with the soil scientists collecting data on basic soil structure, slope, catchment characteristics, depth, water quality and conductivity of groundwater. During discussions in the evening a conceptual understanding of the sites and catchment was discussed with input from other specialists on the team, in particular the vegetation specialist and fluvial geomorphologists.

5.6.1.2 Geomorphology

Two fluvial geomorphologists (Prof. Kate Rowntree and Bennie van der Waal) collected data at each site during the field trip in April 2010.

Data collection: One of the most important and useful activities during the fieldwork was producing a sketch map to indicate the location of channel banks, benches and zones within a 100-200 m length of channel. The various morphological features were named after consultation with other specialists, especially riparian vegetation, and the sketch maps were copied by the various other specialists so that they could indicate where their samples were taken. This facilitated communication between specialist groups. Sketching the maps was greatly assisted if a remotely sensed image from Google Earth or a Spot satellite image was available. A final map of the channel morphology was produced after comparing the surveyed transects to the features shown on the satellite images. The final maps created after the field visit was circulated to all team members.

A basic cross section was done using levelling and a survey staff. The survey was done across a section that would represent the general morphology of that section of river. In some cases two sections were surveyed. Because the flow in the channels was both fast and deep an inflatable boat was used to cross the channel. The current speed hampered the surveying because firstly it was difficult to remain in one position and secondly the current pushed the staff downstream at an angle. The most accurate readings were taken where it was possible to anchor the boat next to reed beds. The GPS readings would also have an error of up to 5 meters, even for a stationary position. Despite these difficulties the surveyed transects give a satisfactory picture of the dimensions, shape and complexity of the different channels.

Deep floodwaters covered and obscured the lower channel features hampering the identification of morphological features in the field.

Four morphological levels could be identified: the low flow channel and three flood zones – Flood Zones 1, 2 and 3. Following discussions with the vegetation specialist it was agreed that these were equivalent to the vegetation zones aquatic, marginal, lower and upper zone respectively (Table 28). In no cases could the channel bed be observed due to the high water depth. Its dimensions were assessed from the cross-section surveys and the bed material from probing the bed with the end of a survey staff. The distinguishing features of Flood Zone 1 were a sandy (or silty) substratum with a sparse or patchy cover of reeds. This zone often graded into a dense reed bed that was thought to line the edge of the low flow channel (in the aquatic vegetation zone). Flood Zone 2 was normally a narrow zone at the foot of the outer bank, raised slightly above Zone 1 and was thought to be equivalent to the lower flood zone (vegetation zone). In this zone grass replaced reeds as the prevalent vegetation. From the cross sections (see Results) these two zones are not so easily distinguished and may better be considered as one morphological zone. A lower Flood Zone 1 may have been located in the low flow channel, under deep water. Flood Zone 3 was identified as the area that would be covered by less frequent floods and was transitional to terrestrial vegetation, with a characteristic tree growth. Flood Zone 3 would conventionally be a floodplain or terrace separated from Flood Zone 2 by the outer channel bank. Where the channel was confined such a level feature could not be developed so Flood Zone 3 was considered to extend somewhat up the hillslope. In this case the upper height of Flood Zone was identified using flood debris from the recent April floods.

Table 28. Interpretation of geomorphological and vegetation zones

Geomorphic zone	Vegetation zone	Flood frequency, water availability and geomorphic process
Channel bed	Aquatic zone	Covered in water at low flows, main sediment transport zone during floods
Flood zone 1	Marginal zone	Covered in water during intermediate floods that would normally occur one or two times a year. High soil moisture status, but surface not saturated for long periods. Erosion or sediment deposition likely during floods.
Flood zone 2	Lower zone	Similar to marginal zone, but less likelihood of flooding and lower soil moisture status between flood events. Deposition may exceed erosion during floods.
Flood zone 3	Upper zone	Covered in water during flood events that have a frequency of 3 to 5 years. Floods deposit sediment and recharge deeper groundwater (+5 m?). Main root zone unsaturated except during flood events.

Sediment samples were collected from each exposed morphological feature including channel bed and banks and the three flood zones. Samples could not be collected from the low flow channel bed, but wherever possible samples were collected from in-channel bars. Particle size analysis was done using sieves to fractionate the sediment into coarse sand (2-0.5 mm), medium sand (0.5-0.25 mm) fine sand (0.25-0.063 mm) and silt and clay (0-0.063 mm). Sediment size was described using the d84, d50 and d16 particle sizes (particle size for which 84%, 50% and 16% of the sample is finer).

5.6.1.3 Water Quality and Algae

Dr. Linda Rossouw and Tascha Vos sampled the water quality and algae at the five sites on the Mokolo River.

Data collection: The sampling methods described in Rossouw and Vos (2008) were used.

In situ measurements were made and subsurface samples (1.5-2 litres) were taken from the shore and brought to the laboratory for further physical and chemical analysis. The samples were kept on ice and stored in a refrigerator ($\leq 5^{\circ}\text{C}$) until the analyses could be done in the laboratory.

The following procedure was used at each sampling site:

- The sampling point was located using a handheld GPS (Garmin:eTrex Vista Personal Navigator GPS) at the site where the samples were taken.
- The water quality observations and samples were taken before the fish or invertebrate sampling.
- The sampling bottles were marked with the date and sampling location.

The following information was recorded on the field data sheets:

- Name of the site and sampling point, the date, the time, the time of sampling, and the names of the samplers.
- Sampling point coordinates from the GPS reading and altitude.
- Water and weather condition observations at the site (for example cloudy or sunny, windy, water colour, sediment and algae, aquatic and other (reeds) plants or odours)
- Any other factors or conditions that may potentially influence the sample results.

Measurements taken: The water temperature ($^{\circ}\text{C}$), conductivity ($\mu\text{S}/\text{cm}$) and total dissolved salts (ppt or g/l), concentration of dissolved oxygen (mg/l), percentage of saturation ($\text{O}_2\%$) were measured with a YSI Model 85 oxygen, conductivity, salinity, temperature meter. These were done *in situ* from the shore. Conductivity serves as an indicator of the dissolved salts in the water. The probe of the instrument was calibrated as per the manufacturer's instructions (once per day). The probe was lowered into the water to just below the water surface, allowed to acclimate and the readings were taken and recorded on the field data sheet.

The above procedure was repeated for the pH and redox measurements *in situ* with a Euteck Instruments CyberScan pH 110 meter (pH/mV/°C/°F with RS232).

Subsurface samples: A number of subsurface water samples were collected. A marked 500 ml sampling bottle was lowered into the water to just below the water surface for the chemical analysis of the sample. All the samples were then stored in a cooler box with ice for transport to the laboratory. The samples were stored in a refrigerator ($\leq 5\text{-}0^{\circ}\text{C}$) until the analyses could be done in the laboratory.

The water that was used for chlorophyll-a analyses was filtered directly after taking the sample on site and stored in foil on ice until the laboratory was reached. Subsurface water to be used for algal composition assemblage (phytoplankton) identification was preserved using formaldehyde (2%).

Diatom samples were collected according to the method described in Taylor et al. (2005) and preserved with 90% alcohol.

5.6.1.4 Vegetation

Marthie Kemp with the help of Dr. Klaudia Schachtschneider collected data on vegetation at the five sites on the Mokolo River.

Data collection: Riparian vegetation was surveyed using the VEGRAI (Riparian Vegetation Response Assessment Index) method as explained by Kleynhans et al. (2007a). A transect that was characteristic of the vegetation of the site, was selected by the geomorphologist and the vegetation specialist. This transect would usually start at the upper bank of the riparian zone and cut across the lower- and marginal zones. At some sites, especially Sites 2 and 4, two transects were surveyed to familiarize the specialist with the variation in the vegetation, although only one data set was used for the purpose of this study. At each of the sites, the different vegetation zones were identified. A quick drawing of the terrain was made and a list of plant species captured on the prescribed VEGRAI field forms, for the different zones. All information needed to populate the VEGRAI model, were captured on site, e.g. possible impacts, exotic species, abundances, etc. When species were not known, a sample, e.g. a twig was cut off and preserved in a plant press for later identification in a herbarium. It is recommended that the vegetation sampling should not be limited to a specific transect but be extended to a surface area that would include all the dominant plant species that are characteristic of the area

5.6.1.5 Macro-invertebrates

Marie Watson sampled the macro-invertebrates at the five sites using the standard SASS5 method (Dickens and Graham, 2002) and the OKASS method (Dallas, 2009).

Data collection: The aim of sampling the Mokolo River was to collect data on the macro-invertebrate community composition at each site and then to investigate the link between the macro-invertebrates present and different flow and habitat types.

Two sampling methods were used namely the SASS5 method as well as the OKASS (Okavango Assessment System) method (Dallas, 2009).

SASS5 method: The current SASS5 (Dickens and Graham, 2002) method was used to determine the community composition as the Mokolo River is a semi-permanent to perennial river where most habitat types required by the SASS5 method are present most of the time. The SASS5 method was also used during the Intermediate Reserve and the River Health Program sampling of the Mokolo

River. This would then make it easier to compare results from all the sampling carried out on the Mokolo River.

OKASS method: A method by Dallas (2009) developed for the Okavango Wetland was tested on the Mokolo River. Dallas (2009) states that this method is in a development stage and needs further testing. It was not developed to be used in non-perennial rivers but as the method uses marginal vegetation (MV) as habitat type to sample and MV is usually available at most sites in non-perennial systems even when only pools are left, it was tested in this study. It must also be mentioned that the invertebrate sensitivity scores used in the method were specifically developed for the Okavango and are therefore not ideal for use in the Mokolo River. The habitat is sampled by one person for 2 minutes by sweeping the net through the vegetation. The sampling is divided into separate samples of approximately 30 seconds each to include all the different types of vegetation present at the site. The net is rinsed thoroughly to remove fine particulate matter and then tipped into a white sorting tray into which clean filtered water had been added. The net is checked for any organisms attached to it. The sample is then searched for approximately 30 minutes or 5 minutes after last new taxa was found. Taxa are identified to family level where possible. Taxa are recorded on a field data sheet and abundances are noted using a rating scale of 1=1, A=2-9 individuals, B=11-100, C=100-1000, D=1000 individuals. After all taxa have been recorded the tray is slowly emptied back into the river while constantly checking if any organisms are stuck to the bottom of the tray (Dallas, 2009).

Constraints during sampling: At the time of sampling (26 April to 2 May 2010) high flow was present at all sites and it was therefore difficult to sample. Access to the main channel was often not possible due either to the long stretch of floodplain which was inundated or the depth and high flow in the main channel which made SASS sampling near impossible. It is recommended as part of the SASS5 method that no samples should be taken during high flow. The only samples taken therefore were in the shallower, slower to no flowing backwaters and the shallow margins (marginal vegetation) in the main channel.

Data obtained during sampling is suspect as it cannot be regarded as representative of the community present at the site due to the fact that most invertebrates would have been washed downstream by the high flow and that the main channel of the river could not be sampled.

5.6.1.6 Fish

Marinda Avenant and Falko Buschke sampled the fish at five sites on the Mokolo River.

Data collection: The river experienced very high flows during 26 April to 1 May 2010, making effective sampling of the fish community very difficult. As a result most of the samples were taken in the flooded areas, which were more accessible than the fast flowing main channel.

A combination of three methods was applied depending on the habitat type and conditions to be sampled (see Table 29).

Table 29. A summary of the sampling methods and effort applied at the five sampling sites, EWR1 to 5, on the Mokolo River between April 27 and May 1st 2010

Sampling site	Electro-narcosis		Seine-net		Fyke-net	
	Sampling effort (min)	VD classes sampled	Sampling effort (hauls)	VD classes sampled	Sampling effort (min)	VD classes sampled
1	40	SD	4	SD		
2	8	SS	4	SD, SS	40	FD
3			4	SS	60	FD
4	64	SD, SS				
5			9	SD, SS		

Depth-velocity classes (VD) according to the definitions of Kleynhans, 1999a; SD=Slow-deep, SS=Slow-shallow, FD=Fast-deep, FS=Fast-shallow where slow flow in pools & backwaters <0.3 m/s and deep >50 cm.

Electro-narcosis: Electro-narcosis, conducting an electric current into the water, which immobilises the fish momentarily, was applied at the fast shallow, fast-deep, slow-shallow and, where possible, slow-deep habitats using a SAMUS 725G backpack-electroshocker. The duration of sampling was recorded at each sampling site in order to calculate the catch per unit effort (CPUE) and to ensure consistency during repetitive sampling. Sampling time depended on the number of habitats present at each site. Note: The low conductivity that prevailed at a number of the sites impeded on the effectiveness of the electro-shocker, making the additional use of seine- and fyke nets necessary.

Seine-netting: The deep slow-flowing pools at Sites 3 and 4 were sampled by means of a small seine-net. A seine net 2 m deep, 1.5 m high and 30 m long with mesh sizes of 16 mm for the wings and 5 mm for the sac was used with one seine sample consisting of three consecutive hauls. CPUE (catch per unit effort) values are based upon the average number of fish captured per seine net haul.

Fyke-net: The sampling effort was recorded as the number of minutes the fyke-net was set in the stream. CPUE was calculated as the number of fish sampled per minute the net was in place.

Measurements: Each fish specimen sampled was identified to species level with the aid of Skelton's (2001) keys, weighed and the fork length noted. Fish were returned to the river after notes were taken on their general health, as well as, the presence of anomalies and external parasites. When there was any doubt of identification the specimens were preserved in a 10% formalin solution and later identified in the laboratory. Sampling data for each sampling point were kept separate.

5.6.1.7 Socio-economics

The population of this study comprised the stakeholder groups that interact with the Mokolo River and included stakeholders from the commercial agricultural sector, the mining and power generation sectors, as well as individual users and development agencies working in the area. Individual farmers along the river, and farmers' associations represented the commercial agriculture sector. Exxaro mining company, the holding company for Grootegeluk Colliery, and Eskom as the energy corporation responsible for Matimba and Medupi power stations represented the mining and industry stakeholder group. Other stakeholders consulted included the Mogul Irrigation Board, as well as individuals residing in Lephalale and Vaalwater, key informants from the health care sector, the Limpopo Department of Health and Social Development and development agencies active in the area.

Data collection: Data were collected by using primary and secondary data collection techniques. Primary data are data that is collected through direct engagement with the population. In this study, primary data comprised mainly of descriptive and qualitative data collected through qualitative data collection methods.

The main method through which primary data were collected was key informant interviews with identified stakeholders. A purposive sampling method was employed in that the researcher selected key stakeholders from the community to provide information on people-ecosystem interactions with the Mokolo River. These stakeholders were selected based on a preliminary descriptive socio-economic analysis and stakeholder analysis of the catchment. Key informants were asked to refer the researcher to other possible stakeholders and key informants. Thus, snowball sampling was used to increase the number of informants that could be consulted in order to achieve the objectives of the study.

Key informant interviews are purpose-driven interviews in which the researcher is guided by a semi-structured interview schedule to gather information from people knowledgeable on the issues that are studied. In the case of this study, key informants had to be people that are living or working in the Mokolo River catchment and that are knowledgeable about the specific interactions between people and this river ecosystem.

To meet the objectives of the study, an unstructured interview schedule was compiled that aimed towards identifying issues and concern of stakeholders to inform the selection of indicators for inclusion in the testing of the methodology under study. While the literature on people ecosystem interactions as it relates to riverine ecosystems does not necessarily distinguish between interaction in perennial and non-perennial systems, there is sufficient literature available to be able to form a general list of possible issues to be raised with stakeholders. These include issues with assurance of water supply and the unpredictability of flow. Some issues such as water quality are not unique to non-perennial systems, but do constitute an important link in the interaction between people and river ecosystems.

Literature sources consulted included internet websites, journal articles, research reports for research institutions and government departments, annual reports from DWAF and Department of Environmental Affairs and Tourism (DEAT). Based on the literature, a checklist of issues and concerns were compiled and this guided interviews with key informants.

Due to a limited budget and time constraints, the focus was on gaining expert opinions from key informants rather than on being able to generate data that can be generalised to the wider population. In fact, in order to be able to generate reliable and valid quantitative data extrapolated to the larger population would entail that several community surveys among different stakeholder groups along the river be conducted. By triangulating the information obtained through key informant interviews with other available secondary data sources, an in-depth understanding of the interactions of people in the catchment with the river ecosystem can be gained and can guide further decision making with regards to determining and implementing the Ecological Reserve.

Field observations also comprised part of the socio-economic study. Through specifically observing the land use along the river, the information gathered from key informants can be corroborated and strengthened.

Secondary data were gathered in the form of population data obtained from Census statistics and other data banks, data on water use and requirements, and data on the socio-economic well-being from various data sources, among other Statistics South Africa, the South Africa Institute, the Health Systems Trust and relevant government departments. The socio-economic data are enhanced by tracking the economic activities along the Mokolo River with the aid of land use maps.

The study unfolded in the following steps:

- A **literature review** on people-ecosystem interactions in river systems was undertaken, with a specific focus on non-perennial rivers.
- A **stakeholder analysis** where initial stakeholders were identified through a literature and internet search.
- **Stakeholders were contacted** telephonically, explaining the purpose of the study and the need to gather data through key informant interviews with stakeholders to achieve the objectives of the study. Face-to-face interviews were arranged with key stakeholders.
- A **field visit** was conducted from 16-19 May 2010 in which key stakeholders were met and interviewed. Field observations were made while in the area.
- **Follow up interviews** were conducted telephonically and contact with stakeholders was continuous for the duration of the study.
- **Secondary data were** gathered in addition to the above primary data, the study also relied on secondary data in the form of population and economic data obtained from Census 2001; the 2007 Household Survey; the South African Institute of Race Relations; the Health Systems Trust. Data gathered in this way is demarcated according to District and Local Municipalities. With the aid of municipal demarcation maps and catchment boundary maps, data were calculated in terms of the proportion or percentage of local municipalities that fell into the specific catchments.

5.6.2 Ecological functioning of Mokolo River (results from fieldwork)

5.6.2.1 General

To simplify the final report on the Mokolo River the complete specialist reports (see Table 30) are made available on compact disc (CD) and include a literature study, methods use and results that include field work results as well as results of the scenario DSS analysis for the specific discipline.

Table 30. List of supporting and specialist reports available on accompanying CD

Reports	Authors	Included on CD
Supporting reports		
Macroreach analysis	Prof. Kate Rowntree and Bennie van der Waal	X
Runoff Potential Unit	Dr. Charles Barker	X
Evaluation of Discharge records	Ewald Steyn	X
Geology Report	Surina Esterhuysen	X
Specialist Reports		
Groundwater Surface Water Interaction Modelling	Dr. Bob Prucha and Douglas Graham	X
Desktop Surface hydrology	Dr. Ingrid Dennis	X
Desktop Groundwater hydrology	Dr. Ingrid Dennis	X
Geomorphology	Prof. Kate Rowntree and Bennie van der Waal	X
Water quality and Algae	Dr. Linda Rossouw and Tascha Vos	X
Soil	Prof. Pieter le Roux, Prof. Leon van Rensburg and Dr. Johan van Tol	
Vegetation	Marthie Kemp	X
Macro-invertebrates	Marie Watson	X
Fish	Marinda Avenant	X
Socio-economics	Dr. Nola Redelinghuys	X

A summary of the general understanding of the ecological functioning of the Mokolo River and related catchment is provided below. For detailed results please see specialist reports on CD.

5.6.2.2 Geomorphology

The Mokolo is an intermittent river subject to periods of high flow when heavy rains fall on a saturated catchment as was observed during the field visit. The predominance of sandy soils throughout the

catchment is likely to moderate the impact of extreme events and accentuate the importance of groundwater in sustaining low flows. It seems likely that low flows have been augmented by irrigation return flow, which probably carries a significant nutrient load. These enhanced low flows and the lack of flash floods will have important effects on channel processes as described below.

The geology of the catchment is dominated by sandstones in the upper and middle catchment and by quaternary alluvium in the lower catchment. Sandstone hills give rise to steep topography and confined channels in the upper and middle catchment, but the upper-middle catchment is characterised by a basin with low to moderate slopes on either side of the river. Site 1 is located in this basin, Site 2, 3 and 4 lie in the more confined sections downstream. Site 5 is located in the much flatter more open area with quaternary alluvium. The long profile is subdivided into three broad sections, the steep headwaters above the study area, the moderately steep section above the Mokolo Dam and the lower gradient section below the dam. The dam thus marks a boundary between river types as well as providing a major longitudinal discontinuity.

The predominantly sandstone geology results in a bedload of fine to coarse sand and a low silt-clay suspended load. The water at the time of the field visit had a low turbidity despite the high flow levels. Sandy bedload therefore dominates the sediment load. There was no evidence of coarse gravels or cobble at any of the sites, but bedrock probably outcrops in the steeper sections.

The main impacts on geomorphological processes are thought to be weirs and reed encroachment due to increased nutrient-rich base flow at the sites above the dam and the dam itself at sites below it. Weirs will trap sediment in long pools upstream. In the upper sites (1 and 2) reed encroachment stabilises sand bars and creates narrow deeper channels between reed clumps with high velocities at high flow. In contrast at the lower sites (4 and 5) lines of dense reeds often marked deeper water, presumably because reeds colonise low points where water availability is greater.

It is thought that the Mokolo responds to floods in a manner more similar to equilibrium perennial rivers rather than disequilibrium non-perennial rivers due to the stabilizing effect of reeds. In the lower reaches where there is greater exposure of sand on the river bed, there is significant channel mobility within the confines of the macro-channel, but the overall channel form is probably relatively stable. Frequent floods ($RI=1.5$) of relatively low magnitude are probably dominant in determining channel form. These floods are those that tend to be most impacted by impoundments such as the Mokolo Dam. None the less, extreme floods, less impacted by the dam, will be important in periodically scouring out the bed, inhibiting reed encroachment and maintaining a wide channel.

5.6.2.3 Water quality

The water quality of the Mokolo River in terms of electrical conductivity (EC) or total dissolved salts (TDS) is good. This was also confirmed in the Intermediate Reserve document of the DWA (2008a). The slightly higher EC value at Site 1 could be attributed to higher irrigation land use than in the downstream areas. The nutrients are also slightly higher and this could be due to fertiliser being used on the irrigated lands. However, one should be careful of placing any confidence in this data set as the samples were taken during flood conditions and the higher than “normal” turbidity readings could be expected.

5.6.2.4 Vegetation

The Mokolo River Catchment is characterised by Savanna Biome, with only small patches classified as part of the Grassland Biome. Seven vegetation units are present in the catchment, with only three major vegetation types bordering the Mokolo River. The species composition present at the five sites was expected if one considers the broad descriptions of the vegetation types present.

The Mokolo River is a semi-permanent river and it is confirmed by the high cover and abundance scores of the riparian vegetation. Since the Mokolo is situated in the Savanna Biome, the abundance of trees will have a major role to play in the hydrology of the catchment. The rich tree diversity in the riparian zone is most likely sustained by baseflow in the dry season.

5.6.2.5 Macro-invertebrates

The Mokolo River has a perennial river macro-invertebrate fauna as a variety of habitat types are present at most of the sites. A total of 25 of the 71 expected families were sampled at the five sites in the Mokolo River from 26 April to 2 May 2010. The few families sampled during the field trip could be attributed to the flood conditions in the river. Most of the macro-invertebrates would be washed downstream and only those which had moved onto the floodplain or which could persist during high flow were sampled. Many terrestrial insects (especially spiders) were also present in the samples.

The species/family richness decreased downstream with 11 families sampled at Site 1 and only 8 at Site 5 and the decrease in families downstream was also found in the Intermediate Reserve Study (DWA, 2008a). The sites downstream of the Mokolo Dam (specifically Site 5) do not have a large diversity of habitat and flow types available for macro-invertebrates and this explains the lower family richness at this site. There does appear to be a slow shift in the community composition of macro-invertebrates as fewer individuals of families (i.e. Perlidae) that prefer fast flow have been recorded in recent studies (DWA, 2008a).

5.6.2.6 Fish

The Mokolo River hosts a relatively species rich fish assemblage comprising of 32 species. Although there is concern that the three migrating eel species might no longer occur in the system due to a reduction in surface water connectivity and river regulation, only one fish species, *Barbus brevipinnis*, is listed as “vulnerable” in the IUCN Red Data List (Skelton, 2001). The fish community can, broadly, be divided into two sub-communities: the fish species associated with upper and lower foothill geomorphological zones upstream of Mokolo Dam and the assemblage of species associated with the lowland river geomorphological zone downstream of the dam. The upper and lower foothill community include a number of sensitive and rheophilic fish species (e.g. the common mountain catfish *Ampilius uranoscopus* and the shortspine suckerfish *Chiloglanis pretoriae*), whereas the lowland river community are dominated by species associated with slow-deep and slow-shallow habitats, lacking flow intolerant species.

A total of 229 fish specimens, representing 13 species, have been recorded during field sampling. The flood conditions at the time of the field survey hampered fish sampling to such an extent that sampling was mostly confined to the flooded and slow-flowing areas. As a result, most of the recorded fish species are pool and floodplain species that are strongly associated with slow-flowing waters and aquatic vegetation.

Aplocheilichthys johnstoni (Johnston’s topminnow) was the most widespread species and the only species to be recorded at all the sampling sites. It was also the most abundant species, contributing nearly 50% to total abundance. Other widespread species were the two cichlids, *Tilapia sparrmanii* and *T. rendalli*, the characid *Micralestes acutidens* and the cyprinid *Barbus paludinosus*. *M. acutidens* and *T. sparrmanii* were the second and third most abundant species, respectively contributing 18% and 13% to the total number of fish caught. Specimens from the families Cichlidae and Cyprinidae dominated the fish sample, together contributing eleven of the thirteen species recorded.

5.6.3 Activity 16: Determine the PES for each discipline

The PES is used in the scenario evaluation to indicate the change at the EWR site from the present to the state expected under that particular scenario. The PES for each of the disciplines has to be determined before the scenario workshop. No formal method to determine the PES for the different disciplines has been developed for non-perennial rivers at present. Most of the non-perennial rivers have little to no historical data and it is virtually impossible to determine a reference (natural) condition with any confidence. Most of the current methods used to determine PES rely strongly if not completely on a comparison of observed data and expected data (reference data). As the reference condition cannot usually be defined for a non-perennial river, there is no high confidence PES method for such rivers and specialists therefore need to use expert opinion supported by collected field data and historical records (if available) to provide a PES category. Explanations and motivation for the PES category decided on has to be included by each specialist (Seaman et al., 2010).

See Table 7 for an explanation of the PES categories used.

Each of the specialists used the available perennial methods to determine the PES for their discipline and adapted or modified as needed for use in the Mokolo River.

5.6.3.1 Geomorphology:

Method: The present ecological state (PES) was assessed using the Geomorphological Assessment Index (GAI) (Du Preez and Rowntree, 2006). GAI assesses changes to the key geomorphological drivers: connectivity, catchment sediment yield and perimeter resistance. Channel morphology was described by means of sketch maps at each site that showed the location of channel banks, benches and channels within a 100-200 m length of channel. Four morphological levels were identified after consultation with ecological specialists: the low flow channel and three flood zones – Flood Zones 1, 2 and 3. Following discussions with the vegetation specialist it was agreed that these were equivalent to the vegetation zones aquatic, marginal, lower and upper zone respectively (Table 28).

Results: Based on field observations the PES of the five sites was assessed using the GAI model described by Du Preez and Rowntree (2006). The PES rating for the five sites is given in Table 31. Significant changes from natural are indicated, based on a score of 1 (change has small or localized impact on ecosystem function) to 5 (change has severe impact on ecosystem function).

Table 31. Geomorphology PES scores for the Mokolo sites based on GAI assessments

Site	Rating	Justification
1	C (75%)	Numerous farm dams in catchment, moderate erosion in catchment but gentle slopes reduces sediment transfer to channel, dirt roads noted as a possible source of any increase in sediment. Without historic information difficult to judge changes to stabilizing effects of marginal and riparian vegetation but irrigation return flows and heightened nutrient levels assumed to have caused a large increase in reed growth in channel.
2	C (70%)	Weirs within the macro-reach negatively affect longitudinal connectivity (impact 2); Roads in the catchment cause a small increase in connectivity between the channel and hillslopes; A small to moderate increase in sediment inputs was assumed due to catchment land use and roads (impact 1.5), and a large increase in the stabilizing effect of reed growth due to nutrient rich return.
3	B (84%)	This site was in a game farm with natural vegetation. Roads in the steep landscape were the major observed local catchment impact, increasing hillslope-channel connectivity and providing a source of sediment (impact 1.5). Upstream weirs in upstream macro-reaches would continue to have a small impact on longitudinal connectivity.
4	B/C (80%)	Large upstream dam (impact 3.5). Moderate increase in reed growth assumed. (impact 1)
5	C (74%)	Upstream dam (impact 3), gravel extraction (impact 3); local channel diversion (impact 1)

5.6.3.2 Water Quality

The format (PAI) as presented in DWA (2008a) was followed in presenting the determination of the Present Ecological State (PES) for water quality.

The sampling sites selected correspond with some of the EWR sites in DWA, 2008a and the results presented in that report were used and not recalculated here.

The following sites were used:

EWR 1A is similar to our Site 2, EWR 2 is similar to our Site 3 and EWR 4 is similar to our Site 4. Where additional data (temperature, oxygen and turbidity) were available these were added to the tables. It is important to note that the added data were a once off sampling event and not at the same time as the other data. The data were used as an indicator of the possible range in which these variables occur.

Site 1 and 5 had very few water quality data and the default format was also used to describe these two sites, however the confidence of the data at these two sites is much lower than that of the other three sites. Site 5 is expected to be very similar to Site 4 and data from Site 4 was then used at Site 5.

Results: The PES for water quality at five sites studied is presented in Table 32.

Table 32. Water Quality PES scores for the Mokolo sites based on PAI assessments

Site	Rating	Justification
1	B/C	Elevated nutrient and electrical conductivity measurements probably due to current land use activities (irrigation). If irrigation stays the same than that of the present conditions, there should be no increase or decrease in EC or nutrient concentrations and if there is a decrease in irrigation activities there may be a decrease in EC and nutrient values. Turbidity levels expected to be slightly elevated due to flood condition during sampling at all the sites.
2	B/C	Present day flows follow more or less the same pattern as natural flows, although zero flows are now sometimes experienced. Land use also influences the water quality.
3	B	Present day flows follow the same pattern as natural flows, although zero flows are now experienced. Land use is mostly game farming and will impact less on the water quality than irrigation and towns.
4	B	The site is below the Mokolo Dam and consistent variability over time is dependent on dam operations. Land use is mostly game farming and will impact less on the water quality than irrigation and towns.
Site	Rating	Justification
5	B/C	Consistent variability over time dependent on dam operations still impacting this site, either too much or too little water released downstream. Land use is mostly game farming and will impact less on the water quality than irrigation and towns.

5.6.3.3 Vegetation

The VEGRAI method was used to determine the PES for the vegetation at five sites on the Mokolo River.

The results are presented in Table 33. According to the VEGRAI assessment the Mokolo River can be classified as an A/B category river.

Table 33. Vegetation PES of the 5 sites in the Mokolo River based on a VEGRAI assessment

Site	Ecological Category	Average confidence	Justification
1	A/B	2.3	This site was in a very good condition and confirms the result of the data analysis.
2	C	3.6	I do not agree with the classification. I would describe the site as a low category B. There were more disturbances at this site than at the other 4 sites, as well as some exotics like <i>Eucalyptus</i> sp. in the area, but the site is

Site	Ecological Category	Average confidence	Justification
			not as deteriorated as a C category would be.
3	A/B	3.7	This site was in a very good condition and confirms the result of the data analysis.
4	A/B	4.1	This site was in a very good condition and confirms the result of the data analysis.
5	Not sampled A/B	-	Although the site could not be sampled, the researcher feels that the site would also be in an A/B category. The surrounding environment was in a good condition and no obvious impacts could be identified.

Constraints experienced when using VEGRAI:

- Not all of the zones are catered for in the excel based model. Only the marginal, lower and upper zones are included in the model. No provision is made for additional zones, e.g. aquatic zone, flood plain zone. The data collected for the additional zone could not be included in the model and the data set is incomplete.
- When populating the model, the species composition for indicator species needs to add up to 100%. At some sites the species composition did not add up to 100%.
- In some cases there are no indicator species that are sensitive enough to detect change. This goes for both woody and non-woody components.
- At site 3, a tree was indicated as “species x” in the spreadsheet since there were no trees in the marginal zone. For the model to compute, a tree species had to be indicated. The metric could not be switched off. The results are therefore compromised.

5.6.3.4 Macro-invertebrates

The data collected during 26 April to 2 May 2010 was used to determine the SASS (Dickens and Graham, 2002), Average Score per Taxon (ASPT; Dickens and Graham, 2002), Index of Biotic Integrity (IBI; Dallas, 2009), OKASS (Dallas, 2009) and MIRAI (Thirion, 2008) scores. The Mokolo River was in flood at the time of sampling and no sampling should have been carried out in these circumstances. Data from other studies (Table 34) were also used to determine the final PES categories.

Table 34. Macro-invertebrate PES for Mokolo River sites determined using different methods and data

Sites	I. April 2010 data using Dallas (2007) interpretation guidelines	II. April 2010 data using IBI score Dallas, (2009)	III. April 2010 data using OKASS score Dallas, (2009)	IV. April 2010 data using MIRAI (Thirion, 2008)	V. Intermediate Reserve data (DWA, 2008a, Data from Thirion and Uys)	VI. River Health Programme data from (Angliss, 2002)	VII. Angliss (2002), survey of Mogol and Nzhelele Rivers
1	E/F	B	C	D		C	
2	E/F	A	A	D	B/C	A	A
3	E/F	C	C	D	C	B	A
4	E/F	B	C	D	C		
5	E/F	B	C			C	C

A=Excellent, B=Good, C=Fair, D=Poor, E/F=very poor.

Explanation for Table 34:

I: Using SASS interpretation guidelines (Dallas, 2007) for the ecoregions in which the sites were situated. An ecological category was determined using the SASS scores obtained from the fieldwork carried out in April and May 2010. (NB: It must be remembered that the samples were taken during

flood conditions. Dallas (1995) and Chutter (1994) warn that SASS is not reliable when used in these conditions).

II. and III: Using two methods (IBI and OKASS) developed by Dallas (2009) on the Okavango to determine the ecological category of data collected during fieldwork in April and May 2010 on the Mokolo River. The highest results from Marginal vegetation in and out of current were accepted as the category for the site. It must be remembered that the methods were developed for use in wetlands (in particular the Okavango) and not for use in rivers in flood conditions.

IV: The MIRAI score (see Thirion, 2008) was determined using data from the fieldwork done in April and May 2010. It must however be remembered that the river was in flood and therefore the results are suspect as sampling is not supposed to be carried out in flood conditions. The reference list of taxa was setup by using the data provided by Thirion (pers. comm.) from the Macro-invertebrate Frequency of Occurrence database (data were selected by using sites close to and in the same ecoregion and geomorphological zone as the site sampled). If no data were available in this database then data from a study by Angliss in 2002 was used as well as data from the Intermediate Reserve completed in 2008. Reference lists taken at Site 1 from A4MOKO-TWEEF and A4MOKO-ALMAB; site 2 from EWR1A AND EWR1B as well as A4MOKO-VAALW, A4MOKO-GROEN; Site 3 from EWR2, A4MOKO-MOKOL, A4MOKO-ABDAM and site 4 from EWR4 and A4MOKO-BEDAM. No MIRAI was completed for EWR5 as no reference list could be determined from existing data.

V: Data collected by Thirion and Uys as part of the Intermediate Reserve Study (DWA, 2008a) was used.

VI: Data from Angliss in the River Health Database (DWA, 2010a) was used.

VII: Data from a study by Angliss (2002) was used.

Final PES determination: Where data from the Intermediate Reserve (DWA, 2008a) was available for a site the PES that was obtained during the Intermediate Reserve was accepted as the Present Ecological Category (PES) for this study. At the other sites (where no Intermediate Reserve Site was in close proximity) the RHP results (Angliss, 2002) were used to decide on a PES for this study (Table 35). Information on the present developments at the site was also considered.

Sites 1, 3, 4 and 5 were in a fair (C) present ecological state and site 2 was in a good to fair category. Similar results to those in the Intermediate Reserve (DWA, 2008a) were obtained when using the OKASS (Dallas, 2009) method, which is an indication that this method could possibly be adjusted for use in non-perennial rivers.

Table 35. Macro-invertebrate PES determined for sites 2, 3 and 4 (using data from Thirion and Uys as part of the Intermediate Reserve (DWA, 2008a)) and sites 1 and 5 (using the highest score at the sites from Rivers database (DWA, 2010a) and data from Angliss (2002))

Site	Ecological Category	Justification
1	C	River has changed from a perennial to non-perennial which would result in a decrease in abundance of some sensitive invertebrate families which prefer high flow and good water quality. The change in available habitat would also impact in invertebrate presence.
2	B/C	Impact of the town Vaalwater on water quality at site as well as a change in flow pattern have resulted in some sensitive invertebrate families (Perlidae), being absent or only present in low abundance at the site
3	C	A change in flow pattern and resultant habitat change has resulted in some sensitive invertebrate families (Philopotamidae, Elmidae, Tricorythidae, etc.), being absent or only present in low abundance at the site
4	C	Flow alteration downstream of Mokolo Dam as well as sandmining have an influence on abundance and presence of sensitive invertebrates
5	C	Flow alteration downstream of Mokolo Dam as well as sandmining have an influence on abundance and presence of sensitive invertebrates

5.6.3.5 Fish

The present ecological state of the fish communities in the respective river sections was determined by means of the Fish Response Assessment Index (FRAI) of Kleynhans (2007). The assessment was mainly based on fish data collected during a field survey of the Mokolo River from 27 April to 1 May 2010. The river was, unfortunately, in flood at the time, hindering effective sampling.

Method: In an attempt to compensate for the poor sampling results obtained, two PES scores were calculated for Sites 1 to 5: the first (PES1) where only data from this survey were used and the second (PES2) where data from other recent surveys were included by means of compiling a derived list of observed fish species.

Results: The PES based on the observed fish species (PES 1) was very low for all the sites, varying between 8.6% (Site 2) and 44.3% (Site 4; see Table 36). The poor PES scores are mainly the result of the low number of species recorded during fish sampling. The high flows experienced at the sites during the period of sampling, greatly reduced species richness and fish abundance in that the sampling methods were less effective in the fast-flowing conditions. Fish sampling was, therefore, mainly limited to the slow-flowing flooded areas with submerged vegetation. As a result, the PES scores based on the observed fish species are considered to underestimate the ecological integrity of the fish communities.

The PES scores based on the derived species lists (PES 2) are between 17% and 60% higher than those based on the observed species (Table 36). The PES categories were fairly consistent throughout the catchment, varying between a Category B/C (Site 3) and a Category C/D (for Site 4). This implies that, based on the fish community, the river is considered to be moderately modified. Although some loss and change of the natural habitat and biota are evident, ecosystem function is still predominantly unchanged (Louw et al., 2005). The impact of the Mokolo Dam was, however, evident in the slightly lower PES scores recorded for the downstream river sections.

Table 36. A summary of the Present Ecological State (PES) of the fish communities occurring in the various river sections represented by EWR1 to 5

Present Ecological State (PES)	Site 1	Site 2	Site 3	Site 4	Site 5
<i>Level Ecoregion II</i>	7.02	6.02	6.02	6.01	1.03
<i>Combined Response Unit</i>	B	D	E	G	H
PES 1 (Observed species)	29.4%	8.6%	21.8%	44.3%	29.6%
PES Category	E	F	E/F	D	E
PES 2 (Derived species)	69.3%	69.2%	78.9%	61.3%	63.3%
PES Category	C	C	B/C	C/D	C

Present Ecological State (PES)	Site 1	Site 2	Site 3	Site 4	Site 5
Justification	Flow modification and regulation (water abstraction, weirs, bridges and dams situated upstream of site) resulting in a loss of fast-deep and fast-shallow habitats. Instream structures also act as barrier to migration. The presence of alien fish species in this river reach, the predatory largemouth bass and the common carp, have a detrimental effect of natural fish community.	Flow modification and regulation (weirs, abstraction upstream of site) resulting in a reduction of fast-flowing habitats. Instream structures also act as barrier to migration. Presence of exotic predatory species (largemouth bass) expected to have detrimental effect on the diversity of natural fish community.	Evidence of flow manipulation in river reach. This could impact habitat suitability and availability. The presence of instream structures acting as barriers to migration. Two eel species possibly lost from this section of the river (Kotze, 2008). The presence of two exotic fish species (largemouth bass and common carp) could reduce species diversity in reach.	Flow modification and regulation due to the presence of Mokolo Dam upstream of site. Reduction in habitat availability and diversity, especially fast-flowing habitats. Barriers to instream migration present.	Flow regulation due to water releases for farming community. Presence of instream structures (road bridges and farm dams) acting as barriers to migratory fish. Reed encroachment on river banks (RHP, 2006).

5.6.3.6 Summary of PES determination for five sites on the Mokolo River

The PES for each discipline at five sites on the Mokolo River is summarised in Table 37. The PES determined by each specialist was used in the DRIFT-Arid DSS to indicate the present day PES so that the change from present day could be determined for the different scenarios chosen.

Table 37. Overall PES for five sites on the Mokolo River

Sites	1	2	3	4	5
Geomorphology	C	C	B	C	C
Water Quality	B/C	B/C	B	B	B/C
Vegetation	A/B	C	A/B	A/B	A/B
Macro-invertebrates	C	B/C	C	C	C
Fish	C	C	B/C	C/D	C

5.7 PHASE 7: Selection of scenarios and hydrological simulation of scenarios and data capture

5.7.1 Activity 18: Choose scenarios

The method used to choose scenarios is set out in Section 4.1.7, Activity 18.

During the fieldwork specialists as well as the socio-economic specialist interviewed stakeholders such as farmers, farm workers, irrigation boards, water boards, agricultural societies, government departments and businesses in the catchment. All future or planned activities were noted and the team then used this information to decide on scenarios for the project.

The team, using the socio-economic, historic and recent data (mostly from DWA reports) on the Mokolo River catchment, decided on five possible scenarios namely:

- Scenario 1(PD) Present Day
- Scenario 2 (Natural) Natural
- Scenario 3 (Game Farming) Sites 1-3: Agriculture converted to game farms
Sites 4-5: No further development
- Scenario 4 (ExtWater) Sites 1-3: No further development
Sites 4-5: Power, mining and interbasin transfer expansion
- Scenario 5 (Combined) All of the changes
(i.e. agriculture to game farm sites 1-3, mining, etc. expansions sites 4-5).

As this project is to test a prototype method and not an actual EWR study no formal consultation with the DWA and stakeholders was done to confirm chosen scenarios.

5.7.1.1 Scenario assumptions:

5.7.1.1.1 Scenario 1: Present Day (PD)

Detailed climate data were available for the Mokolo Catchment from 1950-2000. Flow data were also available for some of the gauging stations for the same period. Data from 1950-2000 was therefore used to simulate the hydrology for the PD scenario. Note that the PD consists of PD infrastructure (e.g. Mokolo Dam and 31 structures including 25 dams (effectively dams across rivers) and 6 weirs. Six of these structures are located downstream of the Mokolo Dam. Of these 6 structures, three are weirs at stream gauges (1 on the Mokolo, just downstream of the Mokolo Dam, and 1 each on Tambotie and Poer-se-Loop tributaries) modelled with the last 50 years of climate data, making the scenarios comparable. Other weirs evident on Google were not included as data were unavailable for them.

5.7.1.1.2 Scenario 2: Natural

The same 50 years were simulated for this scenario. In this instance however, a natural stream profile was estimated through the existing Mokolo Dam based on the upstream and downstream profile. All flow upstream of the Mokolo Dam was routed downstream to the outlet of the Mokolo River (through gauge A4H014). No farm dams, no irrigation, no interbasin transfers and no weirs were included in this scenario.

5.7.1.1.3 Scenario 3: Game farming

The same 50 years of data and infrastructure were used as for the PD scenario. No interbasin transfer was included and vegetation was changed from irrigated to near-natural vegetation upstream of the Mokolo Dam as this is the area which would probably change from agriculture to game farming in future. No change in development was assumed for downstream of the Mokolo Dam.

5.7.1.1.4 Scenario 4: External Water (ExtWater)

The same 50 years of data and infrastructure were used as for the PD scenario, with the addition of the interbasin transfer from the Crocodile River into the Mokolo Basin. No change in development was assumed for upstream of the Mokolo Dam. The interbasin transfer was made to support expansion of the Exxaro mine, Eskom Powerplants (Medupi and Matimba) and Lephalale town water supply. Water was applied in these scenarios using the irrigation module as if the water would be used for irrigation and no water was released back into the Mokolo River after use. The only information provided for this scenario was an estimate of the future amount of water required by the mine; the power plant and the town expansion. No vegetation change was made from the PD vegetation.

5.7.1.1.5 Scenario 5: Combined

The same 50 years of data and infrastructure were used as for the PD scenario, with the addition of the interbasin transfer of Scenario 4. The same change from irrigation to game farming as Scenario 3 was included. Therefore Scenario 5 is a combination of Scenarios 3 and 4.

A hydrological model was now used to simulate a daily time series of flow for each of the scenarios chosen. The integration between surface and groundwater is complex and it is therefore important to develop a common conceptual understanding of the main processes involved in driving the system and for this geohydrologists and hydrologists needed to work together.

It is recommended that the following aspects be included when the hydrology of the chosen scenarios is simulated namely:

- A daily model and not a monthly model should be used.
- A hydrologist and geo-hydrologist with extensive experience in working in non-perennial rivers be included in the team.
- An integrated surface and groundwater model be used.
- The variability of flow and climate in non-perennial river catchment should be taken into account when data are interpreted.

Hydrological Simulation of Scenarios:

The hydrological simulation to produce a daily time series for the scenarios chosen in the Mokolo River was completed using the MIKE SHE integrated groundwater and surface water model. The process started with the PD (baseline) scenario. The daily time series of data provided to the team included data on the river discharge, river stage, depth to groundwater beneath river, baseflow to river and subsurface flow beneath river.

Chapter 6 will elaborate on why the MIKE SHE model was chosen, the initial calibration of the model, conceptualisation and results.

6 PHASE 7 (ACTIVITY 19): HYDROLOGICAL SIMULATION OF SCENARIOS USING GROUNDWATER/SURFACE WATER INTERACTION MODELLING

6.1 Background

One of the main requirements of the method developed for non-perennial rivers was that it should include an integrated groundwater and surface water hydrological model to produce a daily time series of data for each of the chosen scenarios that could be used to determine the values (median, etc.) for each of the hydrologic and hydraulic indicators chosen by the team.

After consultation with prominent hydrologists in South Africa and abroad and input from the project steering committee (see section 1.3.3) the team decided to consider using the MIKE SHE model to simulate the hydrology for the scenarios.

The main criticism against the use of the MIKE SHE code is that it is data intensive and that only experienced modellers are able to run the model. While it is true that codes like MIKE SHE requires an investment in learning how to setup and run the model and interpret outputs, there are significant returns on the investment (i.e. one tool can be used to evaluate very simple problems to very complex problems that other codes simply can't address). The model is also only as data intensive as the modeller wants to make it. In other words a relatively simple model can be setup that includes surface topography, stream drainages, a simple soil type, and a simplified subsurface geologic configuration (i.e. a single layer) and can then produce results that are more meaningful than using an overly-simplified 'lumped' or 'conceptual' approach, which doesn't simulate the distributed physical movement of water within different processes (i.e. providing no detail of how the water flows within each catchment). Using a single integrated code helps with the integration of the surface and groundwater output even if only a simple integrated model is developed (i.e. not data intensive). An approach that would be possible is to first develop a simple, non-data intensive integrated model (MIKE LIGHT) using easily obtainable data and then to increase complexity if and where needed.

Another criticism often expressed against the MIKE SHE code is that it is developed from a hydrological point of view to model hydrological processes on a catchment scale and the aquifer is considered unconfined and discretized as one simple layer. In other words, while the software provides a comprehensive hydrological package for catchments, they are not able to model three dimensional groundwater flows, as detailed for other packages. The current MIKE SHE release also cannot accurately model complex South African aquifers, which are often semi-confined or confined within the catchment. It however provides a comprehensive and promising approach to catchment hydrology, and its applicability should be tested on catchments of different complexities. Currently a MIKE SHE model is being setup and tested in Africa where the catchment used has multiple confined layers. The concept of aquifer confinement in the particular catchment is illustrated in Figure 47. The confinement occurs because of a low permeability formation (i.e. a clay layer) shown as a grey layer in Figure 47.

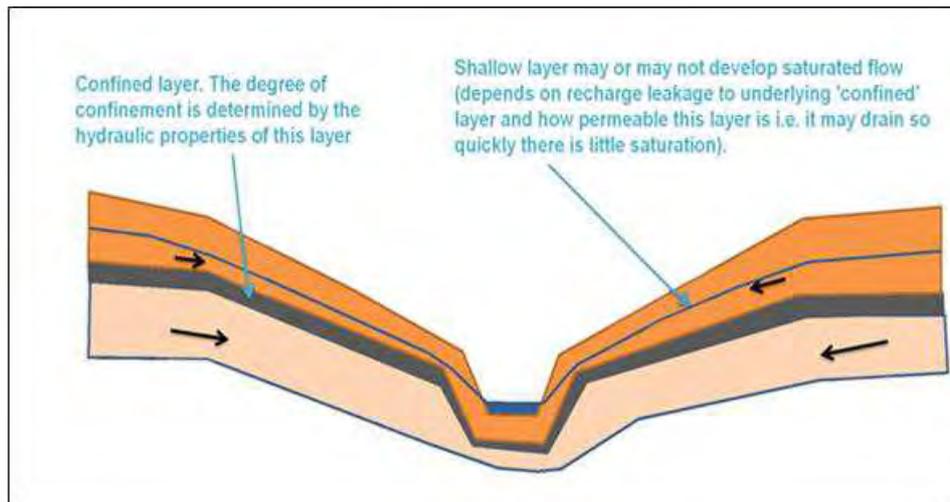


Figure 47. An illustration of aquifer confinement

This acts to limit the flow between the upper aquifer (orange) and the lower aquifer (tan). Confinement rarely reduces flows between two aquifer units 100% as they often leak. In fact the leakage is directly related to the hydraulic properties of the confining layer (grey color), or how permeable it is. The shallow upper aquifer (orange) is something found in all subsurface systems and the degree to which it actually represents a saturated aquifer system depends on the rate of infiltration from precipitation, leakage through the confining unit, and the lateral drainage within the unit which is controlled by its permeability. By definition this layer is unconfined because it is open to the atmosphere and accepts infiltrating rainfall. Some systems can have very low permeability at the surface (i.e. rock outcrops), but they still have some capacity to accept infiltrating precipitation. MIKE SHE is capable of simulating both unconfined and confined conditions with as much flexibility as other most widely used groundwater flow codes (i.e. Modflow2000).

Considering the limitations as well as the positive aspects of the MIKE SHE model, and the complexity in running the model the team decided to use the MIKE SHE model ((Graham and Butts, 2005) developed by DHI (www.dhigroup.com) and to employ specialists from DHI to run a fully integrated, hydrologic, surface and groundwater flow model of the Mokolo River catchment (see Figure 14).

The basic structure of the hydrological simulation project involved:

- **Tasks 1 and 2** – the characterization and conceptualization of the integrated flow system, which started mid-January 2012 when available datasets for the basin were provided to DHI. Much of the data provided to DHI required significant effort to interpret and make ready for input to the model. However, extensive interpretation, such as the development of a 3D geologic model, was beyond the scope of the project.
- **Task 3** – providing a draft report in February 28, 2012, summarizing the characterization and conceptualization of the Mokolo River basin.
- **Task 4** – developing the integrated model.
- **Task 5** – calibrating the model to available hydrologic observations. In response to concerns from the project team related to the difficulty in obtaining non-perennial flows, DHI performed additional sensitivity analysis. This involved a further 66 simulations and a modified calibrated model that was eventually used for the five scenarios.

- **Task 6** – summarising the results of the model development and calibration in a report submitted on May 9, 2012.
- **Task 7** – holding an initial workshop with the project team on March 13-14, 2012 at the University of the Free State in Bloemfontein, SA. The workshop was used to identify and discuss the modelling outputs that could be used as hydrologic and hydraulic indicators for the ecological decision support system (DRIFT-Arid DSS). At the workshop it was agreed to work with four scenarios and a baseline (present day) scenario at each of the five study sites. It was also agreed to develop two local-scale models – one upstream and the other downstream of the Mokolo Dam. Additional data were provided to DHI following the meeting.
- **Task 8** – produce output for the required indicators for five model scenarios at each of the five study sites, and for local-scale models at two study sites.
- **Task 9** – provide a water quality and probabilistic analysis. At the March workshop, it was however agreed that the two components of Task 9 in the original proposal should be dropped. In the first case, it was agreed that there was insufficient water quality data for calibration. In the second case, it was agreed that more effort was required to fully document the modelling methodology in the final report and to develop two local-scale models – one upstream and one downstream of the Mokolo Dam – for each of the scenarios.
- **Task 10** – hold a final technology transfer workshop on October 24-25, 2012 at the University of the Free State in Bloemfontein.
- **Task 11** – provide a final report (Task 11) that summarizes all of the above tasks, including model development, calibration and land-use change scenarios.

6.2 Purpose and Scope of the final hydrology report

This chapter summarizes the characterization and conceptualization of the integrated surface water-groundwater flow system in the Mokolo River Basin, which is located in north-eastern South Africa. Characterization and conceptualization of the system flows forms the foundation for developing the numerical MIKE SHE model. Specifically, this chapter summarizes the:

- Available data types, and their quantity and quality.
- Characterization of the surface and groundwater flow system. Several other hydrological studies exist for the basin. This project does not aim to reproduce previous work, but will summarize key aspects to support the modelling in this project.
- Conceptualization of the integrated flow system. This is a critical component as it forms the basis for the subsequent mathematical modelling.
- Identification and discussion of data gaps and implications for modelling.

The size, complexity and limited available data prevented the development of a highly detailed characterization of the flow system. Instead, the focus of Tasks 1 and 2 and this summary chapter are to identify key datasets relevant to the modelling. Then to provide brief descriptions of the quantity and quality of data required for an integrated groundwater-surface water model. Based on results of the characterization and conceptualization, the data limitations and their implications to the modelling are summarized.

Model development and calibration information is included in this chapter. Following the calibration, concerns were raised about the model's ability to simulate non-perennial conditions. As a result, DHI conducted further sensitivity analysis to evaluate the conceptualization and parameterization affecting non-perennial flows. Results of this analysis are also presented.

Hydrologic and hydraulic indicators used to define the types of model output needed for the EWR is presented and this is followed by a description of the setup, assumptions and results of the five scenario simulations. Conclusions and Recommendations of this study are also provided.

NOTE: The complete final hydrology report is provided as a specialist report (Prucha and Graham, 2012) on the CD included. The complete MIKE SHE Mokolo River model is also available from the Centre for Environmental Management, University of the Free State. Contact: Marie Watson at watsonm@ufs.ac.za.

6.3 Available data types, their quantity and quality.

The characterization of the system hydrology is critical to the development of a sound conceptual and numerical flow model. For an integrated hydrologic flow model, both the surface and subsurface flow systems must be characterized. Characterization generally involves two key steps:

- Raw data are synthesized in a database and then analysed spatially typically with GIS software, such as ESRI's ArcGIS. Temporal analysis is often done with a standard spreadsheet. GIS software allows the modeller to spatially correlate different types of data (e.g. mapped surface geology with subsurface borehole data).
- The raw data are interpreted to characterize the hydrology. The standard practice for characterization in hydrogeology, as defined by ASTM D5979 (2002) or Kolm (1993), is equally applicable to fully integrated hydrologic systems.

In Figure 48 the key elements included in the integrated hydrologic model is provided. The key elements include data on:

- External model stresses
- Model (system) structure, and
- Model (system) response.

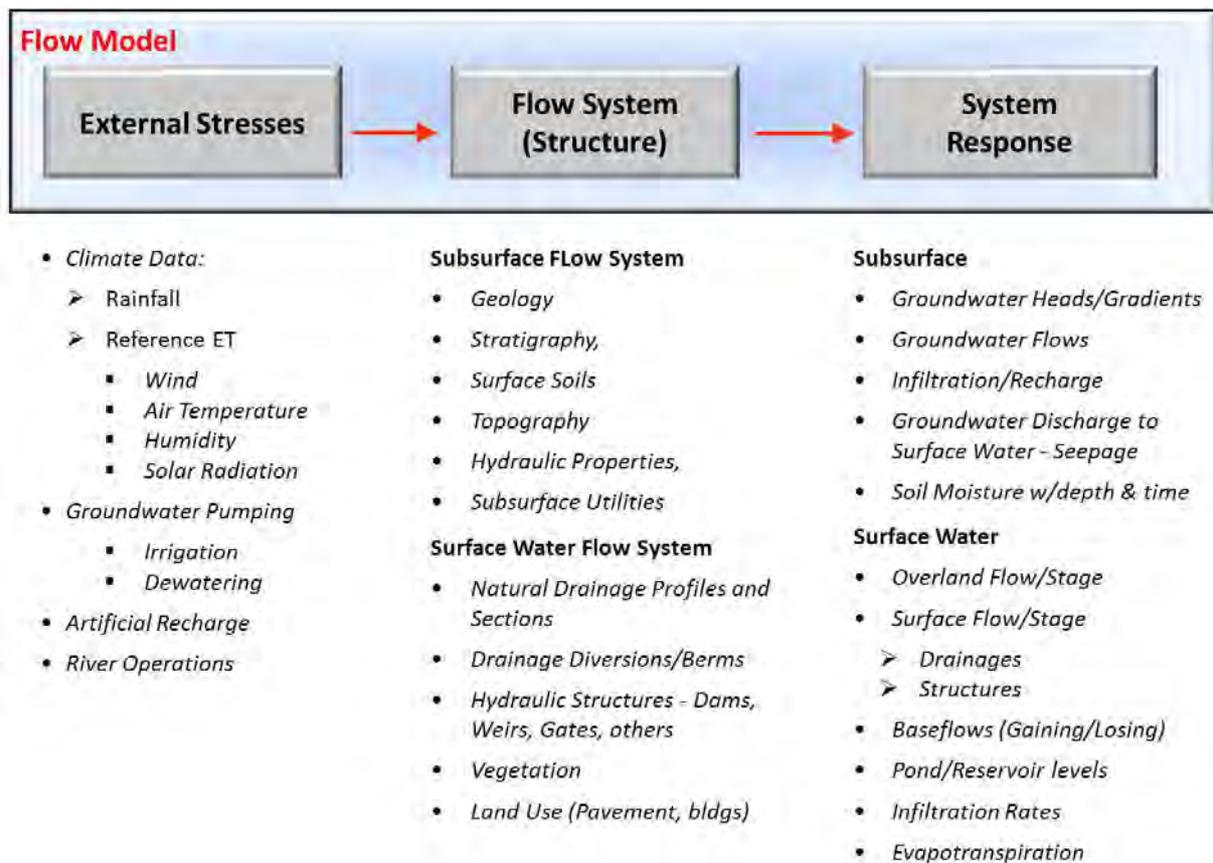


Figure 48. General datasets needed for development of an Integrated Hydrologic MIKE SHE Flow Model

When describing the data needs it is important to distinguish between ‘raw’ data and ‘interpreted’ data (see Figure 49 and Figure 50). Raw data typically refers to information derived from the field, such as borehole logs that have not yet been interpreted into geologic cross-sections, etc.

Unfortunately, much of the available data in the Mokolo catchment is raw data. In particular, there is very few interpreted subsurface data. It was beyond the scope of this project to develop a detailed subsurface interpretation of the available raw data, such as a three-dimensional geologic model. This will limit the ability of the model to simulated local, detailed groundwater flow and stream flow-aquifer responses.

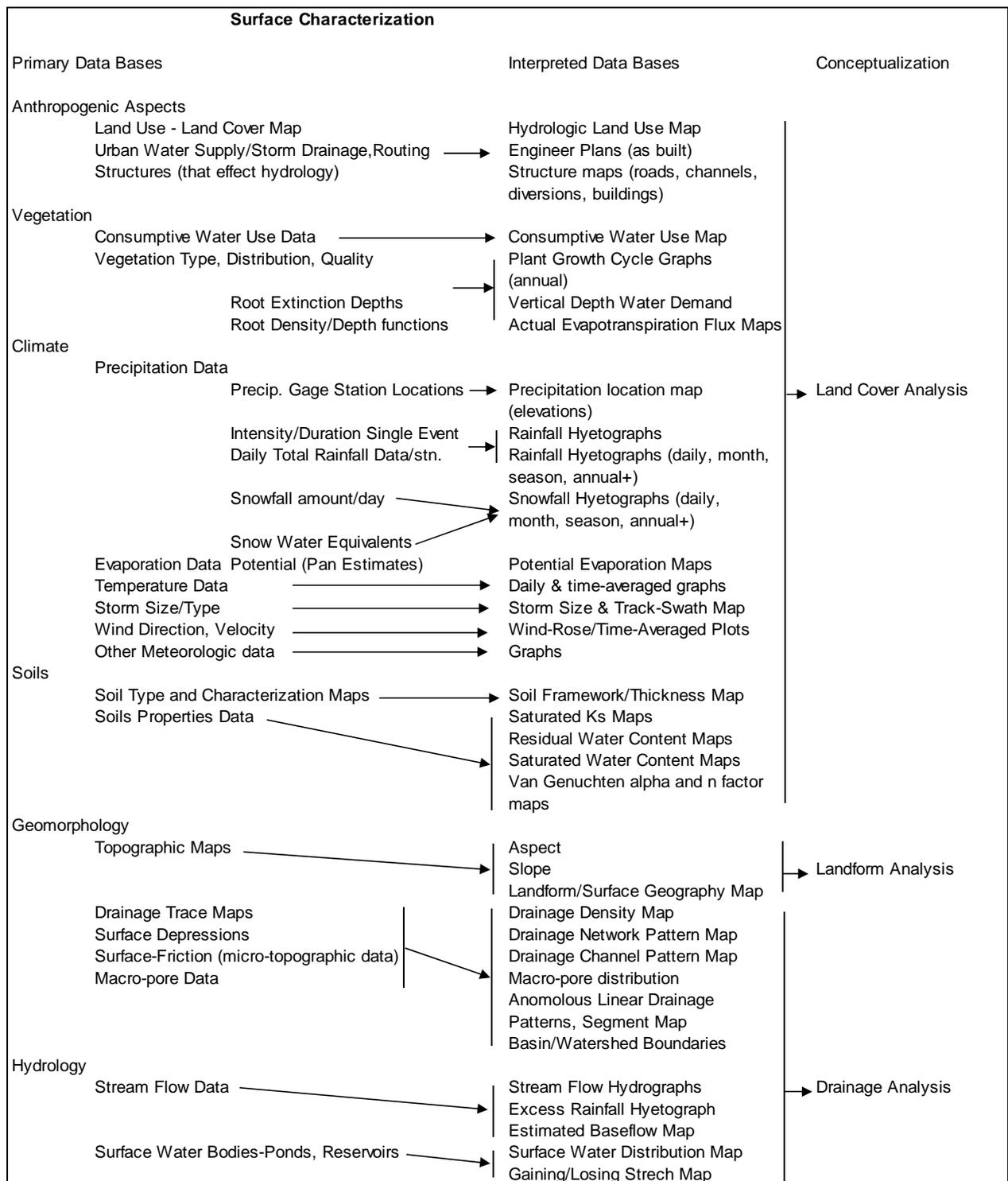


Figure 49. Raw and interpreted data used to characterize and conceptualize the surface water system (from Kolm, 1993)

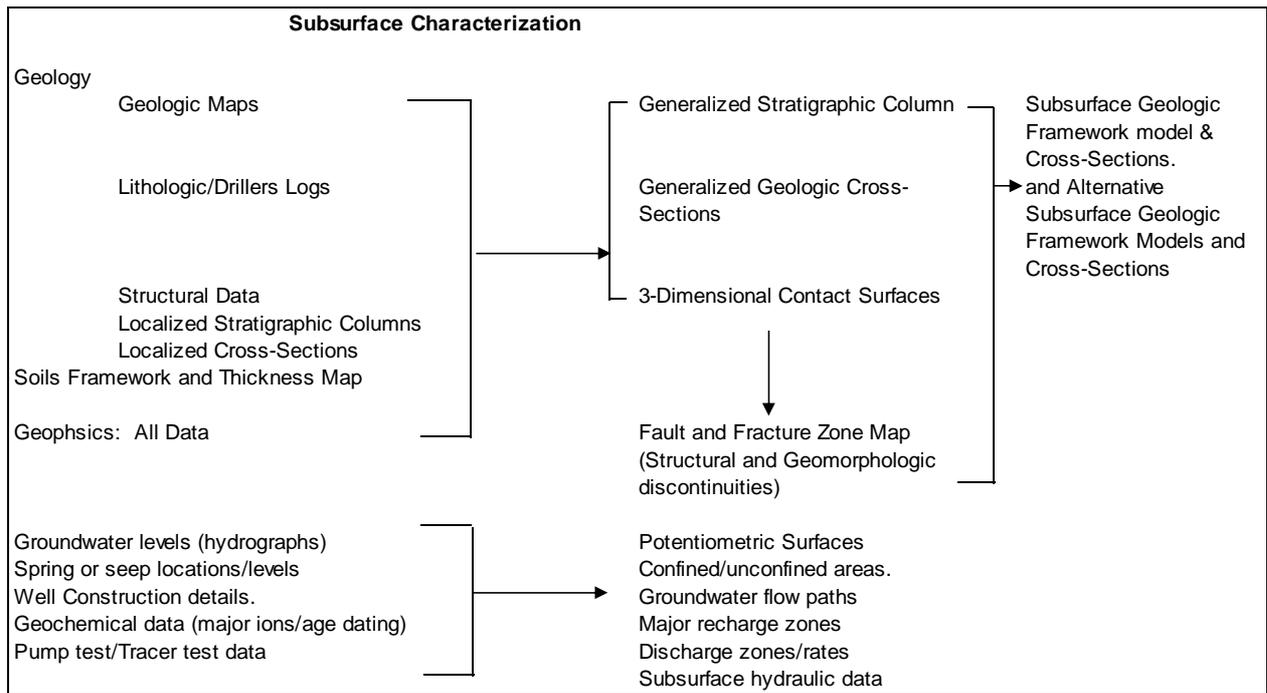


Figure 50. Raw and interpreted data used to characterize and conceptualize the sub-surface flow system (from Kolm, 1993)

6.3.1 Surface Topography

Surface topography is one of the most important datasets in an integrated hydrologic model, aside from rainfall. The topography forms the basis for defining the surface water drainage network and the slopes and stream cross-sections, overland flow drainage into the streams, and, in combination with subsurface geologic information, strongly influences the interaction between the surface water and groundwater flow system. Typically the topography is provided in a Digital Elevation Model (DEM) format that can be used to calculate slopes, contours and profiles. The topography represents the top of the integrated flow model, and the higher the resolution is; the more accurate the topography can be defined. The best available topography data for the Mokolo catchment appears to have a resolution of 21 meters (i.e. a grid with one elevation point every 21 m). Although a 21-m resolution is not useful for determining stream cross-sections (the stream widths are generally less than 21 m), resolutions less than about 30 meters are generally adequate for regional-scale modelling, such as in the Mokolo River catchment. Stream cross-sections are typically surveyed for more accurate modelling of stage and stream dynamics.

6.3.2 Climate Data

Perhaps the most important dataset needed for an integrated flow model is climate data. In climates without snow, only rainfall and potential evapotranspiration (PET) are required for the model.

6.3.2.1 Rainfall

In arid/semi-arid environments, it is usually necessary to use 'event-level' rainfall because rainfall events are typically short (<1 hour), intense and localized. If soils are generally permeable (e.g. sandy), then it is possible to use daily data to simulate integrated flows, as most rainfall will infiltrate. However, if the rainfall rate exceeds the capacity of the soil to infiltrate water, daily rainfall data can promote infiltration at the expense of the surface runoff generated during short, high intensity events that are averaged-out over a day. Ultimately, use of daily climate data must be evaluated during

model calibration to assess whether it adequately simulates surface runoff and infiltration/recharge to groundwater. Ideally, it is always better to use sub-daily rainfall and aggregate up if needed.

A number of climate stations exist in the Mokolo River basin, though no data were available for most of these stations. Daily rainfall is available for each of the nine quaternary catchments for 50 continuous years (1950-2000) (Schulze and Maharaj, 2007). Mean annual precipitation ("MAP") increases with elevation where the MAP is greater than 50% in the higher, southern A42D (Figure 13) catchment compared to the northernmost A42J catchment. The reverse is true for PET, which is about 11% lower in catchment A42D than in A42J, due to the higher elevation. As a result, more rain falls on the higher, southern catchments and has a lower chance of being lost through evapotranspiration than in the northern, lower catchments, probably due to increased average air temperatures at lower elevations and towards the north. Daily rainfall for each of the nine catchments show that the southern, higher elevation catchment A42B, generally has the greatest number of days with higher rainfall amounts, while the adjacent higher, southern catchment A42A has the least. This suggests that higher intensity storms do not always produce the greatest amounts at the highest elevation catchments, though this may be partly due to the algorithm used to develop daily rainfall amounts by catchment. On an annual basis, cumulative daily rainfall emphasizes long-term trends in rainfall over different catchments. Results show that from about 1955 to 1970, upper catchment A42A experienced a long-term decline in rainfall, followed by a period of increase from 1970 to 1980, then a decrease to about 1987. Rainfall amounts seem to have been fairly stable from about 1990 to 2000. Trends are similar for A42J, except that annual trends decline from 1950 to about 1960, and shifted somewhat in time. Results indicate that care needs to be taken in choosing the time periods for calibration of the model to historic data. Typically, calibration periods do not need to simulate the entire available climate data period, but are more focused around periods of time when calibration data, such as stream flow or groundwater levels are available. This information is useful in 'initializing' the integrated flow model to time-averaged conditions.

6.3.2.2 Potential Evapotranspiration (Reference ET)

Penman-Monteith (PM) daily values of Reference ET were provided (Schulze and Maharaj, 2007), though the specific method is unknown (i.e. there are several PM methods). Data were interpreted and when it rains, the calculated PET rates show a corresponding decrease, as a result of decreased air temperature and increased moisture in the air during and after rainfall. This consistent response between rainfall and PET is important in arid/semi-arid environments to ensure that excess water is not removed from rainfall events as ponded water infiltrates into soils and beyond the root zone. The daily time-series show that lower elevations experience higher PET values than upper elevation catchments. As a result, lower elevations are more efficient at removing moisture from the system. The MIKE SHE model incorporates these two points.

6.3.3 Vegetation

In the southern and central section of the Mokolo catchment, upstream of the Mokolo Dam, Central Sandy Bushveld, Waterberg Mountain Bushveld, Waterberg Magalies Summit Sourveld and Western Sandy Bushveld is present. Downstream of the Dam some areas of Central Sandy Bushveld, Western Sandy Bushveld, Waterberg Mountain Bushveld are also present. The Limpopo Flats in the north are mostly covered with Limpopo Sweet Bushveld and a small area of Roodeberg Bushveld is found to the east (Figure 26).

An important factor in the MIKE SHE model which controls how plants remove water through transpiration throughout the year is the Leaf Area Index (LAI). No data were provided on this. However, Level-4 MODIS global LAI data averaged every eight days over the basin, every kilometre was obtained from NASA LP DAAC (2001). This data source can provide an important spatiotemporal

model input (LAI) for any basin in Southern Africa. The 1-km LAI values every eight days were converted into a spatially-averaged time-series by the primary vegetation units (Mucina and Rutherford, 2006) identified in the catchment. No effort was made to assess the spatial-variability in each vegetation unit, but the 8-day 1-km distributions did show spatial variability in each unit. Though it is possible to download other years of data, 2008 was used in the model and the results appear reasonable. Results of the time series show that LAI values across all vegetation units are highest in early Julian days and lowest around day 200. Values are highest for the Limpopo Sweet Bushveld, and lowest for the Roodeberg Bushveld. Variability in daily LAI increases during higher LAI periods, which may be more related to specific climate conditions and subsequent vegetation response than anything else.

6.3.4 Surface Water Flow System

This section describes the surface water flow system, including surface water bodies, streams (or rivers), stream profiles and cross-sections, gauge stage and flow data, structures and surface water abstractions.

6.3.4.1 Surface water bodies

The primary surface water body in the Mokolo River basin is the Mokolo Dam (see Figure 46). Other water bodies (farm dams, weirs and wetlands, etc.) also exist throughout the basin. The location of the Mokolo Dam can be determined from aerial imagery, but smaller water bodies are more difficult to identify and no data were provided on these. The effect of smaller detention storage ponds, and weirs both upstream and downstream of the Mokolo Dam, will:

- Reduce peak flows
- Reduce overall stream flow,
- Increase local ET loss,
- Increase local groundwater recharge, and
- Complicate the calibration process due to unnatural (non-precipitation) releases, or storage effects.

6.3.4.2 River Network

Twenty nine river segments were identified in the basin, based on the provided GIS river coverage, and these were included in the model. Total lengths range from about 10 km to over 230 km (Mokolo River). The Mokolo River is the longest surface drainage feature in the basin; the next longest is the Poer-se-Loop at just over 66 km. Some artificial river names were added to the GIS coverage (e.g. Sand_1) since none were provided.

A review of the river network compared to the 21 m DEM and aerial imagery provided (and ESRI world file imagery) indicated problems with the original river shape file. The trace and resolution of rivers was not very accurate. As a result of the first problem, stream profiles, critical to modelling surface flow successfully, could not be accurately estimated from the 21 m DEM (original streambeds cut across hillsides) without re-tracing most of the network. This was done using the aerial imagery and contours from the 21 m DEM. In addition, to facilitate direct input of the stream network into MIKE 11, the end points of streams were disconnected from main stem branches (i.e. connections with the Mokolo River).

6.3.4.3 Profiles and Cross-sections

The selected river profiles based on the revised trace of the river network is illustrated in Figure 51. For the MIKE 11 modelling of stream flow, river bottom profiles must decrease monotonically where dams are not present, both for accuracy and numerical stability. The Mokolo River has a much lower

slope than any of the tributaries, which decreases with increasing distance downstream. This information was directly incorporated into the MIKE 11 river network. Locally surveyed cross-sections at the five study sites were used (Figure 52). Sections in the upper reach (Site 1) are more incised (indicative of higher baseflow contributions from groundwater), while lower sections (Site 5) indicate widening, more meandering drainage areas with multiple flow areas and increased vegetation. Given the complexity of the section, the coarseness of the DEM (21m grid spacing), and the lack of surveyed information in other areas of the basin, the modelling started with simplified cross-sections (i.e. without the variations observed on Figure 52). Simple triangular cross-sections allow flows to be conveyed downstream, but do not allow for stage to be calculated accurately. This is an artefact of not having accurate topography or accurately surveyed sections along the entire length of all rivers in the system.

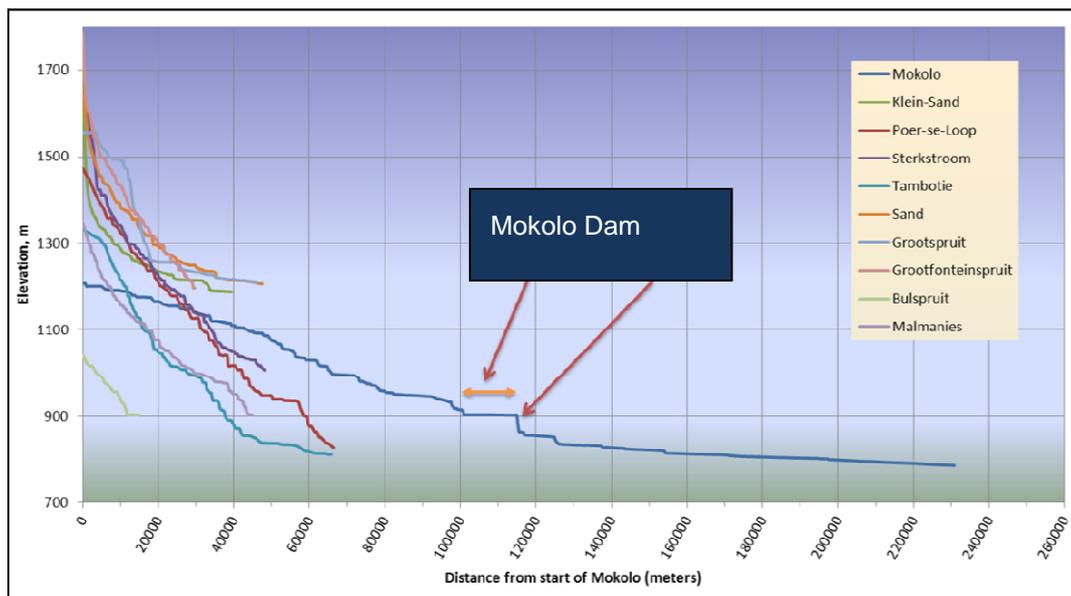


Figure 51. Selected river profiles of the Mokolo River catchment after re-alignment.

It typically does not make sense to use complex sections from only five locations to interpolate how the sections vary along the entire 230 km long, complex river system. Instead, it is often better initially, to see how the simulated surface flows compare to observed discharge data, and then modify the sections accordingly. Where cross-sections are available locally, river network sections in local-scale models can be revised to better represent flows and stage through these areas, using a regional model to provide inflow boundary conditions.

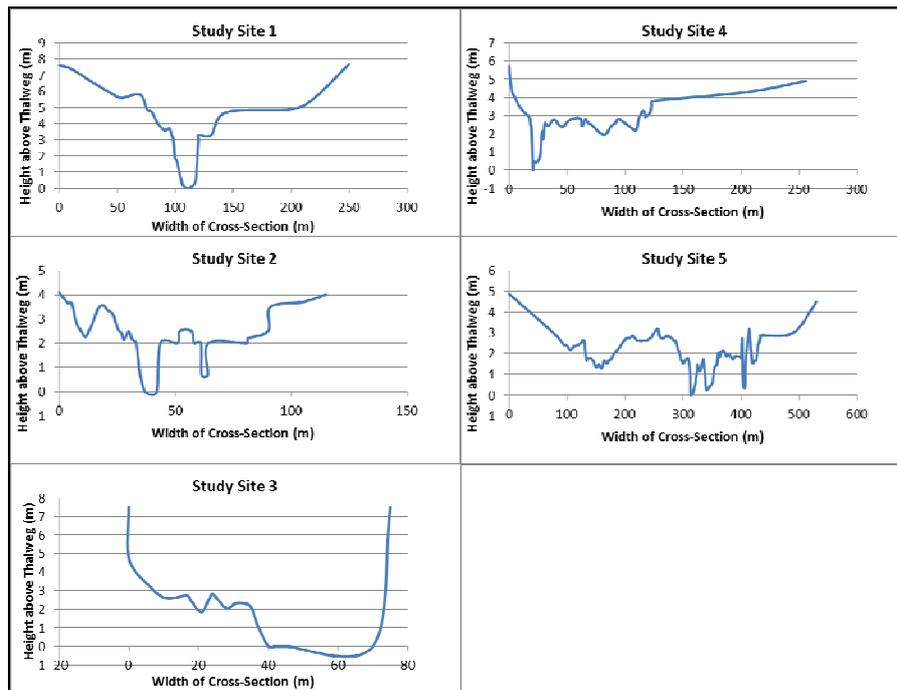


Figure 52. Study site stream cross-section profiles

An important area where cross-sections would be useful is in the Mokolo Dam. It is often helpful to simulate flow through such a system using detailed cross-sections. However, this information was not available at the time of characterisation and calibration and it is likely that the bathymetry, or original surface topography would not likely provide accurate storage, given sedimentation since construction of the dam. Instead, a stage-area-volume relationship for the Mokolo Dam (provided by DHI-SA) was used as the basis for describing flow into, storage in and discharges downstream via the spillway, or as a release from the Mokolo Dam.

6.3.4.4 River Discharge and Stage Data

Daily stream flow gauge data were available from the DWA for a number of locations. Gauge discharge data were plotted from 1946 to the present. Stage levels in time are also available at gauges A4H001, A4H003 and A4H004 (see Figure 14 for location of weirs). This information could be used to help guide calibration, but in this case cross-sections at each location would need to be provided. Discharge characteristics from the gauges with longer datasets (i.e. A4H002, A4H005 and A4H008) suggest that non-zero flows occurred throughout the year for extended periods (i.e. 1966 to 1980). These trends correlate well with periods of increasing rainfall amounts. The river becomes non-perennial (no-flow) during other extended periods of time (i.e. 1986 to 1996) in A4H002. Apparent multi-year (~decadal) variation in annual precipitation amounts may partly drive the Mokolo River (and its tributaries) to go from perennial conditions during high rainfall periods, to non-perennial conditions during low rainfall periods (i.e. low decadal annual rainfall periods). Increased irrigation during these drier periods likely also contributed to the shift from perennial to non-perennial flows. Other characteristics of the discharge measurements show that peaks, upstream of the dam (i.e. less effected by operations, and therefore more natural), typically occur in the January-February time period (and even March), while seasonal low flows (baseflow dominated flows) generally occur in November to December each year. The long, generally smoothly decreasing discharge recession curves from peak values (with few rainfall events) suggests groundwater storage is significant and is a dominant basin-scale process, at least in the catchments upstream of the dam (mostly Waterberg group, Sandstone formations). Integrated model calibration against the long-term daily discharge data

should provide insight into how much storage is derived from alluvial aquifer deposits and underlying regional bedrock aquifers (upstream of the dam).

The mean daily discharge data represents the primary calibration target dataset for the integrated model; groundwater levels will also be used, but little time-varying information on groundwater levels is available, and the subsurface system is comparatively uncertain (compared to the surface water flow system), so less weight will be assigned to this data for calibration.

Discharge data for a time period with the greatest overlap of data (2004 to 2010) for all gauges with data (some not shown) in the upper plot is illustrated in Figure 53. The lower plot shows flows from the gauge downstream (approximately 1.8 km) of the Mokolo Dam (A4H010) and the gauge at the Mokolo River basin outlet (A4H014). This is useful calibration data and appears to validate data showing consistency between flow responses, though it is not possible to assess how much of the response, without discharge data, is from the dam itself. This information represents the primary calibration data used to calibrate model parameters in the lower Mokolo River basin, below the dam.

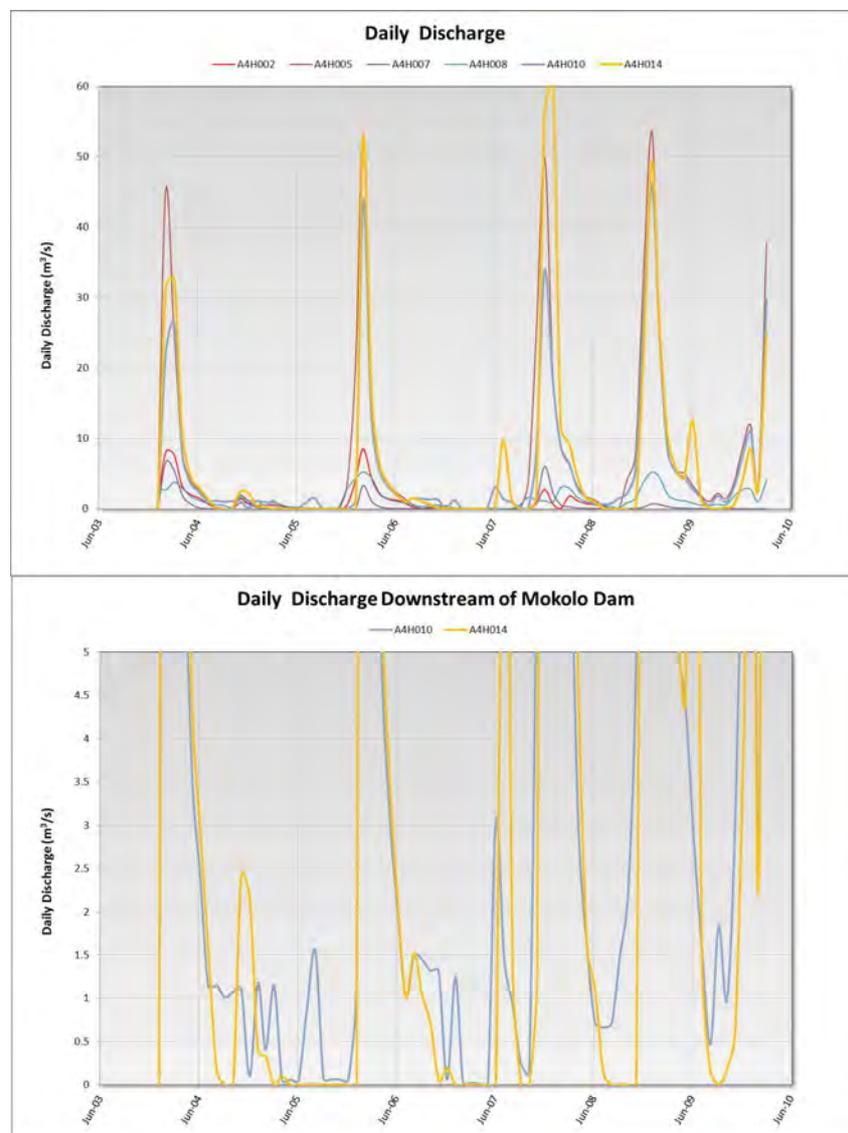


Figure 53. Average Daily Discharge by Month for all gauges (2004 to 2010) in upper plot, and Average Daily Discharge by Month Downstream of Mokolo Dam in lower plot

Dam release discharges (at gauge A4R001) were compared with the discharge 1.8 km downstream at A4H010 and at the basin outlet (A4H014) for the period February to May 2006. Key observations include:

- Very similar discharge curves for A4H014 and A4H010, with a slight delay in time for A4H014 response suggest the combined characteristics of the controlled discharge and uncontrolled releases from the dam strongly dictate much of the hydraulic response downstream to the model outlet. Deviations between the two gauges are due to infiltration, irrigation withdrawals, weir structures and baseflow inflows.
- Dam releases (or spills) into a dry streambed take about four days to propagate downstream to the basin outlet (A4H014). Releases downstream after the system has been flowing continuously for some time propagate downstream much quicker (about a day) probably because bank storage has already filled up, reducing infiltration losses from A4H010 to A4H014. This emphasizes the importance of downstream flow conditions (i.e. dry or flowing) on wave propagation.
- Slow recession curves following a spill or release help parameterize not only shallow aquifer hydraulic properties, but also thickness and extent of the aquifers.
- The discharge information will provide useful calibration constraints on both surface and subsurface model parameterization (i.e. storage and hydraulic conductivities of both alluvial and underlying bedrock aquifers).

6.3.4.5 Structures

Four ungauged weirs are located downstream of the Mokolo Dam but no data or information on these weirs was available. Although locations and estimated volumes for 1431 different farm dams in the basin were provided (GIS coverage) it was difficult to simulate these features without more information. The following information would be required to simulate the hydrodynamics of these dams:

- the source of water to them,
- surface water diversions (from source areas),
- how the water in them is used,
- where it is used,
- how long has the pond operated, and
- measurement of local seepage rates into the subsurface.

6.3.4.6 Surface Water Abstractions – Irrigation

MIKE SHE has the ability to simulate irrigation to crops using water from a variety of sources, such as surface water, groundwater or external supplies. Flexible application of the source water onto fields is possible (i.e. as rainfall, surface application, etc.).

“The largest user of water in this catchment area is the irrigation sector, with an estimated demand of 68 million m³/annum. This is located mostly upstream of the Mokolo Dam, where the main source of water supply are farm dams” (DWA, 2008). The 68 million m³/year is about 2 m³/s, which is significant compared to the observed baseflows in gauges upstream of the reservoir which drop to non-perennial conditions during part of many years from 1950-2000. Irrigation may be the main reason flow conditions become non-perennial in this part of the river although a decrease in rainfall was also noted during these periods.

Irrigation water is obtained from boreholes, springs, wetlands and surface water (river, farm dams). Although rates were provided for irrigated amounts, specific source locations were not provided for non-well locations. A summary of the sources of water (either well, river, wetland or farm dam) was used in the model setup.

6.3.5 Unsaturated Zone Flow System

Soil data were provided and are shown in Figure 54. Soil hydraulic data, including macropore-bypass flow for each zone, is summarized in van Tol and Le Roux (2012). Further delineation and properties based largely on slope (curvature) and proximity to streams in each zone were also provided.



Figure 54. Soil type in Mokolo River Catchment

An alternate soils coverage (Schulze and Horan, 2007) was also provided and this dataset included hydraulic properties, such as A and B-horizon wilting point and field capacity saturations, porosities, K_{fact} values (which are assumed to be hydraulic conductivity values) and layer thicknesses.

6.3.6 Groundwater Flow System

6.3.6.1 Surficial Geology

The majority of the basin (upper two thirds) is primarily comprised of the Waterberg Group, which overlies the older Transvaal Supergroup formations in the very southern, highest elevation areas. It is unclear how this occurs, except other information reviewed suggests the presence of a syncline in the area, which could help explain this feature. In the northern model area, Quaternary deposits overlie the Karoo Supergroup, which occurs stratigraphically over the Waterberg Group formations and also occurs at a lower elevation. Further breakdown of the formations in the Groups can provide useful zonations for assigning hydraulic properties to the subsurface bedrock units in the system.

6.3.6.2 Borehole logs

It was not possible to determine the subsurface stratigraphy of various units from borehole information obtained from the borehole geological logging data for the National Groundwater Archive boreholes from DWA (National Groundwater Archive) in South Africa, but maximum depths at boreholes with coordinates (not all had coordinates) were plotted. Most boreholes show depths from 100 to 300 m; the maximum depth is 900 m. Assuming most of these are related to drilling for water, the implication

is that groundwater is readily available to depths up to about 300 m. Lithology data in this dataset gave an indication of the maximum depth range for each borehole and underlying surficial geology by lithological type. In many cases, depths well below 100 m showed lithology as 'soil', suggesting unconsolidated soil is present for considerable thicknesses above bedrock (i.e. sandstone). This therefore also suggests higher permeability unconsolidated material may be present over much of the bedrock and may dominate shallow aquifer flows. However, many locations show clusters of boreholes, slightly offset, that also suggest that multiple wells may be drilled in the same area at differing depths to find water strikes.

A three-dimensional geologic model should be developed as part of the characterization of the Mokolo Basin subsurface flow system based on borehole logs and surficial geologic information. However, this is a time-consuming task and requires careful preparation. Thus, it was outside the scope of this study, but it is strongly recommended that a geologic model be prepared. Multiple aquifer units (or hydrostratigraphic units) should be developed based on the major lithological units apparent in the surficial geology.

6.3.6.3 Geologic Structure

A study by DWA (2010) indicates that fractures, dikes and faulting structures are dominant in the Mokolo River catchment. These structural features extend over the area immediately downstream of the Mokolo Dam. Faults in the north-western part of the basin were also described in a report on the impacts of mining associated with the Waterberg coal reserves on water quality and quantity (Vermeulen et al., 2009). The faults shown have a pronounced effect on water levels in many groundwater wells on either side of them (e.g. varying from artesian to water levels exceeding 150 m).

6.3.6.4 Hydrostratigraphy

The general characteristics of the alluvial aquifer system within the Mokolo basin are described in a groundwater assessment of the Mokolo River catchment (Dennis, 2010; specialist report available on CD). Details for different zones, starting in upper catchments and proceeding down the Mokolo River include:

- **Unit A:** Mountainous area of the Waterberg. High recharge is expected in the mountains (10-19 m/year). Very little alluvium is present as the Mokolo River passes through a steep gorge. Average conductivity of the alluvium expected to be about 175 m/day.
- **Unit B:** Mountainous area of the Waterberg. Moderate recharge is expected (5-9 mm/year). Alluvium is present as the Mokolo River flows through a largely flat undulating plain with a steep rocky area. Average conductivity of alluvium is expected to be about 175 m/day. The alluvial aquifer is approximately 15 m thick. Intense agriculture is present. The depth to the groundwater varies between 20-25 m.
- **Unit C:** Foothills of the Waterberg. The average recharge drops to about 4-5 mm/year. Intense agriculture is present. Average conductivity of alluvium is expected to be about 175 m/day. The alluvial aquifer is approximately 12 m thick. The depth to the groundwater varies between 20-25 m.
- **Unit D:** Foothills of the Waterberg. Intense agriculture is present. Average conductivity of alluvium expected to be about 175 m/day. The alluvial aquifer is approximately 12 m thick. The depth to the groundwater varies between 20-25 m. The average recharge of the regional aquifer is about 4 mm/year. Artificial recharge and seepage will occur as a result of the Mokolo River.
- **Unit E:** Low lying land underlain mainly by the Karoo and Basement Formations. The alluvial aquifer is present through the area. The average thickness of the alluvial aquifer is about 8 m. The conductivity of the aquifer drops to 130 m/day. The depth to the groundwater varies between 20-30 m. Regional groundwater recharge varies between 3-6 m/year.

No information on the hydrostratigraphy of the bedrock units was available. It is difficult to assess the nature of subsurface flow between alluvial and bedrock aquifers without detailed hydrostratigraphic information on aquifers and aquitards. In the absence of any other information, the bottom of wells in the basin could be used to define the hydrostratigraphic base of the aquifer system interacting with surface waters.

6.3.6.5 Groundwater Depths

A database of the time-averaged groundwater depths was provided by the DWA (National Groundwater Archive (NGA)) and the depth are assumed to extend below ground surface, rather than from another datum (i.e. the top of well casing) but it is unclear whether the depths were measured during initial installation of boreholes, as some wells show multiple measurements. Depths associated with the Mokolo River range from 20 to 25 m and may be deeper due to increased pumping or diversion in this area. Depths generally increase with distance from rivers. Depths in a 2 km buffer around the river are generally shallower (up to 20 m) in the upper tributaries, with the exception of tributaries in the mid-basin Waterberg Group area (25 to 30 m). The integrated flow model will attempt to reproduce the average groundwater depths, rather than elevations to avoid introducing additional errors from the topographic dataset used.

6.3.6.6 Groundwater Pumping

The time-averaged groundwater discharge data in litres/second was provided by the DWA (NGA) and is believed to be related to the initial borehole pumping to determine possible well yield. These data do not correlate with well pumping summarized in the irrigation database used. Discharge rates are mostly below 5 l/s although some range from 25 to 76 l/s. Using this dataset, discharge rates can be specified in the model at these locations during model calibration and for scenarios.

6.4 Gaps in Data/Knowledge and Implications for Modelling

The degree to which existing or historical flow conditions can be reproduced strongly depends on available data quantity and quality, characterization of the surface and subsurface hydrologic data, and conceptual flow model. In data limited systems with complex surface/subsurface flow systems, conceptualizing detailed flow conditions becomes increasingly difficult.

The type of model input (e.g. input stress, structure or system response), data type (e.g. climate, pumping), gaps in the information provided, and the modelling implication is summarised in Table 38. **Shaded rows indicate the gaps that most significantly affect the modelling.** Main datasets needed or incomplete were irrigation data, discharge from the Mokolo Dam, accurate topography and detailed distribution of soil.

Table 38. Summary of data gaps and modelling implications.

Model Input	Data Type	Gap in Information	Modelling Implication
Input Stress	Climate Data	Precipitation is only available at daily time periods	Short-term stream discharge events (i.e. peak flows) may not be captured well for high-intensity, sub-daily storm events. May affect parameterization of overland and channel flow resistance and soil hydraulic properties
Input Stress	Climate Data	Precipitation is only available from 1950-2000 -spatially distributed by catchment.	The model is unable to simulate post-2000 conditions without spatially distributed (by catchment) precipitation data during this period. The model is 'driven' by external climate inputs

Model Input	Data Type	Gap in Information	Modelling Implication
Input Stress	Irrigation Data	Source point locations, irrigated acreage and annual volumes provided, but not linked to specific irrigated areas.	This is an important limitation. The source of irrigation water, its application rate and the application area must be known. Otherwise, based on just the irrigation database, too much water is applied at each 'point location' rather than at plots further from streams. More water would be lost to ET, instead of going back into rivers as return flow. Too much localized recharge can increase groundwater recharge, which increases baseflow to rivers. This can reduce the ability of model to simulate non-perennial conditions.
Input Stress	Irrigation Data	Irrigation rates provided monthly for some locations, but most only show an annual amount.	Varying irrigation rates over the year would improve the model's ability to simulate annual effects of irrigation correctly.
Input Stress	Irrigation Data	Groundwater pumping details (i.e. screened depth, rates in time, etc.) in irrigation database are not provided.	This limits the ability of the model to draw groundwater from the appropriate aquifer units/depths
Input Stress	Groundwater Pumping	Groundwater pumping database doesn't correlate with irrigation 'wells'. Rates mostly from 'driller's log. No other information provided. Also, don't know when wells are turned on/off, or if rates are variable.	Without good understanding of pumping information and hydrostratigraphy (aquifer units) or well screen information, can't impose this stress on system with any sense of accuracy. The lack of correlation with irrigation wells, suggest these wells may be domestic. In either case, these wells remove groundwater, most of which is probably lost to ET. Not simulating discharge from these wells doesn't reduce groundwater levels in the model.
Input Stress	Mokolo Dam Discharge	Mokolo Dam operation scheme unavailable (either existing or future scenario scheme)	This limits the ability of the model to reproduce historical uncontrolled spills and releases downstream, and diversions to Town/Industry. Ultimately, this dominates future scenario discharge response in the Mokolo River, downstream of the dam.
Input Stress	Mokolo Reservoir Discharge	Discharge diversion to Town/Industry (locations and rates) unavailable.	This limits the ability of the model to reproduce historical reservoir levels, and discharges downstream. Typically, reservoir levels are used as a calibration target dataset, and used to help parameterize factors controlling inflows and outflows through the reservoir.
Structure	Topography	Relatively coarse. Accuracy unknown.	At a regional-scale, affects ability to prepare accurate stream profiles, and cross-sections. This is critical to modelling groundwater-surface water flows.
Structure	River Cross-sections	Only five 'study-site' sections were provided and only along the Mokolo River. No sections were provided in any other tributary.	Only simplified cross-sections can be included in the model based on the relatively coarse 21 m topographic DEM. The topography is NOT accurate enough to create pools/riffle or braided channel sections similar to the study sites. This limits the ability of the model to simulate localized hydraulic response at the pool-scale.
Structure	Vegetation	LAI or Root depths with time unavailable for vegetation distribution provided.	This affects the model's ability to simulate ET dynamics and magnitude throughout the model domain.
Structure	Vegetation	Riparian Vegetation types, water use, LAI, Root depths with time unavailable.	This would increase ET loss of groundwater in shallow river alluvium. In turn this would reduce baseflows along streams, and could increase potential for non-perennial flow conditions.
Structure	Soils	Different soil distributions provided (which is correct?). The distribution provided with hydraulic properties is loosely defined on relative 'hillslope' location. Detailed distributions should be defined, taking into account variations in surficial geology, vegetation, and climate.	This is a critical dataset for the modelling. It strongly influences the ratio of surface runoff to baseflow, and determines how much available precipitation is lost to ET.
Structure	Aquifer Delineation	Alluvial aquifer thickness/extent is largely unknown, except for the lower Mokolo River, downstream of the dam.	This is an important factor that strongly influences the stream-aquifer interaction. Without information on the extent and width (if any) along each river and its tributaries, the model requires these be assumed. Effectively this becomes a calibration parameter that increases overall model accuracy and predictive uncertainty.

Model Input	Data Type	Gap in Information	Modelling Implication
Structure	Aquifer Delineation	Configuration of bedrock aquifer units (depths, extents). Little information, except in the Exxarro mining area in the northwestern lower Mokolo catchment was available. Generalized thicknesses of bedrock units are provided.	Same as above.
Structure	Aquifer Delineation	Aquifer hydraulic properties were unavailable for bedrock units, and for alluvium outside of the lower Mokolo.	This is a critical dataset in model calibration. Though typically a calibration parameter, it is important to have some basis for modelling (i.e. range observed, relative values for each unit). Without these data, conceptual and parameter uncertainty increases, causing increased uncertainty in predictions.
Structure	Dikes/Faults	No hydraulic properties, testing or extent/depth of these features is available.	These structures, within the bedrock may dominate groundwater flows throughout the Waterberg formation, and more importantly, how groundwater interacts with surface flows. Flows can be impeded perpendicular to these structures, but enhanced parallel to them. Not modeling these increases conceptual uncertainty, which in turn affects calibration in these areas and increases overall predictive uncertainty.
Structure	Mokolo Dam	Bathymetry	Affects stage-area-volume relation. Sediment build-up over time reduces volume, decreases leakage to groundwater
Structure	Streams	Major streams GIS coverage was provided, but GIS coverage of higher-order drainages (as non-perennial) was provided after calibration was complete. No information or discharge information was provided on tributary streams. Many farm dams appearing to be located on these smaller tributary drainages are likely filled by them.	Not simulating local tributary streams can reduce main-stem river discharge peakiness and promote recharge in these areas. This in turn promotes more baseflow to main-stem rivers, which can reduce the ability of the model to simulate important indicators like non-perennial flows. This information needs to be carefully developed and provided at the start of modelling. Integrated models are built around these critical features
Structure	Weirs	Locations and construction details unavailable - yet present based on Google-earth imagery.	These features dam up water behind them, effectively increasing attenuation of peak flows. Locally, increased groundwater leakage and ET loss occurs beneath and upstream of the weirs
Structure	Farm Dams	A database was provided, but no information on volumes, depths, leakage, and source of water, application rates/locations or diversions to or from source was provided.	Similar to weirs described above. If the source of water is from rivers, this reduces the natural stream flows that occur in the river. The mainstem rivers may actually be perennial if these waters were not diverted. Much of this water is lost to ET, or increases groundwater leakage, which may increase baseflow downstream. Without these dams, these streams would contribute more flow and increase peak flows downstream.
Structure	Surface Water diversions to farm dams	Unavailable.	Diversions could be modelled, but specific locations and routes would need to be known. Diversions leak, which in some areas may increase groundwater levels and return 'baseflow' to river
System Response	Groundwater levels	No transient data	Severely limits ability to calibrate the groundwater flow system, which in turn affects surface water discharge.
System Response	Groundwater levels	Single measurement in time. It is unclear whether it is during initial drilling, or subsequent testing.	High associated uncertainty reduces accuracy of model calibration. Does the data represent 'natural' conditions, or pumping state? Which aquifer unit does it represent? What is time-average level? The model produces time-varying levels, so comparing against one measurement introduces error that could easily be similar to seasonal variation.
System Response	Stream discharge	Only daily data are available	Sub-daily storm events are particularly useful in conceptualizing flow within the system (i.e. overland runoff vs. baseflow) and for adjusting parameters affecting short-term system discharge response. Without sub-daily precipitation, this is difficult to utilize effectively in the modelling.

Model Input	Data Type	Gap in Information	Modelling Implication
System Response		Flows are only available at a few locations, on main-stem rivers.	It is not possible to calibrate discharge along streams without discharge data. Combined with other data gaps, it is difficult to develop accurate conceptual flow models, or to demonstrate where the source of water is in the main-streams.

6.5 Hydrologic Conceptualization

The conceptualization is based on the characterization of available data described under section 6.3. The integrated hydrologic flow modelling depends heavily on the conceptual flow model and it is commonly accepted in the hydrologic community that the chief source of uncertainty in hydrologic models comes from inadequate description of conceptual flow models (Neuman and Wieranga, 2003).

6.5.1 Conceptual Flow Model

A generalized hill slope flow model with key structural features and flow processes that explains much of the integrated surface water-groundwater flow processes was developed (Figure 55).

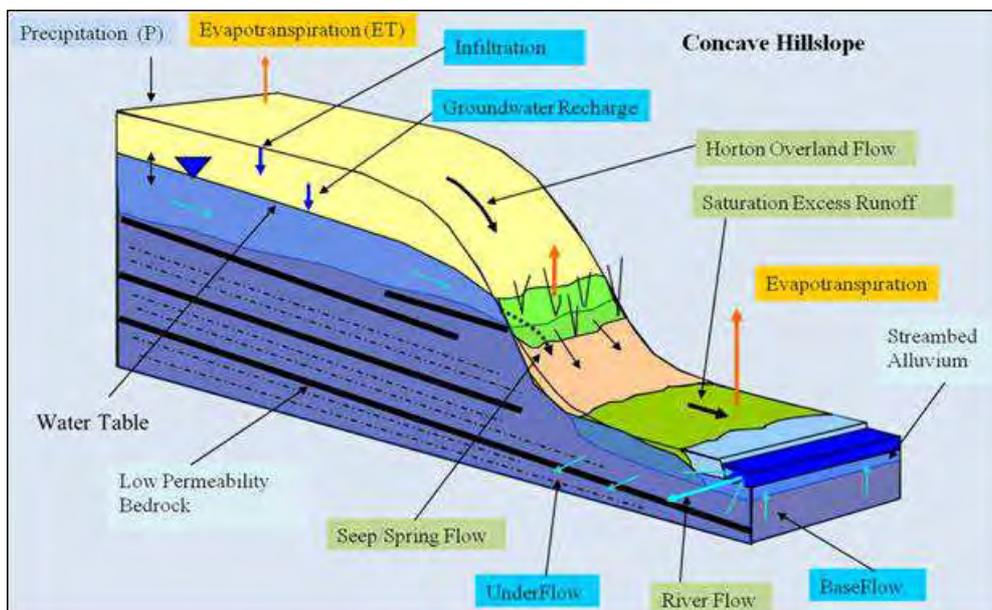


Figure 55. Generalized hill slope conceptual flow model for the Mokolo River Catchment

Rainfall is intercepted by the vegetation at the ground surface, and the precipitation that does not evaporate from the canopy reaches the ground surface as throughfall. Throughfall will either infiltrate, runoff, or remain ponded depending on the local topography. Typically in large arid/semi-arid basin flow systems, most rainfall either evaporates at the soil surface, or infiltrates and is then returned to the atmosphere via plant transpiration. Larger rainfall events lead to increased infiltration, and eventually basin recharge (typically only a few percent of annual rainfall), though most is still lost through evapotranspiration. High intensity rainfall events can increase the ratio of runoff to infiltration when the surface infiltration capacity is exceeded (Horton flow), or when soil saturates from below (saturation excess), which typically occurs near streams.

The configuration of subsurface geologic contacts (i.e. bedrock surface, or a clay/coal layer) can cause surface discharge of groundwater (i.e. springs), or can strongly influence how groundwater flow

interacts with surface flows. Deeper, lower permeability layers provide more groundwater storage and shallow layers can cause faster, more peaky responses, with rapid recession in surface discharge. Only three natural sources of water in the integrated hydrologic system contribute to flow in rivers; overland flow, groundwater baseflow and direct precipitation. Baseflow is the net groundwater flow into the river. A negative baseflow simply represents a case where the river infiltrates to the groundwater system, because river stage levels are higher than groundwater levels beneath the river. A gaining river is one in which groundwater discharges into the river (i.e. positive baseflow). Saturated zone flow beneath (and parallel to) the river is referred to as underflow. It is DHI's experience, particularly in regional-scale models, that interflow (build-up of saturation in a shallow hillslope near a river) can simply be combined with groundwater baseflow (from the regional, connected aquifer system), because the model grid size in regional model is typically larger than the scale of this local, near-river flow process. To correctly simulate near-river lateral unsaturated flow, you generally need to use a model capable of simulating variable saturation and at very small scales (e.g. a grid size of 10 meters or less) to capture these small contributing areas.

A generalized profile lengthwise through the Mokolo River basin is illustrated in Figure 56. The figure shows a possible conceptual subsurface configuration describing bedrock layering. A syncline is required to account for the spatial distribution of the geologic formations based on the surficial geology. With faults and dikes, groundwater flows through the system are expected to be influenced by the larger-scale structural features and bedding contacts.

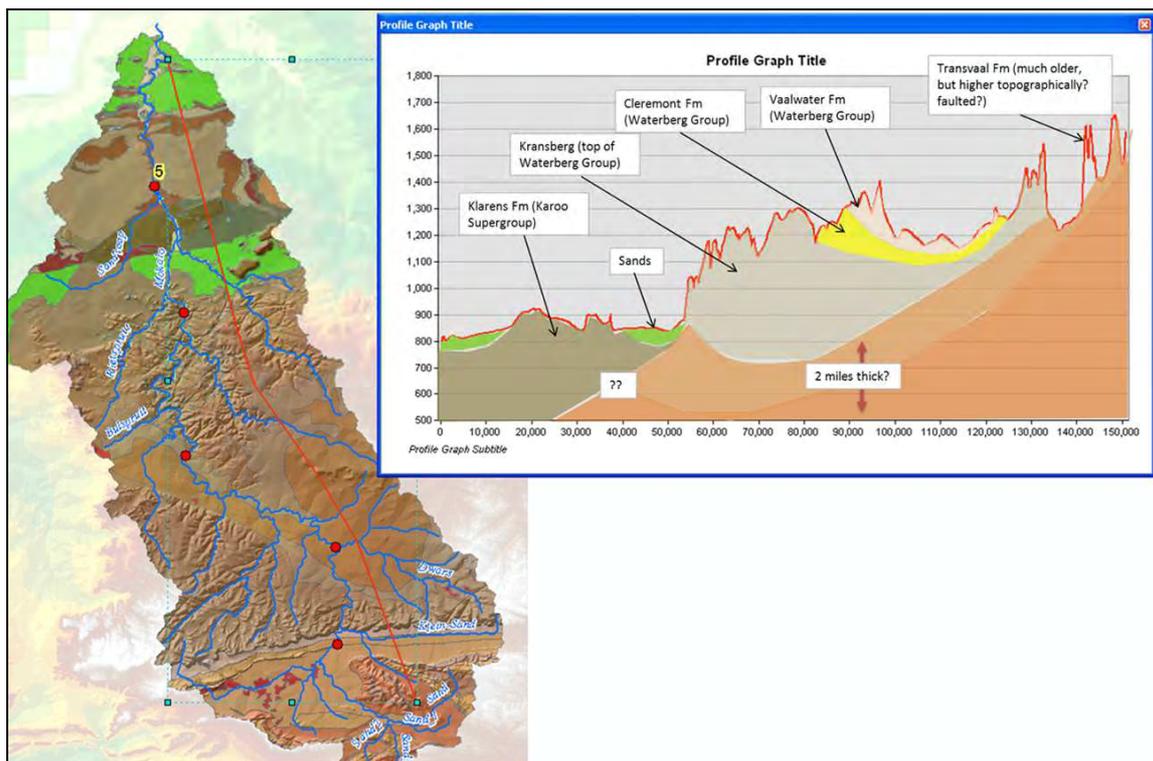


Figure 56. Generalized profile of geologic formations (approximately North-South along red line shown). Depths are only based on a visual estimate based on surficial geology and stratigraphic order

A local conceptual flow diagram to explain surface water-groundwater flows related to the numerous linear drainage features in the Mokolo River catchment aligned with river segments is presented in Figure 57. The integrated flow model developed in this study assumed no influence of structural features, such as faults and dikes on flow conditions. This assumption was made because of the lack

of hydraulic information associated with dikes and faults in the system (including extent and depth). However, it is clear that large-scale groundwater flow is probably dominated by these features (DWA, 2010). In addition, it is also likely that these features strongly influence river-groundwater flow interaction, where they cross rivers. High permeability parallel to these features and likely low associated storage may strongly influence peak flow, stream flow recession, baseflow and non-perennial conditions.

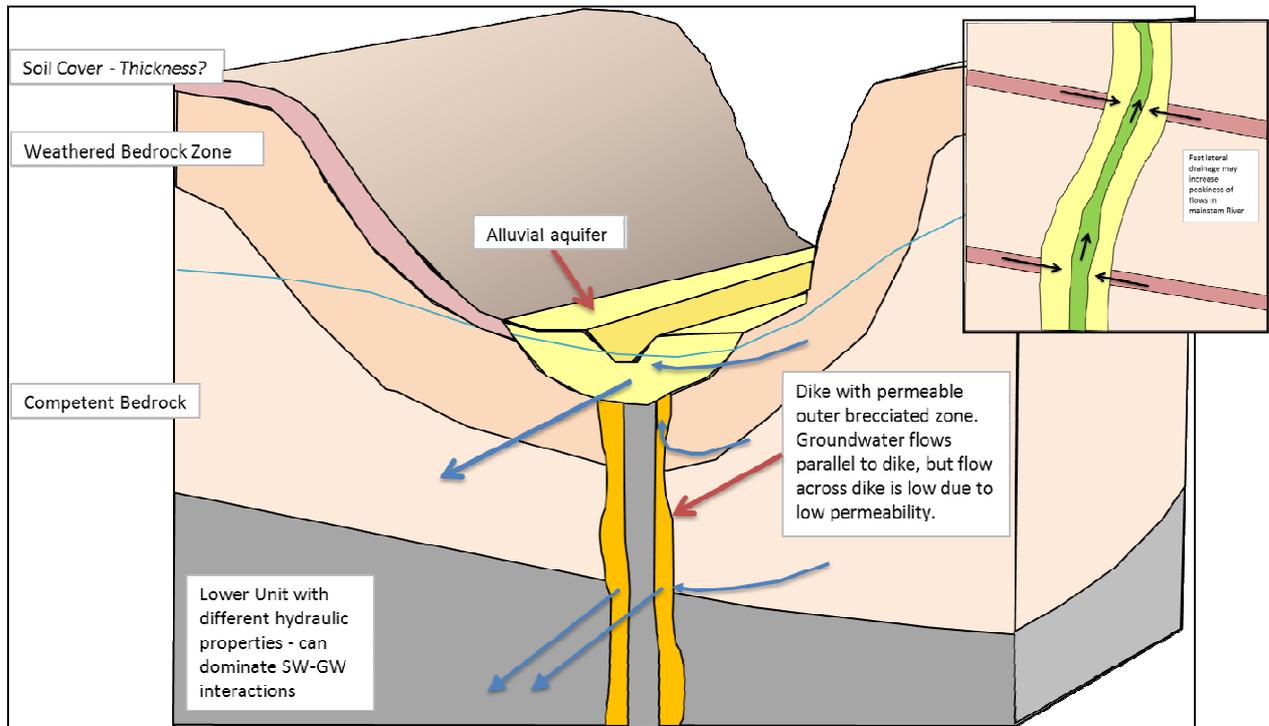


Figure 57. Conceptual flow model – local stream system with subsurface controls (dikes, layered units, weathered bedrock zones)

6.6 Integrated Hydrologic Model Development

This section describes the selection of the numerical hydrologic code and its capabilities, and the development of the model input and associated assumptions.

For a detailed description of model development refer to Prucha and Graham (2012).

The integrated hydrologic flow conditions of the Mokolo River require a code that is able to account for the spatial-temporal variation in climate, soils, vegetation and geologic properties across the catchment. Additionally, the code must also simulate coupled surface runoff, channel flow, unsaturated zone flow, groundwater flow and effects of irrigation, to account for the dynamic and integrated nature of the hydrologic system. Traditional single-process groundwater or surface water codes do not meet these needs. Hydrologic flow conditions in integrated codes are driven by external climate data, while in single-process codes, processes such as recharge must be estimated externally, usually with little physical basis, and therefore, considerable uncertainty. Integrated codes simulate all of the hydrologic processes, whereas in single-process codes assumptions about boundary conditions must be specified. The MIKE SHE code was selected for use in this study because of its broad world-wide use and application in similar hydrologic systems, and because it is based on rigorous, physically-based flow equations that allow specification of physical, rather than empirical inputs. This allows the code to simulate future scenarios in which various landuse, or

subsurface parameters (e.g. surface topography, vegetation, soil, and climate) can be changed using physically-realistic or measureable values.

6.6.1 Numerical Model Development

The development of the MIKE SHE model datasets and associated assumptions are presented in this section.

6.6.1.1 Model boundary and grid discretization

The MIKE SHE model boundary coincides with the study area boundary (see Figure 14). This boundary was defined in part because it represents a surface water divide based on topography. This boundary also appears valid as a groundwater divide given the anticlinal (inward dipping) structure of the catchment. Surface and groundwater divides represent good boundaries in integrated models because despite fluctuations in groundwater levels at the boundaries, no flows are expected across them. Simulation of subsurface and overland flows requires specification of a regularly-spaced, square finite difference grid across the model domain. A 500-meter grid was selected.

6.6.1.2 Unsaturated Zone Flow

The full Richards Equation method was used to simulate unsaturated zone flow in the Mokolo basin, mainly because groundwater depths are relatively deep, averaging between 20 to 25 meters.

The general soils distribution provided (Van Tol and le Roux, 2012) was used as the basis for input into the MIKE SHE model. Only two Terrain Morphological Units were actually defined in the model; one zone is adjacent to major rivers, and the other represents all uphill soils zones. Initial modelling indicated that a better stream discharge response could be obtained by allowing macropore bypass. Higher macropore bypass was assigned to alluvial soils (30%), compared to uphill soils (5%). The vertical discretization of each soil column is the same throughout the model and starts with 1 cm cells at ground surface to account for the non-linear soil evaporation and transpiration in this top cell. Vertical cells were smoothly increased in size to a constant 0.5 m to below the groundwater table.

6.6.1.3 Saturated Zone Flow

Vertical Aquifer Delineation is illustrated in Figure 58 that shows the final saturated zone layering and hydraulic properties used in the calibrated model. Groundwater flow in the saturated zone is simulated using three different vertical zones: alluvial or unconsolidated deposit overlying weathered bedrock that overlies more competent bedrock. These zones were based on review of borehole logs, which indicate the presence of an unconsolidated deposit of variable thickness which overlies the bedrock.

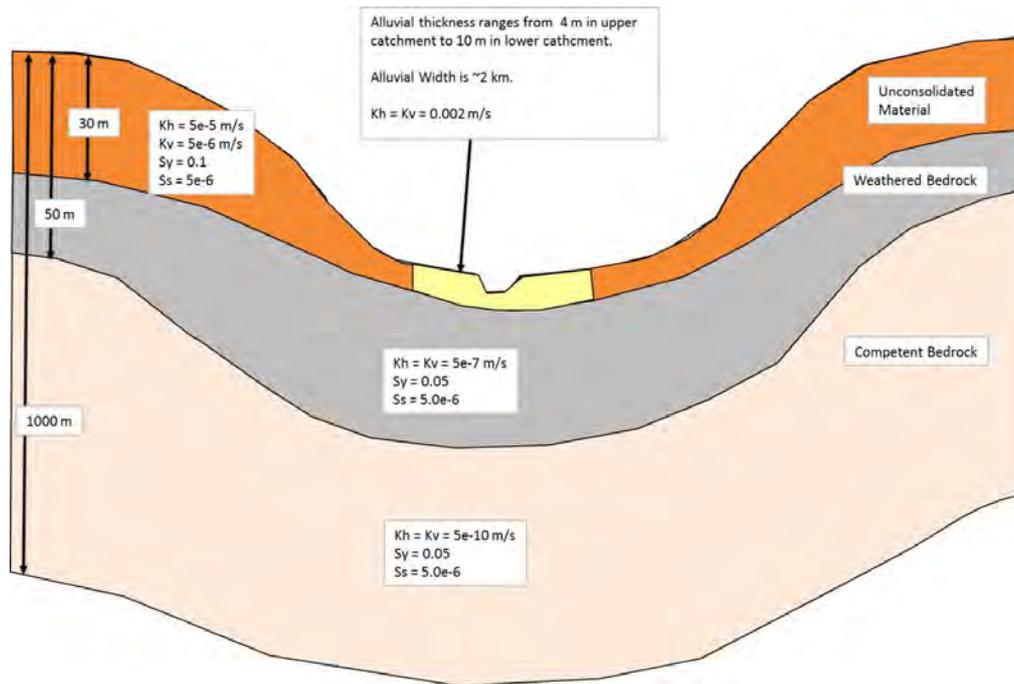


Figure 58. Saturated zone layering and hydraulic property distribution

6.6.1.4 Overland Flow

Surface resistance controls the rate of runoff from overland areas. A single surface resistance value (Manning M) is specified for the entire Mokolo catchment. Although site-specific data were unavailable, the value was set to $10 \text{ m}^{(1/3)}/\text{s}$ based on dense brush in summer or a heavy stand of trees with a few down trees (Chow, 1959) in floodplains. Another parameter affecting overland flow is a threshold value controlling the amount of surface depression storage. In the model, this was set at 2 mm depth. Once ponding depths exceed this depth, overland flow can occur. Boundary and initial conditions also need to be specified in the model for overland flow. Since overland flow is a rapid process relative to subsurface flows, initial depths of overland water were set at 0 mm. The Mokolo model has a grid resolution that is too large to capture individual springs, but instead simulates the combined effect of these inflows to streams as groundwater baseflow, or as groundwater discharge to ground surface and then to streams.

6.6.1.5 Stream flow Network

Flow in 29 rivers is simulated in the Mokolo Catchment. Sections were placed every 2 km in rivers longer than 20 km, and every 1 km for all others. Upstream boundary conditions in all streams were set as no-flow and the only down-stream boundary condition required was along the Mokolo outlet to the Limpopo River. The surface water elevation was set about 1 m above the streambed to allow for continual outflow of discharge from the system.

The construction of the Mokolo Dam by early 1980 effectively breaks the Mokolo River system into two parts, two separate Mike 11 network configurations needed to be created; one prior to 1980 (no reservoir) and one after 1980 (with a reservoir). Completion of the Mokolo Dam occurred sometime in early 1980. In the post-dam configuration, the following features were modified:

- a spillway weir was added, developed based on the spillway elevation (911.98 m) and width,
- a discharge from the reservoir based on flows in the A4H010 gauge, 1.8 km downstream of the dam (this accounted for both controlled and uncontrolled releases).
- Evaporation from the dam surface area (variable in time).

Given uncertainties in input, gauge discharge data from A4H010, 1.8 km downstream of the Mokolo Dam was used as the historical discharge (1980 to 2000) to the Mokolo River because it includes both uncontrolled and controlled releases.

Flows were simulated using the fully hydrodynamic St Venant option in MIKE 11 so that backwater effects and flows in steeper slopes could be simulated. An option to use automatic time-steps was also specified.

Cross-section banks and invert elevations were adjusted based on the regional-scale topography and the need to have banks lower than adjacent model cells, to allow surface inflows from overland areas. About 1038 kilometres of stream length are simulated in the Mike 11 network.

6.6.1.6 Climate

Daily precipitation and potential evapotranspiration (PET) was specified for each Quaternary catchment based on the 1950 to 2000 data provided.

6.7 Integrated Hydrologic Model Calibration

Before the integrated flow model can be used to simulate future conditions, it must be calibrated against hydrologic data that describes the response of the system to variations in climate. This section focuses on describing the approach and results of the model calibration.

The calibration process attempted to reproduce a range of system responses, including:

- timing/duration of no-flow along gauged streams (dry periods),
- duration and magnitude of stream flows (low and high flow periods),
- flow duration,
- groundwater baseflow (end of non-rainy season),
- average and transient groundwater levels (wet/dry season),
- areas/rates of spring discharge, and
- gaining/losing reaches along the Mokolo and tributaries.

Calibration performance was assessed visually and using standard statistical measures, such as: Correlation coefficient, ME (mean error), MAE (mean absolute error) and RMSE (root mean square error) of river discharge, and ME and RMSE of monitored well water levels (< 2 m for the catchment).

6.7.1 Available Calibration Data

The Mokolo catchment is data limited (most data are raw and not integrated). Despite the limited calibration data, available information was used to the extent possible to calibrate the model. Two key datasets were used to calibrate the model namely mean daily river discharge and groundwater level data. The river discharge data represents the priority calibration dataset.

Key characteristics of the river discharge hydrographs that calibration attempts to reproduce include:

- Peak flow rates (some gauges, for example A4H002 do not include peak flows as the gauge is drowned above a certain level),
- Duration and shape of ascending/receding hydrograph:
- Early recession curve response tends to indicate near-stream subsurface storage (which in turn reflects subsurface structure and hydraulic properties), and
- Late recession curve response tends to reflect more of the subsurface flow system characteristics and hydraulic properties further from the stream (e.g. uphill areas).
- Baseflow rates during low precipitation periods (typically September time frame), and

- Flow rates (peak) and volumes.

For the purposes of this modelling effort, reported groundwater depths were assumed to relate to shallow screened wells, across the water table. It was also assumed that simulated transient groundwater levels (1950 to 2000) could be compared directly to the single water level reported and that this level was representative of the local groundwater conditions. Clearly, this would not apply to irrigated and mined areas where active groundwater pumping is occurring.

6.7.2 Calibration Approach

The approach used to calibrate the distributed-parameter integrated hydrologic flow model of the Mokolo Catchment follows the general approach outlined in Refsgaard et al. (2007). A step-wise, iterative approach to develop and calibrate the hydrologic model developed by Prucha (2002) and Kaiser-Hill (2002) was also used to guide the model calibration. In this approach, individual catchment models are used to help calibrate local-areas, without the numerical overburden of having to simulate the full regional-scale model. Manual calibration was used where a set of parameter values are adjusted, the model run and then assessed to see how well the model reproduces observed hydrologic system response (i.e. calibration targets) and then process is repeated until stop criteria are met. A high-level calibration was not possible for this model. Instead, the goal of the calibration was to attain the best calibration possible using the available data. Ultimately the calibration approach is dictated by available data, complexity of flow conditions (natural and anthropogenic) and required accuracy needed for ecological assessment. It is important to appreciate that if the integrated hydrologic flow model is unable to provide the level of accuracy required by the ecological DSS assessment, more data must be collected to reduce model calibration error and predictive uncertainty.

6.7.2.1 Calibration Parameters

The most important model parameters adjusted during the modelling in the context of the hill slope conceptual flow model is illustrated in Figure 59. In a given river drainage basin, this is a useful way to understand how adjustments to specific parameters affect the integrated hydrologic response, or unsaturated zone infiltration, recharge, groundwater level fluctuations, groundwater flows in the respective 3-layer system, baseflow into, or out of the river, and river discharge.

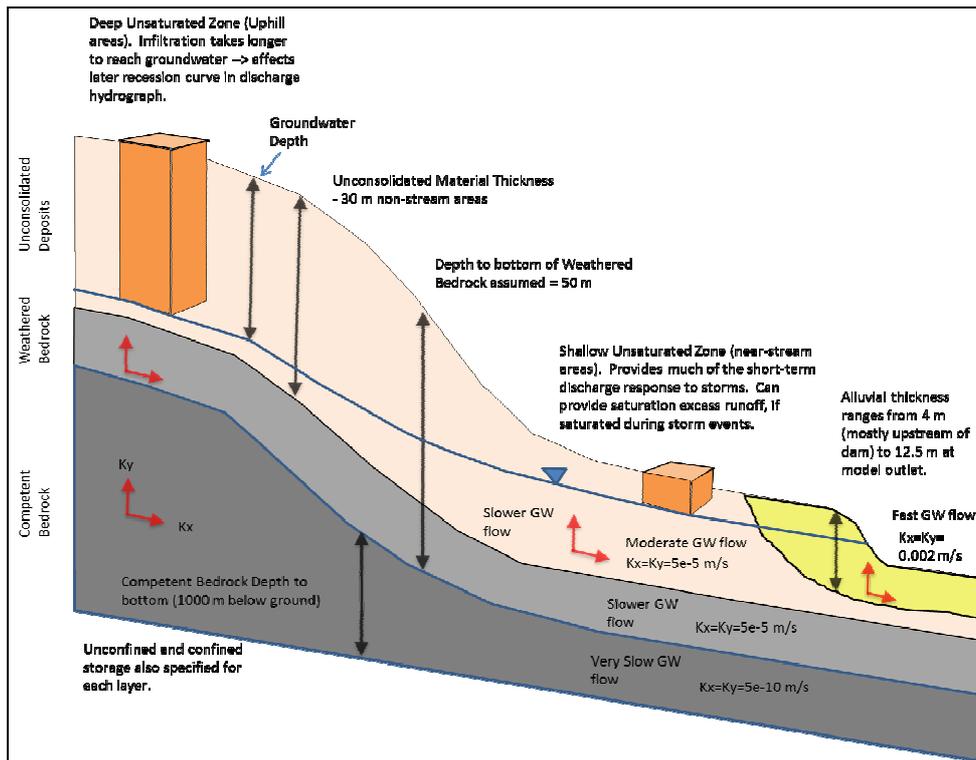


Figure 59. Key Model Parameters Adjusted during Calibration

6.7.2.2 Model Initialization

The Mokolo River basin hydrologic system is large, and assumed to be hydraulically connected. As a result, it has a large “hydraulic memory”, which means that the system requires a relatively long period of time to reach a dynamic state of equilibrium from imposed initial conditions. It is therefore, necessary to develop stabilized model conditions to new parameter values for, in the case of the Mokolo catchment model, 10 to 20 years (or longer, depending on parameter values specified), such that changes in groundwater levels, or baseflow to rivers have reached seasonal fluctuations, rather than long-term increases, or decreases due to initial conditions. For this model, initial steady state simulations were used to help determine long-term, stable groundwater potentiometric surfaces across the model. Simplified (spatially constant) steady state recharge rates were assumed in these simulations. A table indicating specific model parameters used and adjusted is available in Prucha and Graham (2012).

6.7.3 Calibration Results (1950 to 2000)

6.7.3.1 Model Characteristics

Model Run Times:

Pre-Dam (1950 to 1980) is about 21 hours. Model output is ~60 Gb.

Post-Dam (1980 to 2000) is about 9 hours.

Model Error: 0.08%.

6.7.3.2 Comparison of Simulated and Observed Data

A description of the comparison between simulated and observed data starts first with river discharge as the priority calibration target. Calibration of river discharge is considered more important than calibrating to groundwater levels because the discharge represents the cumulative effects of both groundwater and surface water runoff. In addition, the groundwater levels are less certain and not

transient compared to discharge data. As such, stream flow calibration is described first, followed by a discussion on calibration to groundwater depths.

Results of one gauge upstream and one downstream of the Mokolo Dam will be presented. For a detailed discussion of all gauging weirs please see Prucha and Graham (2012).

A4H002

This gauge has been operating the longest, and therefore its discharge is available from 1950 to 2000. Simulated discharge captures about 60% of observed discharge for both pre- and post-dam periods (Figure 60 and Figure 61), which makes sense because the gauge is located upstream of the dam. Peak flows cannot really be compared directly in this gauge because flows are drowned out above approximately $6 \text{ m}^3/\text{s}$. However, simulated peak flows (output every 2 hours) are slightly higher than the observed mean daily discharge, which is appropriate.

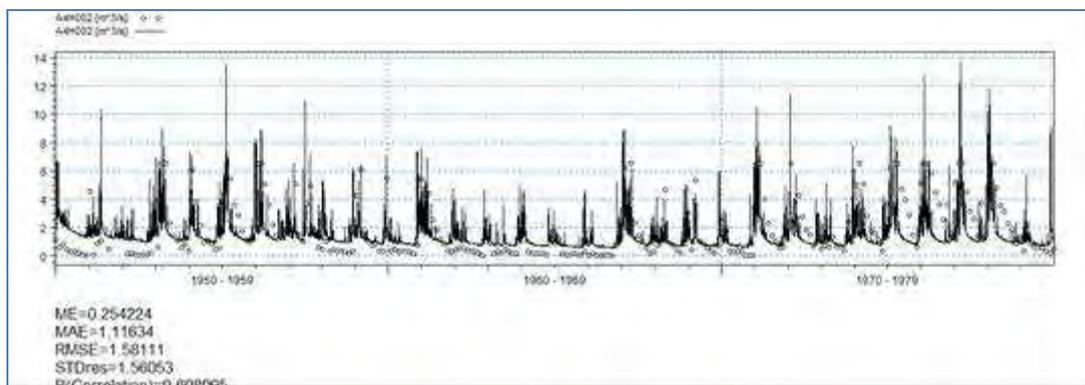


Figure 60. Pre-Dam (1950 to 1980) Daily Simulated (dots) and Observed (line) River Discharge at gauge A4H002 (Uppermost Mokolo River area). Correlation Coefficient is about 0.61

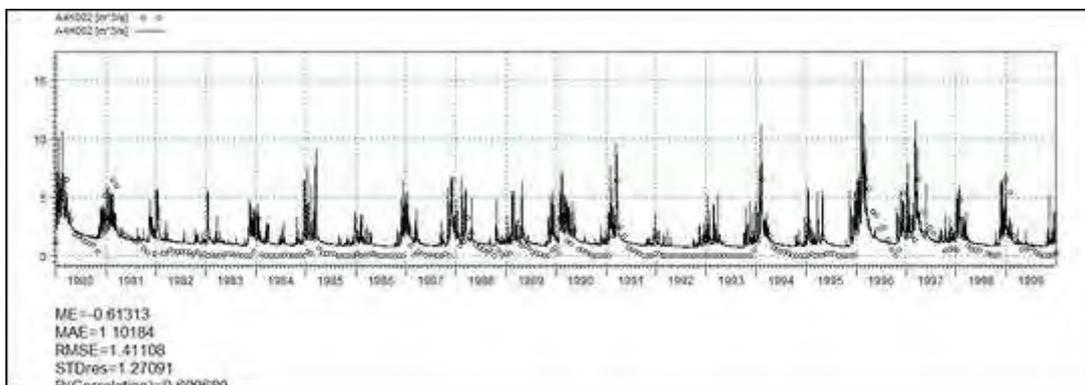


Figure 61. Post-Dam (1980 to 2000) Daily Simulated (dots) and Observed (line) River Discharge at gauge A4H002. (Uppermost Mokolo River area). Correlation Coefficient is also about 0.61

Inter-annual baseflow is generally captured well, though at no time does surface water cease to flow, which does occur during some years (1960s) according to gauge data. This is also a period of declining annual precipitation. However, the lack of zero flow can be caused by several aspects (most of these are a result of lack of data or incorrect data provided), including:

- Not accounting for irrigation properly (e.g. not enough is removed from rivers, or nearby groundwater, not enough is lost to evapotranspiration because it is not correctly applied to crop areas). No information is provided on where the irrigation occurs, but the reported irrigation (and from Google Earth) suggests it occurs above the A4H002 gauge.

- Not all groundwater pumping is accounted for in the model (only irrigation pumping from groundwater was specified in the model, despite data suggesting many more wells exist throughout the entire model, and not just in irrigation areas).
- Vegetation root depths are not specified deep enough, or LAI is not high enough to account for declines in low-flow (baseflow) surface water loss to ET.
- Not accounting for the effect of numerous small farm dams, or weirs on the Mokolo (e.g. at least six occur downstream of the dam and numerous upstream).
- Not accounting for in-stream storage increases flow through the system that should be stored in pools, or side channels.

Recession curves take months to decline, which is similar to observed. Observed recession curves generally take longer and indicate a greater discharged volume, suggesting that a greater volume of near-stream groundwater storage is available to discharge than represented in the model. This is supported by the simulated discharge associated with the annual rainy-season occurring too early (e.g. a few weeks to a month), which further suggests that the near-stream saturated zone storage needs time to fill as the rainy season initiates, and then the longer, more voluminous discharge during the end of rainy season takes longer to empty the storage.

A4H014

No gauge data exist during the calibration period. However, flows at this gauge depend heavily on the Mokolo Dam releases, which in turn depend on a poorly known operating strategy that produces controlled and uncontrolled releases. Observed data post 2004 provides some insight into the general behaviour (see Figure 62). Although there are no correlations in the non-overlapping discharge data, peak flows and recession curves are similar. Discharge at this gauge is similar to, but delayed and somewhat damped from propagation of releases from the Mokolo Dam as recorded 1.8 km downstream of the Dam at gauge A4H010.

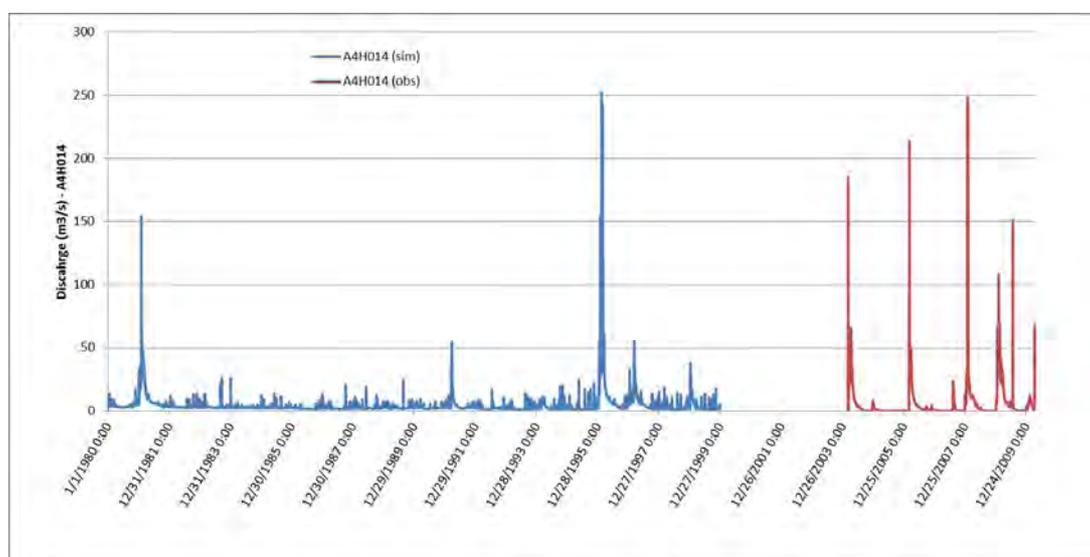


Figure 62. Observed Post-Dam (red line) and Simulated (blue line) Mean Daily Discharge at gauge A4H014 at Outlet of Mokolo River Basin, upstream of Limpopo River confluence

Groundwater

An average of all Mean Error (ME) values is about -5.5 meters, indicating that average simulated levels across the entire Mokolo Catchment are generally higher than observed. This trend is more apparent in the northern, lower elevation basin area (toward the outlet of Mokolo River). In contrast,

simulated levels in the upper 2/3 of the basin tend to be too low. Levels that are under-simulated (i.e. positive values) in the Waterberg Formation may reflect shallower occurrence of lower permeability bedrock, which would maintain higher heads in these areas. Results for post-dam periods show little difference to results from the pre-dam periods.

There are many reasons why simulated groundwater levels may be higher than observed levels, but one reason may be that the observed data reflect levels influenced by pumping in the well itself, or pumping nearby. Reliable information on groundwater abstractions over time (e.g. depths, rates, and durations) was not provided.

Other Simulated Hydrologic Responses – Present day

A water balance for the entire Mokolo River Basin catchment from 1950 to 2000 is summarized in Figure 63. Results show that much of the annual precipitation is lost to actual evapotranspiration (AET), and in some years, AET exceeds the annual precipitation. Most of the AET is in the form of soil evaporation, rather than plant transpiration, though this may be different with improved data on LAI and root depth.

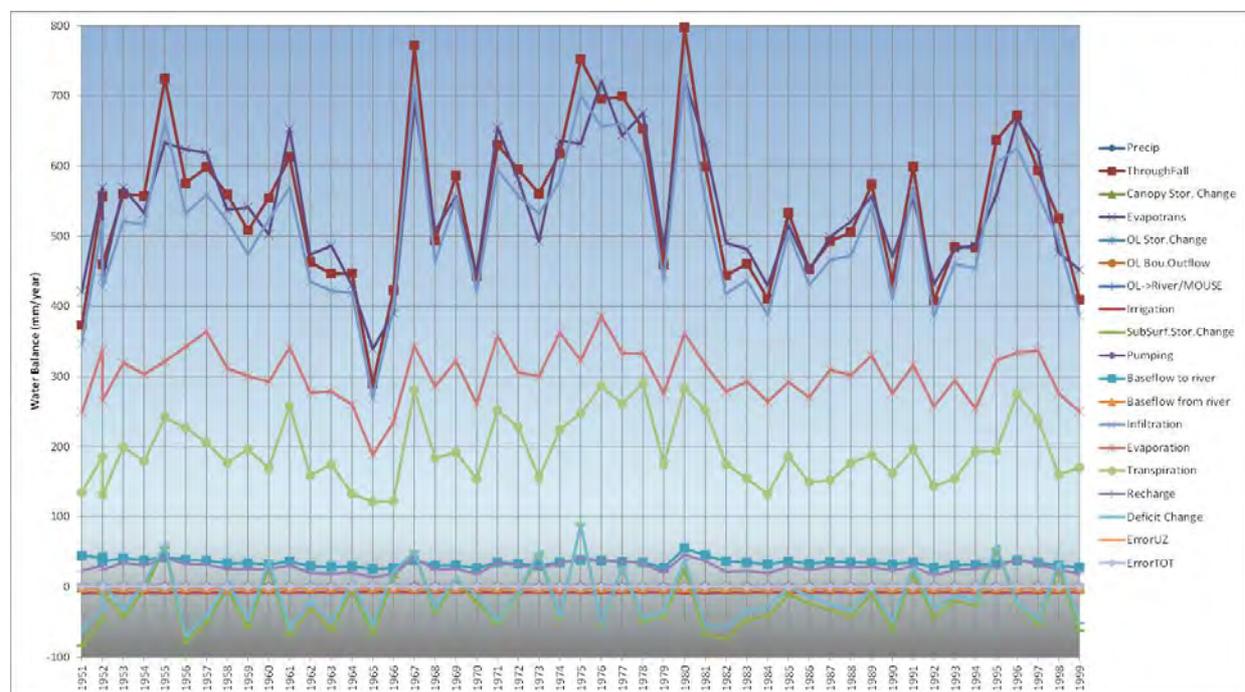


Figure 63. Water Balance for the Entire Mokolo River Basin System (1950-2000)

Only a low percentage of annual precipitation is translated into recharge (about 5.1% of annual precipitation). As expected, a higher recharge rate, as a percentage of annual precipitation occurs in the uppermost quaternary catchment, where the most annual rainfall occurs (7.4% in A42B) and the least occurs in the lowest catchment A42J (0.8%). Some of the higher recharge in upper catchments, where more irrigation occurs, is actually due to irrigation return flow, though this remains somewhat uncertain, due to the uncertainty in irrigated application areas (likely specified as too small an area, which would reduce the return flow and increase loss of ET). Areas where groundwater levels are simulated at or above the ground generally correlate with areas denoted as wetlands. Typically these areas occur along drainages, or groundwater discharge areas. It also suggests that the wetlands in these areas are sustained by groundwater, rather than by surface runoff into depressions that have low permeability material beneath them. Higher Actual ET levels occur in shallow groundwater areas

and in irrigated areas. Actual ET levels are higher in the lower elevation northern part of the catchment due to higher PET values. Lower values occur in the central part of the catchment north of the Mokolo Dam due to a combination of hydraulic properties of the shallow responsive soil types and vegetation properties of the Waterberg Mountain Bushveld.

6.7.3.3 Calibration Sensitivity Analysis

Following the calibration process, a total of 66 simulations were conducted to further evaluate the sensitivity of model results to parameter values and assumptions. A desired goal was to evaluate the sensitivity of model inputs and assumptions on producing non-perennial flow conditions in the rivers while attempting to reproduce observed system response, which included the annual cumulative flows and groundwater levels. A result of this analysis produced a new model setup that was subsequently used to define the present day (baseline) and future scenario setups.

An important observation was that the model was unable to reproduce non-perennial conditions, probably because water extraction was underestimated in the alluvial layer. To test this assumption, a subsurface drain (internal boundary) was added that extracts groundwater in the river alluvium. This was a way of simulating the net effect of irrigation on decreasing available alluvial groundwater that provides baseflow inflow to the river. The assumption was not really “tested”, but rather imposed to demonstrate that it forces the river flow to equal zero when baseflow is effectively removed via the subsurface drain. Figure 64 shows the required extraction in the alluvial layer estimated by the calibrated model. Adding the subsurface drain in the stream alluvium improves the model’s ability to simulate non-perennial conditions and produces a sudden drop in flow at the beginning of September that is otherwise not observed.

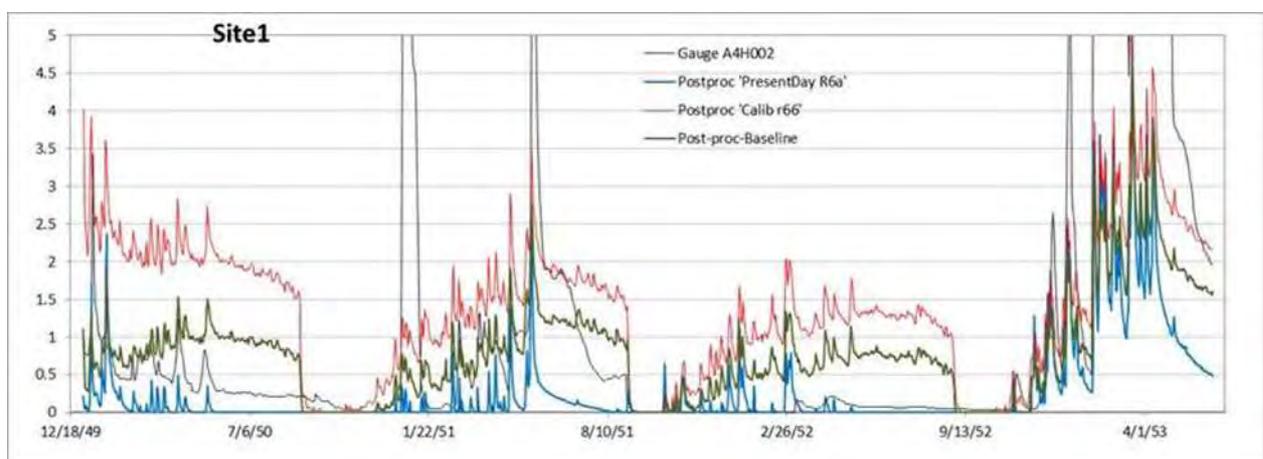


Figure 64. Flow results at site 1 with and without the internal boundary set

Figure 64 shows that the shape of the observed flow curve is similar to the previous model results without using the subsurface drain/internal boundary condition.

In the revised calibrated model, a total of 2521 groundwater cells were defined with this internal boundary condition. The selected cells all satisfied three conditions:

- they have baseflow interaction with the rivers,
- the top layer thickness is less than 10m, and
- they are not beneath the Mokolo Dam footprint or beneath the study sites.

The head drain time series was set to a monthly time step. The topography plus 50 meters was used as the drain head, which turns off the boundary. At the beginning and the end of September, the drain head was changed to the bottom elevation of the alluvial layer to turn on the boundary in September

A complete discussion of the calibration sensitivity analysis can be obtained from Prucha and Graham (2012).

6.7.3.4 Revised Calibration

Following the sensitivity analysis, the initial calibration was modified to produce a present day (baseline) model for the scenarios. The summary of the specific changes are detailed below.

Initial Conditions – The initial conditions were taken from the previous simulation, thus shortening the warming period.

Overland Solver – The OL (Overland) solver option was changed from SOR (Successive Over-Relaxation) to Explicit to reduce potential mass balance errors.

MIKE 11 Time Step – The time step in MIKE 11 was reduced from 2 to 0.5 minutes, which generally made the simulation more numerically stable, but increased simulation time.

Mike 11 Channel resistance – The Mannings resistance at the banks in all the cross-sections was changed from 0.05 to 0.1 which decreased the peak amplitude in the flows.

Mike11 Weirs – Weirs (structures) were introduced in the model to account for 25 dams (effectively dams across rivers) and 6 weirs. All 31 of these 'structures' in the river network modelled were done so with a broad-crested weir. Six of these structures are located downstream of the Mokolo Dam. Of these 6, three are weirs at stream gauges (1 on Mokolo River, just downstream of the Mokolo Dam, and 1 each on Tambotie and Poer-se-Loop tributaries). The additional weirs had no significant effect on the model results.

Mokolo Dam Operations – The Mokolo Dam releases under post-dam conditions was modified to use two discharge control structures, one for the gate and the other for the spill way, with a specific stage-discharge relationship.

Mokolo Dam water users – A culvert was added upstream of the dam to simulate additional water removed by water users.

Irrigation demand – The irrigation demand rate was changed from a fixed rate to a method driven by a crop stress factor, where water is applied whenever the plant stress goes below 0.95.

Irrigation application – The maximum application rate was doubled from 1.5 to 3 mm/day, which is closer to the average Reference ET (Evapotranspiration) rate.

Unsaturated flow – The maximum bypass fraction was set to 0.2 for all soils. The water table elevations and stream flows are very sensitive to this parameter.

Saturated zone specific storage – The specific storage in all the saturated zone layers was halved to 0.5e-5 from 1e-5, which is within the expected range.

Saturated zone alluvial drainage – An internal head drainage boundary was defined in the alluvium to simulate unrecorded pumping in September.

Saturated zone lateral conductance – A solver option was activated to reduce the dependence of lateral cell conductance on dry cells (Extra Parameter: "disable harmonic mean of sz conductivity")

6.8 Future Scenario Simulations

6.8.1 Approach

6.8.1.1 Hydrologic and Hydraulic Indicators

At a workshop, with the project team, in March 2012 it was agreed that DHI would provide specific outputs at the five study sites related to the ecological indicators (Table 27) required by the other members of the project team.

Most of the values for each indicator can be derived from a small set of model outputs for each study site:

- River discharge at the site,

- River stage at the site,
- Groundwater depth beneath the site
- Groundwater flow parallel to the river beneath the site, and
- Net groundwater baseflow to the river at the site.

6.8.1.2 Scenarios

The five scenarios are summarized in Table 39. The scenarios are numbered 1-5, where 1 is the Baseline, or “Present Day” scenario. With the exception of scenario 1, each of the scenarios simulates a continuous future 50-year period, using climate data from 1950 to 2000. For simplicity, the future model runs are assumed to start at climate year 1/1/1950. This time period was chosen because it corresponds with available climate data. Climate data (precipitation and reference ET) post-2000 was not provided for the basin. It is also important to note that the future simulations were conducted using the 1950-2000 dates and times, rather than projecting future dates. Using the 1950-2000 dates and times allowed a direct comparison between the future scenarios and the present day.

The Baseline (Present day) scenario is simply an extension of the calibrated model, except that it assumes the Mokolo Dam is present during the entire 1950-2000 period. It is essential to simulate this scenario to understand how the present day conditions change due to proposed changes in Scenario 2 through to Scenario 5. Results of the future scenarios, 2 through 5 are then compared against results of Scenario 1 to obtain the relative changes in system flow conditions.

Table 39. Future Scenario Assumptions (Highlighted areas are different from the Baseline/Present day Scenario)

Scenarios	1. Baseline / present day	2. Natural	3. Irrigated Areas to Game farms	4. Expansion in Mine/ Power & Town	5. Combination of 3 and 4
Mokolo Dam	Yes	No	Yes	Yes	Yes
Farm dams	Yes	No	Downstream stays the same	Yes	Downstream stays the same
Weirs	Yes	No	Yes	Yes	Yes
Interbasin water transfer from Crocodile River	No	No	No	Yes	Yes
Irrigation	Yes	No	Downstream stays the same	Yes	Downstream stays the same
Vegetation	No	No	Yes	No	Yes

The following assumptions (a detailed discussion is available in Prucha and Graham, 2012) were made for future scenarios:

Mokolo Dam

The Mokolo Dam is simulated for all 50 years in all scenarios except for the Natural scenario (2). In this instance, a natural stream profile was estimated through the existing reservoir and dam based on the upstream and downstream profile. All flow upstream of the Mokolo Dam was routed downstream to the outlet of the model (through gauge A4H014). The post-dam simulation period was 20 years (1980-2000). The simulation period for future scenarios is 50 years (1950-2000). Therefore, the conceptualization of the Mokolo Dam was modified in the future scenarios. The flow released through the gate was set based on the monthly averaged flows at station A4H010. The rate of water extraction from the Mokolo Dam was assumed constant at 2.5 m³/s. This value is lower than the average extraction in the calibrated post-dam model (1980-2000) which is 2.8 m³/s. However, a constant extraction above 2.5 m³/s in the scenarios could cause the upstream water levels to decrease unrealistically during dry years.

Farm dams

For the future scenarios, 25 local farm dams were simulated in the Present Day (1), Game Farming (3), Expansion (4) and Combined (5) scenarios. These were selected along streams, to account for additional storage and evaporation losses to the regional flows.

Observation Weirs

Weirs were simulated in Mike11 at all stream gauge locations to simulate discharge at these locations.

Cross-sections

To produce simulated stream stage at the five study sites, it was necessary to include cross-sections measured in the field. The sections shown in Figure 52 were used as the basis for calculating stage at the five study sites. Ideally, sections would have been measured upstream, downstream and through each study site to produce more accurate stage levels. In the absence of additional cross-sections, these sections were repeated upstream and downstream of each site. The thalweg elevations were based on the stream profile already in Mike 11.

Interbasin water transfer from Crocodile River

In the Expansion (4) and Combined (5) scenarios, the effect of the interbasin transfer from the Crocodile River into the Mokolo Basin was simulated. The transfer was made to support expansion of the Exxaro mine, Eskom Powerplants (Medupi and Matimba) and Lephalale town water supply. Water was applied in these scenarios using the irrigation module. The only information provided for this scenario was an estimate of the future amount of water required by the mine; the power plant and the town expansion. No information was provided to describe how the additional water might be used in the expansions. For a more realistic scenario, the following information is required:

- Where will the water be applied?
- How is the water to be 'applied' to each expansion area?
- What is the estimated application rate?
- How is unused water returned to the surrounding environment?
- How much water is consumed in each expansion area?

Irrigation

Irrigation was turned off over the entire model extent for the Natural scenario and upstream of the Mokolo Dam for the Game Farming and Combined scenarios. Irrigated vegetation was changed to game farm native vegetation. Irrigation was left on downstream of the Mokolo Dam for the Game Farming and Combined scenarios and for the entire model in the Baseline/PD and Expansion scenarios.

Vegetation

The highlighted vegetation types (Mixed Bushveld, North-eastern Mountain Sourveld and Sour Bushveld) show zero acreage in Present Day, Natural and Expansion scenarios in which the vegetation is not changed upstream of the Mokolo Dam (Table 40). The calibration vegetation distribution in these areas was specified as shown in the GIS (Mucina and Rutherford, 2006) coverage provided (see Prucha and Graham, 2012), which is different from the "Land Cover (Acocks)" vegetation distribution that was used to define the Game Farm 'native vegetation'. Different vegetation input data were used for the Natural and Game Farm scenarios. The input data used for the Game Farm scenario was ACRU Acocks Kc to LAI and the MODIS LAI input data on Mucina and Rutherford (2006) vegetation types was used for the Natural scenario. **This should not have been done and would not be repeated if model was rerun.** In the Game Farm scenario, the original land cover types were converted to Mixed Bushveld (from cultivated temporary-commercial irrigated), Sour

Bushveld (cultivated temporary-commercial dryland), and North-Eastern Mountain Sourveld (cultivated temporary-semi-commercial).

Table 40. Vegetation parameters specified for each scenario

	Parameters			Scenarios			
				Present day, Natural and Expansion		Game farming and Combined	
	LAI	Root	Kc	Area		Area	
Vegetation type	---	mm	---	hectare	%	hectare	%
Central Sandy Bushveld	0.39-1.6	2000	1.0	241284	28.6	179763	21.3
Limpopo Sweet Bushveld	1.39-2.43	2000	1.0	192843	22.9	192843	22.9
Mixed Bushveld	0-1.29	1000	0.2-0.75	0	0	14743	1.7
North-Eastern Mountain Sourveld	0-1.29	1000	0.25-0.75	0	0	42	0.0
Roodeberg Bushveld	0.26-1.62	2000	1.0	34663	4.1	34663	4.1
Sour Bushveld	0-1.29	1000	0.2-0.75	0.0	0.0	56832	6.7
Subtropical Alluvial Vegetation	1.02-1.96	2000	1.0	1792	0.2	1792	0.2
Waterberg Mountain Bushveld	0.39-1.56	2000	1.0	315992	37.5	306365	36.3
Waterberg-Magaliesberg Summit Sourveld	0.27-1.08	2000	1.0	18369	2.2	18328	2.2
Western Sandy Bushveld	0.33-1.76	2000	1.0	38773	4.6	38441	4.6
			Total	843716	100	843812	100

6.8.2 Results

Simulated scenario results are described by discharge, stage, net groundwater baseflow to the river, underflow and groundwater depth. Results are described first by study sites to see the relative change against Present Day (baseline) conditions, and then against each other.

Only results from sites 1 and 4 will be presented here (for results of other sites see Prucha and Graham, 2012).

Stream discharges at Study Site 1, the site most upstream of the Mokolo Dam show that discharge from the Game Farm (3) and the Combined (5) scenario, which includes the conversion of existing vegetation upstream of the Mokolo Dam to game farm native vegetation, results in the highest flows (Figure 65). The conversion to Natural conditions (2), where all irrigation is removed, is slightly lower, and the Present Day/Baseline (1) and Expansion (4) scenarios are lowest because upstream of the dam, they have identical conditions. It is important to note that peak flows increase significantly (up to about 70 times) above Present Day/Baseline conditions in the Natural, Game Farm and Combined scenarios, reflecting the notable effects that irrigation has on overall stream discharge characteristics. The increase in the Expansion scenario is primarily due to initialization effects.

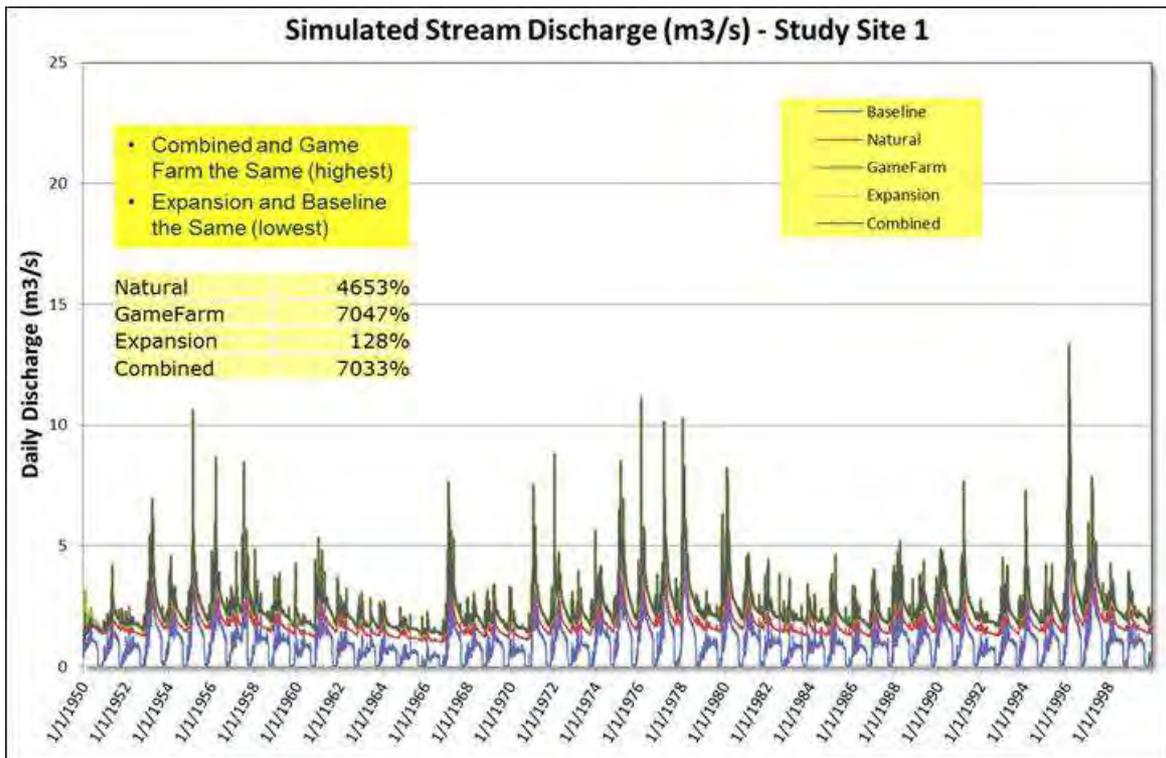


Figure 65. Simulated post-processed daily stream discharge for all scenarios at Site 1 (m³/s) on the Mokolo River. (Percentage values in box are average changes in stream discharge at site 1 relative to the PD scenario)

Similar patterns to the changes in stream discharge are found downstream of the dam at Study Site 4, except that the Natural scenario shows the highest discharge of all scenarios, primarily because the Mokolo Dam has been removed, allowing discharge to flow unimpeded downstream (Figure 66). Increased discharge upstream of the Mokolo Dam, relative to PD/Baseline, for the Game Farm and Combined scenarios are passed downstream of the dam. Perhaps the most important observation is that little effect of the inter-basin transfer is seen in the discharge in the Expansion scenario. The discharge is nearly identical to the PD/Baseline scenario. This can be explained by the fact that the return flow from the inter-basin water is lost to evapotranspiration and groundwater storage. The increased groundwater storage would not significantly change the Mokolo River discharge because the application areas are several kilometres from the nearest stream.

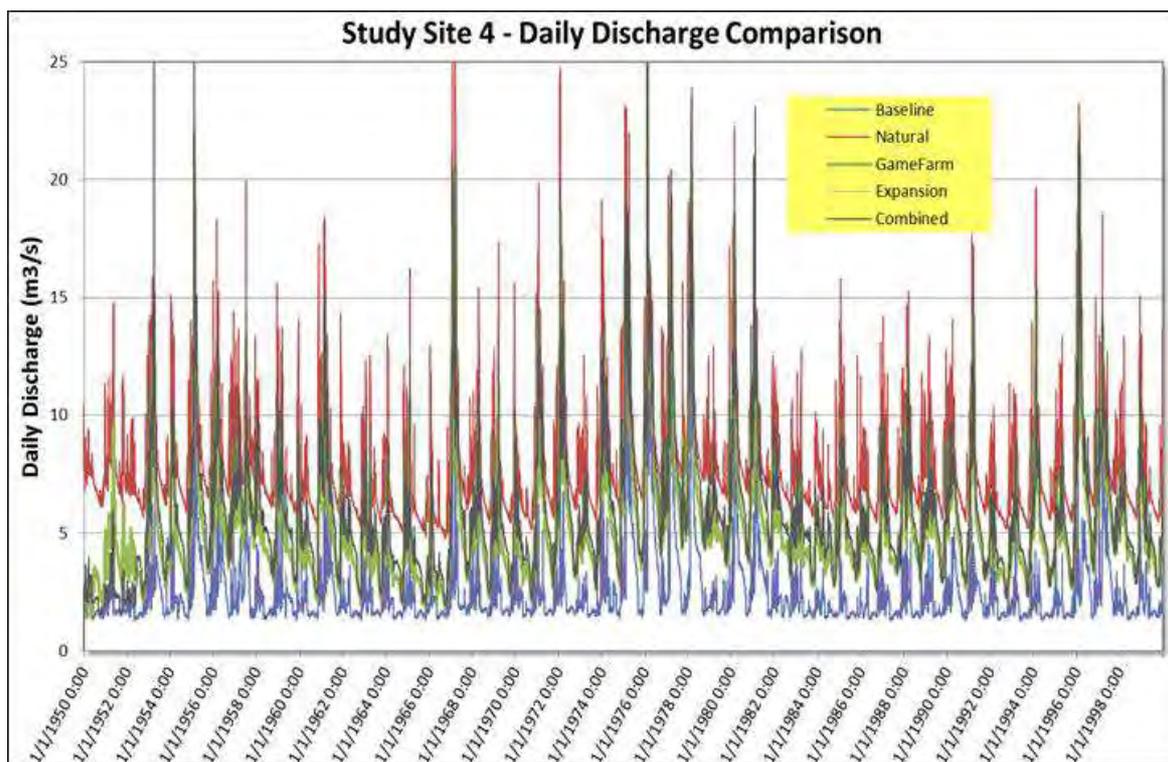


Figure 66. Simulated daily stream discharge for all scenarios at Study Site 4 (m³/s) on the Mokolo River. (This discharge was not post-processed)

Changes in river stage show similar trends in increase in the Game Farm and Combined Scenarios, but the relative change is much lower than for the discharge (Table 41). The Expansion scenario shows little change in stage. The non-zero maximum and minimum changes in stage in the Expansion and Combined scenarios is likely due to slight differences in the numerical solution (i.e. differences in error) during peak or minimum flow periods. The means are however near zero as expected.

Table 41. Scenario percent change in river stage relative to PD/Baseline at Sites 1 and 4 on the Mokolo River

Scenario	Study Site	Mean (%)	Max (%)	Min (%)
Natural	1	76	1588	1
	4	60	128	4
Game Farm	1	96	1748	12
	4	34	112	-9
Expansion	1	-1	158	-61
	4	0	18	-25
Combined	1	96	1744	-77
	4	33	111	-91

The change in baseflow is determined from the two adjacent model cells on either side of the river and not the entire segment upstream of each study site (i.e. between sites), The baseflow changes in Table 42 reflect very local conditions and not necessarily changes in discharge. The baseflow at Site 1 in the Game Farm and Combined scenarios increase with increasing discharge and stage. In this case, change to the local groundwater conditions has also increased the baseflow discharge to river (i.e. changes in irrigation and vegetation).

Table 42. Scenario percent change in Baseflow relative to PD/Baseline at Sites 1 and 4 on the Mokolo River

Scenario	Study Site	Mean (%)	Max (%)	Min (%)
Natural	1	0	59	-41
	4	4	1250	-83
Game Farm	1	70	301	-21
	4	3	2058	-77
Expansion	1	0	12	-12
	4	3	929	-61
Combined	1	71	301	-5
	4	4	2079	-73

Changes in subsurface/underflow flow, parallel to and beneath the river are similar to changes in baseflow (Table 43). Because the flows are controlled by similar subsurface flow conditions (cells beneath the river have the same hydraulic properties) the change would be expected to be similar.

Table 43. Scenario percent change in Subsurface (groundwater) flow beneath (and parallel to) the river relative to PD/Baseline for Sites 1 and 4 on the Mokolo River

Scenario	Study Site	Mean (%)	Max (%)	Min (%)
Natural	1	-7	836	-91
	4	2	402	-71
Game Farm	1	32	7766	-95
	4	1	147	-84
Expansion	1	1	971	-81
	4	0	368	-86
Combined	1	33	7793	-91
	4	0	335	-90

Virtually no change is observed in groundwater depths (Table 44). This is mostly due to the fact that only a small change in depth is needed to produce a larger change in baseflow. This is because of the relatively large grid size next to the rivers in the regional-scale model (500 m x 500 m). If a higher resolution grid (e.g. 10 m) had been used, simulated changes in groundwater beneath the river would be dominated by changes in river stage and they would be virtually the same (assuming no low permeability material exists between the river bed and groundwater).

Table 44. Scenario percent change in Groundwater Depth relative to PD/Baseline for Sites 1 and 4 on the Mokolo River

Scenario	Study Site	Mean (%)	Max (%)	Min (%)
Natural	1	0	2	-2
	4	0	2	-1
Game Farm	1	-1	3	-18
	4	0	1	-1
Expansion	1	0	2	-2
	4	0	1	-2
Combined	1	-1	3	-18
	4	0	1	-1

Changes in baseflow for the Game Farming and Combined scenarios appear to increase over the entire 50-year simulation, suggesting that the land-use modifications will take more than 50-years to stabilize. Baseflow increases by about 30% for these two scenarios. For the Natural scenario, the baseflow actually declines over the same period from about 23% to 18% which is likely due to the slow drainage of groundwater surrounding the Mokolo Dam (which is removed in this simulation). This scenario was initialized the same as other scenarios to allow for direct comparison with output from

the other scenarios. The effect of the increased groundwater storage around the Mokolo Dam was not removed which would have been ideal. Baseflow downstream of the Mokolo Dam for the Natural scenario also shows a similar decline when compared to the Game Farming and Combined scenarios.

The net effect of the Game Farm and Combined conversion upstream of the dam increases the surface runoff to the river. These changes are probably due to increased saturation excess runoff near streams in areas where the vegetation was changed to the native types (using different LAI, Kc and root depths in Game Farm and Combined scenarios compared to the MODIS LAI approach used in the Baseline).

6.9 Local-Scale Modelling

6.9.1 Model setup

Two local-scale models were created to evaluate the effects of scale on the simulated scenario outputs. The locations of the two models were selected at Study Sites 1 and 4. The grid size of the local-scale models is 100 m. Time-varying head boundaries were set along the perimeter of both models and linked to the regional-scale scenario outputs. The model was pre-run to develop equivalent initial conditions for all scenarios. The local-scale model boundaries were defined away from the Mokolo River to limit the effects of the lateral boundary conditions. Overland flow across the local model boundaries were assumed to be zero, which is reasonable given the limited overland runoff in non-stream areas (limited Hortonian flows). Inflow discharges were set at the upstream Mike 11 river boundary, and a constant stage was set at the outlet to allow flows to discharge, unimpeded out of the local model. This boundary has no effect upstream in the local-scale model.

6.9.2 Results

Results of the local-scale simulations show an increase in discharge (Figure 67) of 9 to 103% compared to the regional-scale simulations. The main reason why the Expansion scenario shows a 103% increase relative to the regional model results is that numerical stability parameters had to be changed in this simulation to allow the model to converge to a solution. The net increase in surface discharge is likely due to improved simulation of hydrologic processes near the river with the increased grid resolution.

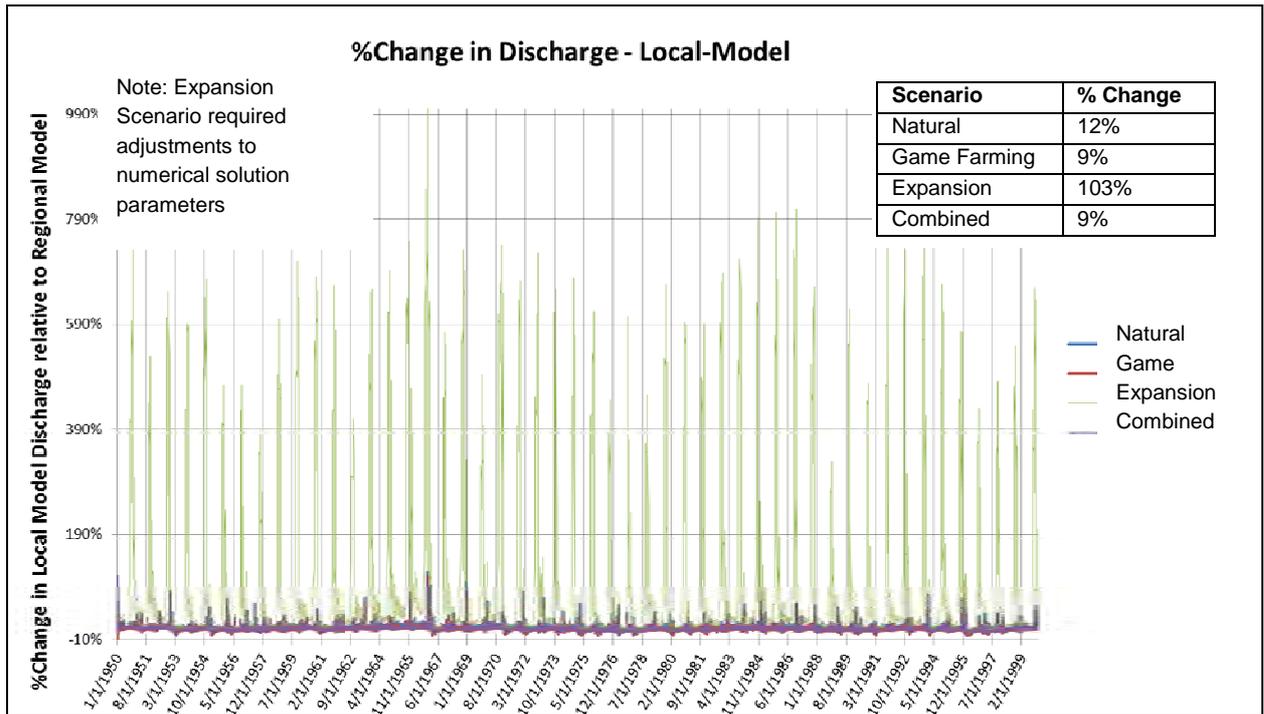


Figure 67. Percentage change in Discharge of Local Scale Model compared to regional model

Figure 68 shows that groundwater depths decrease 67 to 72% and baseflow decreases with 102-112% in the local-scale model, relative to the regional scale model. The only way to account for this decrease in groundwater depths and baseflow with a corresponding increase in stream discharge is that there was an increase in overland flow to the river. This probably occurs because the topography near the river is better resolved, allowing for steep gradients.

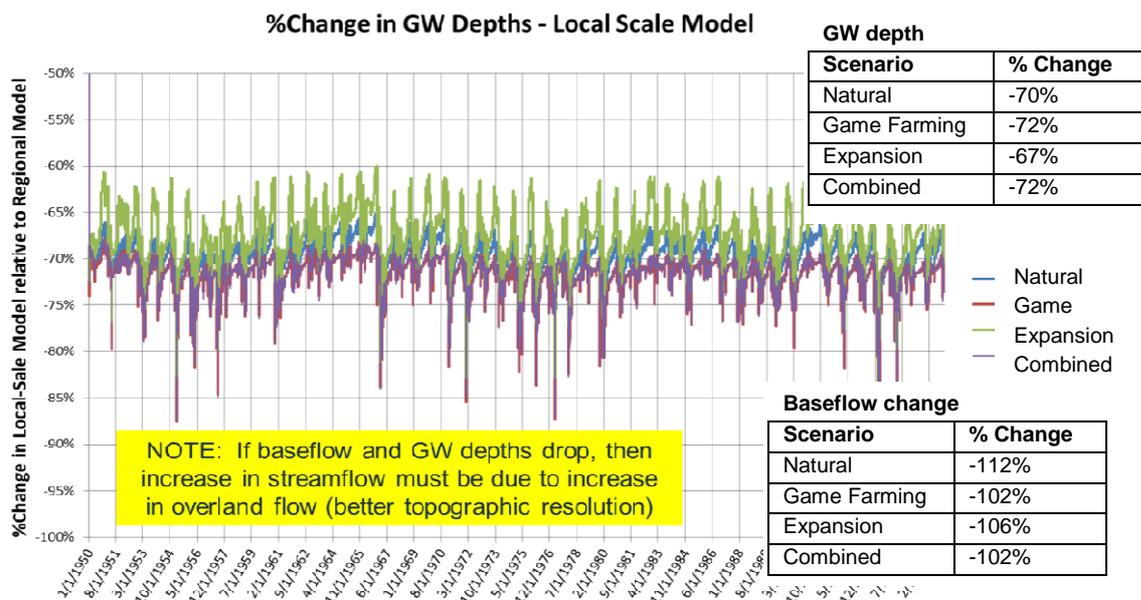


Figure 68. Percent Change in Discharge in Local Scale Model compared to regional scale model

6.10 Hydrological model output provided to team for input into DSS

A daily time-series of data were provided for:

- River discharge
- River stage
- Depth to groundwater beneath river
- Baseflow to river and
- Groundwater flow beneath river for all five study sites and five chosen scenarios.

6.11 Activity 20 Hydrological and hydraulic indicator values as input into DRIFT-Arid DSS

Dr. Alison Joubert calculated the flow and hydraulic indicators (a value for each indicator for each year) as well as the medians, ranges and standard deviations from the daily time series of flow, depth, groundwater depth, baseflow and groundwater flow beneath river produced by the DHI using MIKE-SHE. The perennial river DRIFT DSS includes a module which determines the flow indicator values for perennial rivers but not for the specific non-perennial rivers indicators chosen for this study, so new routines were created (using Excel formulae and VBA) in order to calculate these. The flow indicator values were entered into the DRIFT-Arid DSS. A discussion of the DRIFT-Arid DSS and the results for each scenario chosen will be presented in Chapters 7 and 8.

7 PHASE 8: KNOWLEDGE CAPTURE USING THE DRIFT-ARID DECISION SUPPORT SYSTEM (DSS)

7.1 Introduction: the purpose of the DRIFT DSS

In essence the DRIFT-Arid DSS is the “engine” of the DRIFT-Arid method, which, in particular, helps to complete PHASES 8 to 10 of the DRIFT-Arid method, i.e.:

1. Phase 8: The capture of the project system and specialist knowledge in terms of:
 - Mapping data pathways
 - Capturing data in a database, including site names and information, scenario names and information, flow indicators, all other indicator names and all their linked indicators.
 - Creating response curves for each link
2. PHASE 9: The analysis of scenarios through:
 - Interpreting the changes predicted by the response curves for the present day scenario
 - The calibration of the model using all dry, all wet and combined dry and wet scenarios
3. PHASE 10: The evaluation of scenarios through:
 - Evaluating the impacts of scenarios on each indicator and discipline
 - Evaluating the overall impact of scenarios on sites and the catchment as a whole

7.2 Background

DRIFT and associated DRIFT-DSSs have evolved over the last couple of decades. In the latest version of DRIFT (WRC project K5/1873: Brown et al. (2013)), the following major changes have been included:

1. The original DRIFT scoring system and response curves concept have been adjusted to create a time-series approach. The response of an indicator over time is now predicted, rather than a single number being used to represent the change over a number of years;
2. Indicators can now respond to indicators other than flow (e.g. a fish species indicator can respond directly to the abundance of a macro-invertebrate indicator, rather than having to link to flow and try to internally infer the likely intermediate links in order to indicator the fish species’ response) (the so-called “linked indicator” approach; and
3. The DSS has been encoded in a software package rather than using Excel and VBA like previous versions of the DRIFT-DSS.

In the earlier phases of the development of non-perennial methods (WRC K5/1587), some prototype alternatives to or variations of DRIFT were attempted. However, during the current project it became apparent that DRIFT was an appropriate EWR approach, and together with the (Excel-based) DRIFT-DSS, some adjustments would make it suitable for non-perennial systems. This adjusted approach, now referred to as “DRIFT-Arid” is described in this document. The associated Excel-based DSS, now referred to as the “DRIFT-Arid DSS” is described in this chapter, providing an overview of the DSS conceptual model, together with some detail where relevant. A full user manual is not provided as, in its current state, the DSS needs considerable further development in order to be available for general use. Moreover, a more sensible approach would be to incorporate the DRIFT-Arid adjustments into the new encoded DRIFT-DSS (Brown et al., 2013), rather than to spend those resources on the Excel-based DSS.

The DRIFT-Arid DSS drew on concurrent development in WRC project (No. K5/1873, Brown et al., 2013) and vice versa. Adaptations made to form DRIFT-Arid and to accommodate non-perennial systems include.

1. The addition of new flow (and hydraulic) indicators which are relevant for non-perennial systems;
2. The creation of weighted (as opposed to un-weighted) lag periods, such that more recent results have a greater influence than those further in the past (now also incorporated in DRIFT); and
3. The creation of links within disciplines (now also incorporated in DRIFT)¹.

Furthermore, the Mokolo case study provided the first testing of the “linked indicator” approach.

Another adaptation that was considered concerned the possibility of creating a two-state model (or a state and transition model), given that a different set of indicators will be relevant depending on whether the river system is in a flowing state or an isolated pool or dry state. Alternatively, a different set of response curves might be relevant, where the same indicators are relevant, but the responses to inputs will be different depending on which state prevails. Although this did not appear to be required as DRIFT-Arid was able to accommodate the modelling of both states in an integrated system, it might be interesting for further research.

It is envisaged that DRIFT-Arid and the DRIFT-Arid DSS will evolve from its current state as the underlying conceptual understanding of the functioning of non-perennial systems evolves and is tested on other rivers.

This section gives an overall view of the underlying concept, structure and functioning of the DSS, but does not provide a full user manual.

A zipped file containing a draft version of the DSS is included in the electronic submission. This contains a subset of the files that are required, for illustrative purposes.

7.3 Caveats and conventions

- NOTE:** All Excel files within the DSS are in the Excel “binary workbook” format, which is a compact format that allows for VBA macros. i.e. all files have the .xlsb extension.
- CONVENTIONS:** Folder names are written in Arial font e.g. MOKOLO FLOWS DSS.
File names are written in Arial Narrow font e.g. Water Quality_Site 1_TweeF.xlsb
- CAVEATS:** The DSS is in constant development and no guarantees are made regarding the correctness of calculations and results.
The DSS discussed in this report is based on the information available for the Mokolo River and is not necessarily applicable to other non-perennial systems.

7.4 The conceptual model

DRIFT and the DSS are built up from a number of levels of concepts and assumptions.

7.4.1 Primary assumptions and premises

There are three primary assumptions or premises on which *any* flow assessment method are based. These are:

1. Changes to the flow in a river cause change to the biophysical and socio-economic environment.
2. Changes to the environment can be predicted (to some extent) based on expert knowledge, existing related data, or new field work.

¹ Kate Rowntree and Bennie van der Waal developed several conceptual models of the links for various geomorphological models. These included feedback loops within geomorphology as well as from vegetation back to geomorphology. They also developed a model for channel width which included weighted lags. Thus, their work contributed significantly to adaptations 2. and 3.

3. Changes to the environment in consequence to changes in flow can be captured by building relationships between ‘predictors’ and ‘responses’ using statistical or modelling methods such as, e.g., regression, neural networks, or more simply “response curves” (the latter being the DRIFT approach: Section 7.4.2.1) (Figure 69).

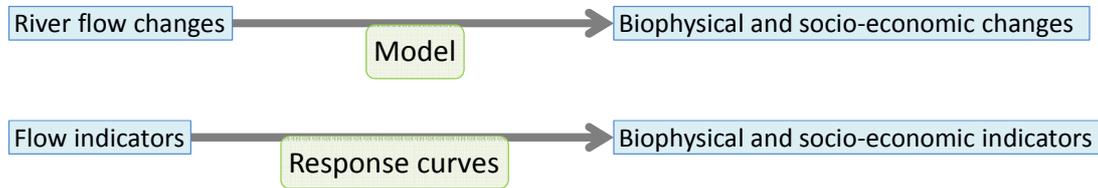


Figure 69. Broad conceptual model (top) and the broad level operationalization (below)

7.4.2 Operational assumptions

In order to make these premises useful, they need “operational assumptions”. These are, in particular, aimed at the operationalization of the third of the primary assumptions: i.e. building predictive links between predictors and response. A number of widely divergent approaches could be followed at this stage, and these are not discussed here, rather the particular approach adopted in this project is outlined. These operational assumptions include:

- The particular flow changes that occur need to be encapsulated in a way that is meaningful for the biophysical and socio-economic environment, and to the experts who will predict changes. In DRIFT, this is operationalized by defining “**flow indicators**”. Different flow indicators will be relevant for different types of flow regimes (flood pulse, flashy, non-perennial). Much of the work in this project has been aimed at defining and calculating relevant **flow indicators for non-perennial rivers**. Examples of flow indicators include: week of onset of the wet season, duration of the wet season, week of onset of the dry season, duration of the dry season, mean five day minimum discharge of the dry season (The set of flow indicators calculated for this project are given in Section 7.5.3.2).
- Once relevant flow indicators have been defined for the type of river and calculated for a particular river (more specifically for a site or reach of a river), relationships can be developed to model and therefore predict the environmental and social responses to each relevant flow indicator. In the case of DRIFT, the relationships are built with **response curves** (Section 7.4.2.1)
- Indicators need to be defined for each significant part of the biophysical and socio-economic environment. For example, for a particular discipline such as Fish, there may be three relevant fish indicators, such as rapid or riffle-dwelling fish species, deep pool-dwelling species and shallow pool-dwelling species.
- Each **biophysical or socio-economic indicator**² (e.g. deep pool-dwelling fish) needs to respond to the flow and other indicators that are relevant to it. Thus, a number of response curves are developed for each biophysical / socio-economic indicator in response to the relevant indicators (Figure 70).

² For the remainder of this report, where either a biophysical or socio-economic indicator is being referred to the term “indicator” will be used, whereas, flow indicators will always be referred to in full so as to differentiate between the two main types of indicators.

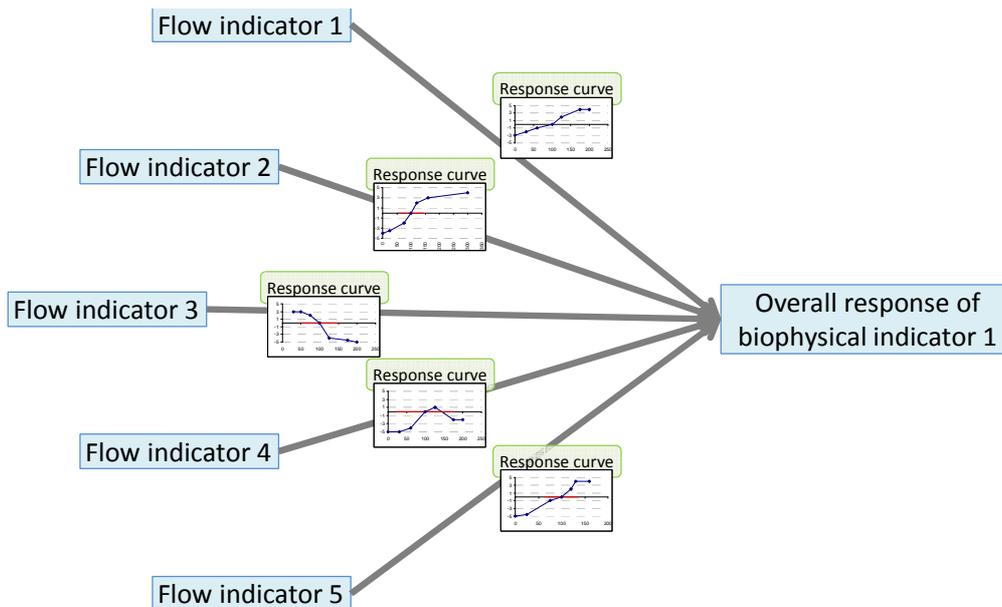


Figure 70. Operationalization of the conceptual model through the secondary assumptions: response curves developed to show the response of a particular indicator to each relevant flow indicator are aggregated to find the overall response

7.4.2.1 Response curves

Response curves, as the name suggests, describe how an output indicator will respond to a particular level of an input indicator. For example, Figure 71 shows the hypothetical relationship between marginal vegetation abundance and the duration of the dry season. The Y-axis in this case is in terms of a percentage of the present day value. The X-axis shows a range of durations of the dry season (from 0 days to more than a year), including the current range (the standard deviation is indicated by the red horizontal line) and a broader range in order to encompass possible future scenarios. The Y-axis is a relative scale, and not absolute, and could thus be on any scale 0 to 1, -5 to 5 or as presented: as a percentage of present day.

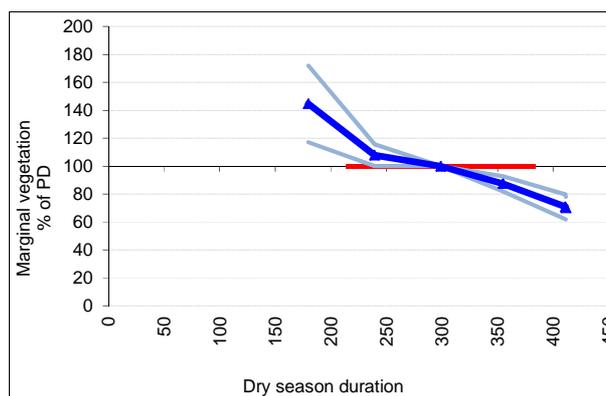


Figure 71. A response curve relating marginal vegetation to dry season duration. The paler blue lines indicate uncertainty ranges, while the horizontal red line indicates the normal range of present day dry season durations

7.4.3 Secondary level of operationalization

Secondary assumptions arising from this approach are:

- That indicators respond in some cases directly to flow indicators, and in others they respond directly to another biophysical or socio-economic indicator. Thus the overall response of an indicator may be due to its links to a number of flow and other indicators. The indicators to which another responds have been termed “**linked indicators**”. But more specifically, the “**linked indicator approach**” implies the inclusion of links to indicators other than flow.
- That the overall response of an indicator (e.g. deep pool-dwelling fish) to the input flow and other indicators can be captured by **aggregating** (in some way) the responses to separate parts of the flow regime as encapsulated by the flow indicators, or separate parts of the ecosystem as encapsulated by other predictor indicators. The particular form of the aggregation forms another assumption of the model (discussed in Section 7.4.3.1).
- That the response curves capture a particular response to a flow (or other) indicator for a season or year (discussed in Section 7.4.3.1), allowing for the creation of a **time-series** of responses.

7.4.3.1 Aggregation of responses and creation of a “time series”

The method of aggregation of individual responses used in the current form of the DSS is a simple addition (within a season). So, for example, if the response to the first indicator for a season causes a drop of 5% (e.g. reading off Figure 71, a duration of about 300 days causes a drop of about 5%), the next indicator causes an increase of 15% and the next a drop of 2%, the overall response for that season will be an increase of 8% (-5+15-2). If this is the first response for the entire time series it is added to 100 (i.e. 100% of present day), so that for that season, the result is 108% of present day (e.g. a fish abundance of 108% of present day).

A time series of responses is then developed. The next season’s overall response is calculated in the same way (results from each response curve are added), and the overall result is added to the previous season’s result. For example, in the next season, there is a decrease of 20% for one response and a decrease of 5% for the next response, the overall response is -25% which means the end of season two’s result is 108-25 which is 83% of present day. This process continues to build up a “time series” of responses for each season across the period of record. This is not strictly speaking a time series, as seasons are not uniform time periods. An annual time series – a true time series is also produced.

7.4.3.2 Linked indicators

It became apparent through various applications of DRIFT, and in the prototype non-perennial model developed in the earlier WRC project on non-perennial rivers (WRC K5/1587), that a linked indicator approach was needed, where an indicator (e.g. a fish) might respond to both flow indicators (e.g. dry season duration), and indicators of other parts of the ecosystem (e.g. the abundance of certain invertebrates). This was felt to be particularly important for non-perennial systems, where surface flow might be zero for months or even years.

The Mokolo River case study formed the first testing of the linked indicator approach, further testing is described in Brown et al. (2013).

The incorporation of linked indicators adds huge complexity to the DSS modelling as well as to the broader flow assessment process itself:

1. As far as process is concerned, in a “usual” flow assessment process, the hydrology is modelled before the response curves and scenario evaluation specialist workshops. All the input information is thus available beforehand, and is already in place in each specialist data entry file, to be ready for the workshop start. The specialist can thus immediately see the effects on the time-series of adjustments made to response curves.

With linked indicators, the flow indicators will similarly be available beforehand to all specialists. However, **non-flow input indicators are not available** until the specialist dealing with that input has completed his/her response curves. Therefore, the specialists will not be able to interactively assess the time-series of responses, apart from the time-series arising from flow indicators, which may be a small subset of all the linked indicators, or there may be no flow indicators relevant at all.

This means that the specialists will have to complete their flow indicator response curves, and then complete a first estimate response to a hypothetical range for other input indicators. The specialist will only be able to view the overall time-series results once all the information has been run through the DSS.

- The DSS has to run through all the information at all sites (as there may also be upstream/downstream linkages), through each of the specialist data entry files **season by season**. To illustrate this, a linked indicator sequence to deep pool-dwelling species is shown in Figure 72 (this refers to the links shown in Table 46).

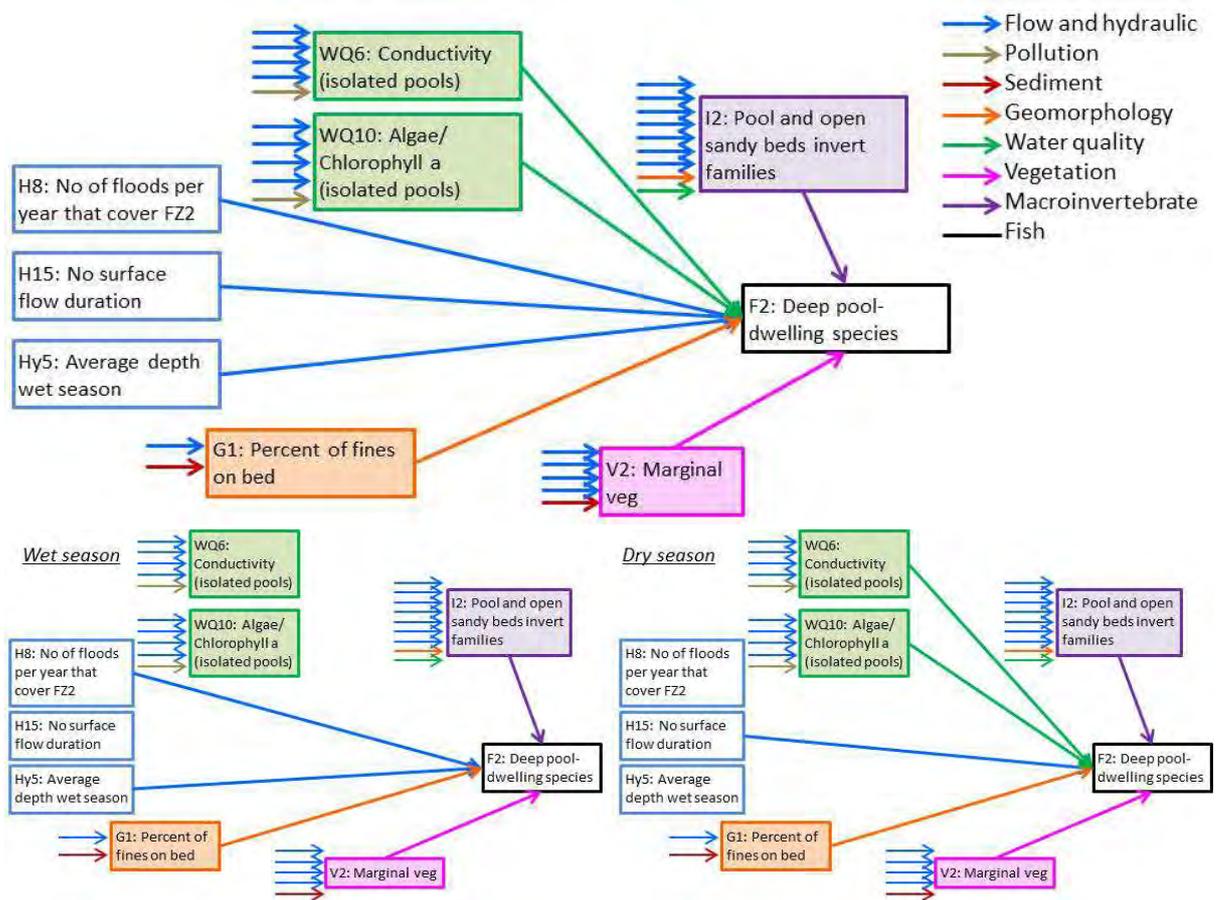


Figure 72. Top: The indicators linked to Deep pool-dwelling fish species (as specified for the Mokolo River, Site 4). The figures below (left) show the calculations for the wet season, and (right) those for the dry season

Initially, the geomorphology (orange), water quality (green), vegetation (pink), macro-invertebrate (purple) and fish (grey) specialists complete response curves relating to flow indicators (blue) and calibrate them based on the time-series response. However, response curves for all other

indicators will not affect the time series (initial input values for other indicators are constant for the time-series), and so cannot easily be calibrated.

Once the initial response curves are complete, the DSS goes through the following steps: (Figure 72, bottom left) first the geomorphological response is calculated for season 1 (wet), then the wet season water quality response, then the wet season vegetation, macro-invertebrates, and finally fish. The overall deep pool-dwelling fish response for the wet season is then calculated. Then the whole series of calculations is repeated for the dry season (or the season after the wet season) (Figure 72, bottom left), and so on, through all the years.

3. Thus, an initial time-series is developed. During specialist workshops, each adjustment of response curves, means running the DSS through the chain of calculations again. In Excel-VBA this is very time consuming, but the encoded DSS (Brown et al., 2013) takes only a few minutes. However, even with the latter fast programme, linked indicators do make the workshop process more complex, probably requiring more than one calibration iteration.

7.5 The Decision Support System

7.5.1 Basic structure

The DRIFT-Arid DSS consists of a number of linked folders and Excel files (Figure 73). Calculations and data manipulations are done within the Excel files and with Visual Basic for Applications (VBA) macros.

The main folder is named for the particular river system (e.g. MOKOLO FLOWS DSS) and contains the main setup file and a subfolder for each site (e.g. SITE 1, SITE 2). Within each site folder there is a data entry file for each specialist area (e.g. Fish) as well as a hydrology file and a site summary file.

The sub-folder and specialist file names follow a particular convention:

Site folder names: "SITE" & site number & site name

e.g. SITE 1 TweeF

Specialist file names: specialist area "_Site" & site number & "_" & site name & ".xlsb"

e.g. Vegetation_Site 1_TweeF.xlsb

The main file used to set up the DSS for a particular river system is the "Scenario Interface", named for the particular river, e.g. Mokolo Scenario Interface.xlsb.

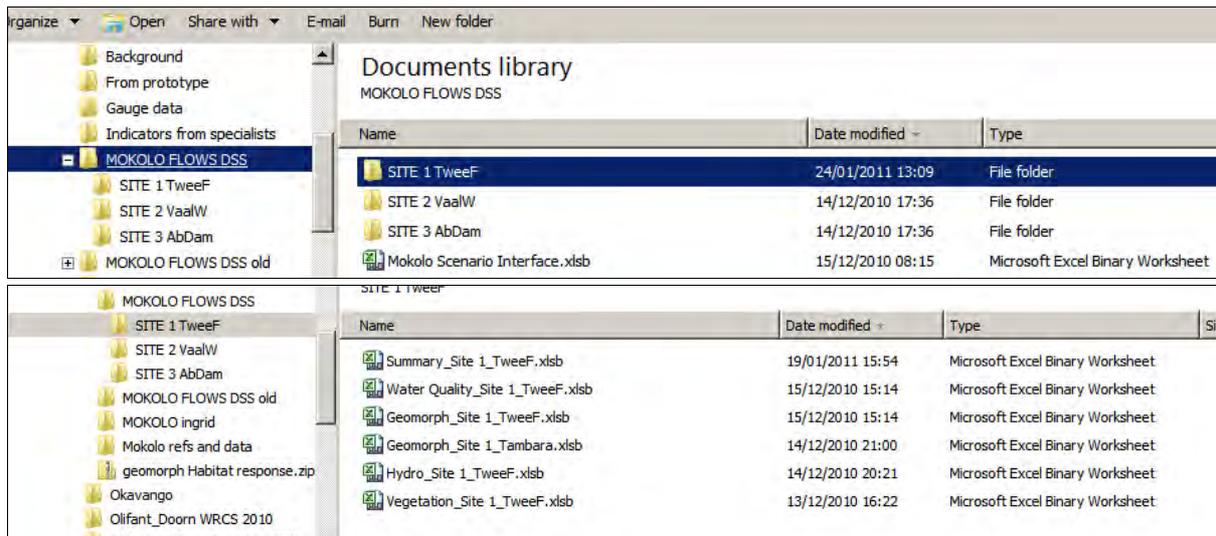


Figure 73. File and folder structure of the DSS. Main folder (top) showing the “scenario interface” and the site sub-folders, and a site sub-folder (bottom) showing the specialist files

7.5.2 Initial setup

In the scenario interface file in the main folder, the site names, scenario names, indicator names and other required information is entered. Each of the specialist files has direct links to this information. Thus, if the DSS is transferred to another computer location, these links need to be updated. A single source for this basic information means that calculation and macro errors do not arise due to incorrect spelling or numbering being entered into individual data entry files.

A baseline scenario needs to be identified: this is the scenario against which all other scenarios are compared. DRIFT uses the present day scenario, but other scenarios could be used. However, this confirms with the decision to use present day for non-perennial systems discussed in Section 3.5.

The first file that needs to have data entered is the hydrology specialist file for each site. The flow indicators are entered into these files for each scenario. The values are entered as a table with a row for each year and a column for each indicator. In other words there is a time-series of values for each flow indicator. Various calculations are automatically made within this file, such as finding the median value across the years for the particular indicator. This information (e.g. median and ranges across the baseline scenario and across the scenarios) is used to automatically populate the response curves in all the other specialist files.

Once the flow indicators have been entered into the site hydrology files for at least the baseline scenario (present day), a macro can be operated from the scenario interface file (by pressing the appropriate “button”), which populates each specialist data entry file with the appropriate flow indicator values and thus prepares the response curves for the specialists to complete. Each specialist can then enter their responses in their data entry files.

7.5.3 Activity 21 and 22: Mapping data pathways and data capture. The Mokolo River example

7.5.3.1 Setup

In the case of the Mokolo River the setup page was populated with the names of the five sites, the 17 flow indicators, 5 hydraulic indicators, and 5 scenario indicators, the scenario names, and other

information such as the start year of the hydrology (1950). A screen shot of the part of the setup page dealing with scenarios, sites and specialist areas is shown in Figure 74.

All the indicators to be used by specialists are also entered into the scenario interface file – these names are then automatically linked to each site level specialist file. Once again this avoids errors due to misspellings. If an indicator is not relevant at a particular site it can be ‘switched off’ within that particular site level specialist file.

Figure 74. Part of the setup page of the Scenario Interface file for the Mokolo River, showing scenarios, disciplines and site names

7.5.3.2 Flow indicators

The flow indicator names are entered into the scenario interface file, together with their units, relevant seasons (e.g. wet or dry), and abbreviations (Table 45 lists the indicators). Each site level hydrology file links to this list and so the names are pre-populated in the site level hydrology files. Note that hydraulic indicators and “scenario indicators” are entered in the same place and dealt with in exactly the same way as flow indicators.

Table 45. Flow indicators selected for the Mokolo River. The rows shaded in grey are flow indicators that were specifically calculated for DRIFT-Arid

Group	Abbr	Description	Code	Season
Flow indicators	MAR	Total annual volume of surface flow (MAR)	H1	Year
	DDepCh	Depth of water table, channel, dry	H2a	Dry
	WDepCh	Depth of water table, channel, wet	H2b	Wet
	DGr	Perc contribution of groundwater to surface flow, dry	H3a	Dry
	WGr	Perc contribution of groundwater to surface flow, wet	H3b	Wet
	WoDry	Onset of surface flow after period of dry river bed	H5	Dry
	WoWet	Onset of hydro wet season after a period of wet river bed	H6	Wet
	WFZ1	No of floods per year that cover FZ1	H7	Wet
	WFZ2	No of floods per year that cover FZ2	H8	
	WIndFZ2	Longest duration of inundation of FZ2	H9	
	WFZ3	No of floods per year that enter FZ3	H10	
	W13	Flood greater than PD 1.3 magnitude	H11	
	WPk	Peak flow discharge	H12	Dry
	Wdur	Surface flow duration	H13	
	Do	No surface flow onset	H14	
	Dd	No surface flow duration	H15	
	Dsub	Channel subsurface flow, dry	H16	
Hydraulic indicators	FloodH	Height of max flood per year	Hy1	Wet
	FlowLT	Length flow LT 0.3	Hy2	Dry
	FlowGT	Length flow GT 0.3	Hy3	Dry
	Ddep	Average depth dry season	Hy4	Dry
	Wdep	Average depth wet season	Hy5	Wet
Scenario indicators	Pol	Pollution	P1	Year
	Sed	Ratio fine to coarse	S1	
	HaCult	Hectares of cultivated land	Sc1	
	HaGame	Hectares of game farms	Sc2	
	ExtWat	Power produced by power plants	Sc3	

Within each site level hydrology file (e.g. Hydro_Site 4_BeDam.xlsb) the time-series of flow indicators then have to be entered for each scenario (although initially, just the baseline scenario is used). Figure 75 shows the time-series of flow indicators entered into Site 4's hydrology file for the Mokolo.

The screenshot shows an Excel spreadsheet with a grid of data. The columns are labeled with various indicators such as 'Flow', 'Sediment', 'Pollution', and 'Scenario'. The rows represent years from 1950 to 1985. The data is organized into a grid with many columns and rows of numerical values. The spreadsheet is titled 'Hydro_Site 4_BeDam.xlsb' and is open in Microsoft Excel.

Figure 75. Screenshot of the present day flow, hydraulic and scenario indicators entered into the hydrology file for Site 4 of the Mokolo River

Scenario indicators can include pollution and sediment indicators: these have a constant value for all years. The values are indicative of the relative differences in pollution or sediment supply from different scenarios. For example, the PD scenario might be given a pollution value of 1, whereas with a scenario with more agriculture one would expect more non-point source pollution, so it might be given a value of 1.2. A scenario where there was relative less agriculture and relatively more game-farming might be given a value of 0.7. In these cases, the numbers are not important but it is important to try to capture the relative differences between scenarios. Scenario indicators also include values relating to the scenarios such as the hectares of agriculture, or amount of power produced, etc. In these cases, the actual values might well be available.

7.5.4 Activity 23: Response curve data entry for specialists

Each specialist data entry file is pre-populated, from links to the scenario interface file, with a list of flow indicators, the particular indicators for the discipline, and other standard information such as site and scenario names. For a particular site the specialist needs to select the relevant flow indicators from the list, and “switch on” or off indicators relevant to that site (e.g. not all fish indicators might be relevant at all sites).

Then, the specialist needs to specify which flow and other specialist indicators influence each of his/her indicators, i.e. the specialist specifies “the linked indicators” or “the links”.

Once the linked indicators are specified, a macro will prepare the data entry files, so that the relevant response curve input (X-axis) values are ready for each response curve for each link.

The response curves specify for each input value, what the response will be in terms of percentage of present day values, for that season. The response can be modified, by specifying: if there is a slow or fast return to median values after high or low periods, if conditions are favourable; if there is a certain maximum or minimum that the population can reach; if there is a lag period; and if there are density dependent limitations.

The overall response is calculated for each season, based on the response curve value for that season as modified by the various modifiers. The result is then presented as a “time-series”, showing a response for each season, over the period of record. Note that this is not a true time series as the seasons are not evenly spaced. This result can be condensed into an annual time series (which constitutes a ‘true’ time-series).

7.5.5 Mokolo River example

Figure 76 shows the sheet on which the specialist’s indicators are listed (for fish in this example), and where they can be switched off for a particular site if they are not relevant there.

Num Char		Indicators / Process(sub)-indicators	Indicators (if process indicators present, else EMPTY)	Description	Switch indicators ON (1) or OFF (0)	Is an INCREASE a move towards (T) or away (A) from natural?
7	21	1 Rapid, riffle dwelling	0		1	T
8	18	2 Deep pool dwelling	0		1	T
9	21	3 Shallow pool dwelling	0		1	T
10	7	4 Blank 4	0		0	
11	7	5 Blank 5	0		0	
12	7	6 Blank 6	0		0	
13	7	7 Blank 7	0		0	
14	7	8 Blank 8	0		0	
15	7	9 Blank 9	0		0	
16	8	10 Blank 10	0		0	
17	8	11 Blank 11	0		0	
18	8	12 Blank 12	0		0	

Figure 76. Specialist data entry file (Fish), showing the list of indicators where they can be “turned off” for a particular site

The specialist then has to specify which flow and other indicators are linked to each of his/ her indicators. A macro can then be run which will prepare the data entry sheets with the response curves just specified for each linked indicator. Part of the sheet for entering links is shown in Figure 77.

	Code	Indicator	Link code								
Vegetation	V1	Aquatic veg	H5	H6	H13	Hy5	WQ8				
	V2	Marginal veg	H2a	H12	H15	Hy5	S1				
	V3	Lower bank veg	H2a	H8	H15	S1					
	V4	Upper bank veg	H2a	H10	S1						
	V5	Floodplain veg (switched off at Site 4)	H2a	H2b	H8	H10	S1				
invertebrate	I1	Riffle / rapid families (incl. rocky interpools)	H5	H13	H14	H15	Hy5	Hy2	Hy3	G1	WQ5
	I2	Pool and open sandy beds families	H15	H16	Hy4	G1	WQ6	WQ10			
	I3	Aquatic and marginal vegetation families	WQ5	WQ10	V1	V2					
Fish	F1	Rapid/riffle-dwelling fish species	H5	H9	H13	H14	Hy4	G1	WQ5	I1	
	F2	Deep pool-dwelling species	H8	H15	Hy5	G1	WQ6	WQ10	V2	I2	
	F3	Shallow pool-dwelling species	H9	H15	Hy4	G7	WQ10	V1	V2	I3	
Socio-economics	SE1	Employment	Sc1	Sc2	Sc3						
	SE2	Household income	Sc1	Sc2	Sc3						
	SE3	Tourist numbers	Sc2	WQ11	Ecosystem integrity						
	SE4	Incidence of diarrhoea in under 5 yr. olds	P1	WQ11							
	SE5	Pesticide poisoning	P1	Sc1	Ecosystem integrity						
	SE6	Impacts of floods and droughts	WQ5	WQ5	WQ11						

Figure 78 shows a part of a page of the Fish data entry file (Fish_Site 4_BeDam.xlsb), dealing with the fish indicator “Shallow pool dwelling species”. Three of the response curves are shown dealing with the duration of inundation of flood zone 2 (FZ2), duration of time with no surface flow, and average depth in the dry season. The values in the yellow shaded cells (Column D) are filled in by the specialist in response to the values to the right (column C). The value in Column C are a range of values for that input indicator including the median PD value, the present day range, and an extended range to accommodate scenarios. The DSS is set up so that a range of response values (Column D and E) can be inserted to allow for uncertainty. The range is shown in the response curve graphs as paler blue lines.

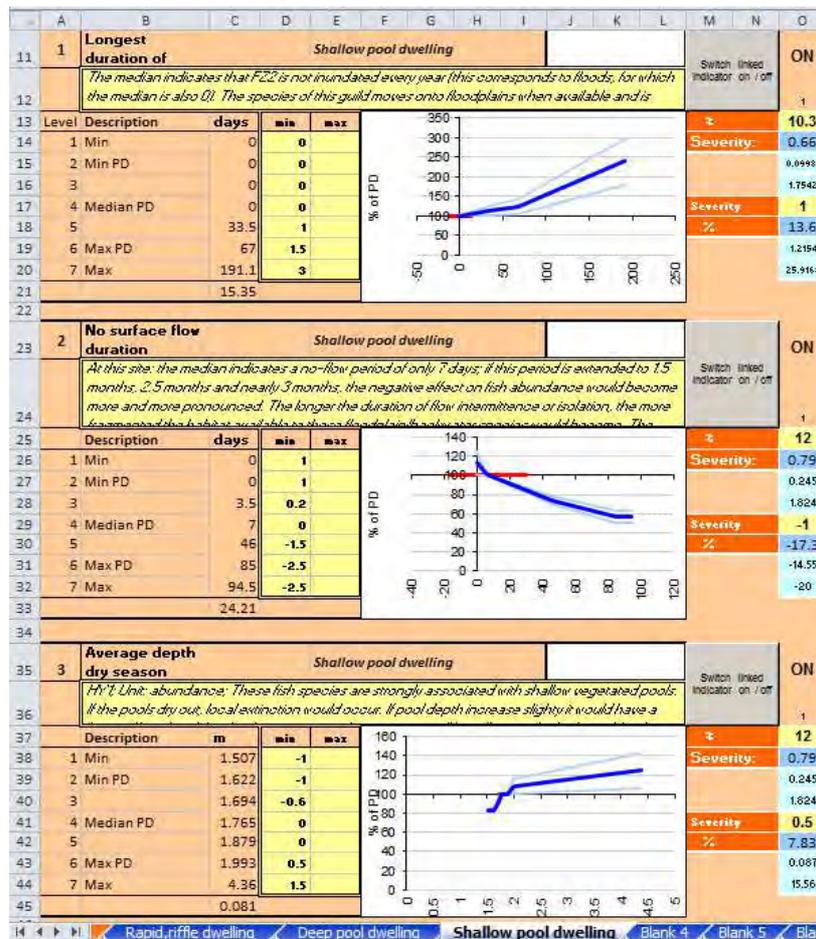


Figure 78. Response curves for Fish indicator: Rapid and riffle dwelling species, for the first three linked indicators (onset of wet season, surface flow duration, onset of dry season)

7.5.6 PHASE 9: Scenario analysis

7.5.6.1 Activity 24: Interpret change in driving indicators as response in all other indicators for present day scenario

A seasonal time series is built up from the response curves and the time-series of input values and shown on the top of each indicator's page (Figure 79).

Also shown in Figure 79 to the right of the time-series, are various modifications that can be made to the responses, in order to adjust the overall time-series response. The possible adjustments include: the speed with which an indicator might revert to median values under favourable conditions, the degree of dependence on the previous year's value, a lag period, minimum and maximum values that the population can reach, and density dependent modifications.

Also produced in the DSS in each specialist file are various summaries, including an annual time-series (Figure 80) (as opposed to the seasonal one in Figure 79).

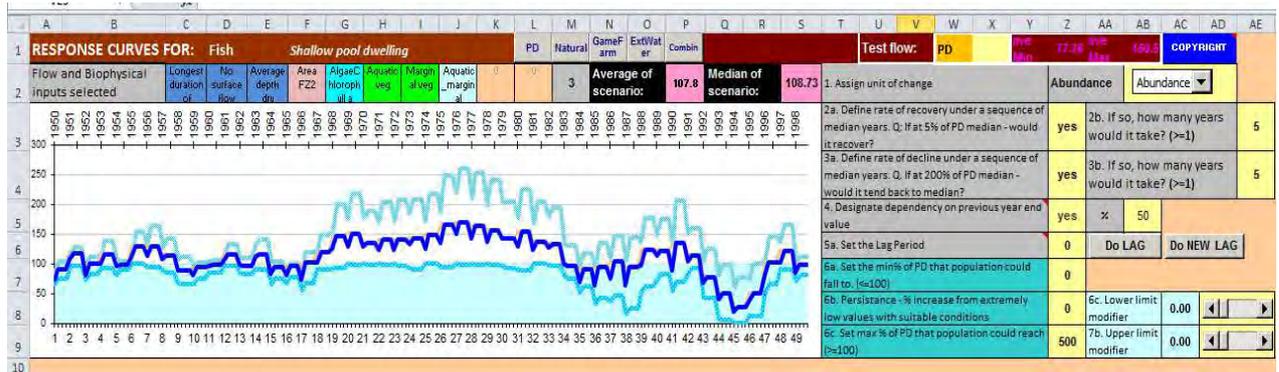


Figure 79. Screenshot of the seasonal time-series response built up from responding to a time-series of eight input indicators for Site 4 of the Mokolo River. To the right (grey and blue blocks) are various modifications that can be made, e.g. inclusion of lag periods

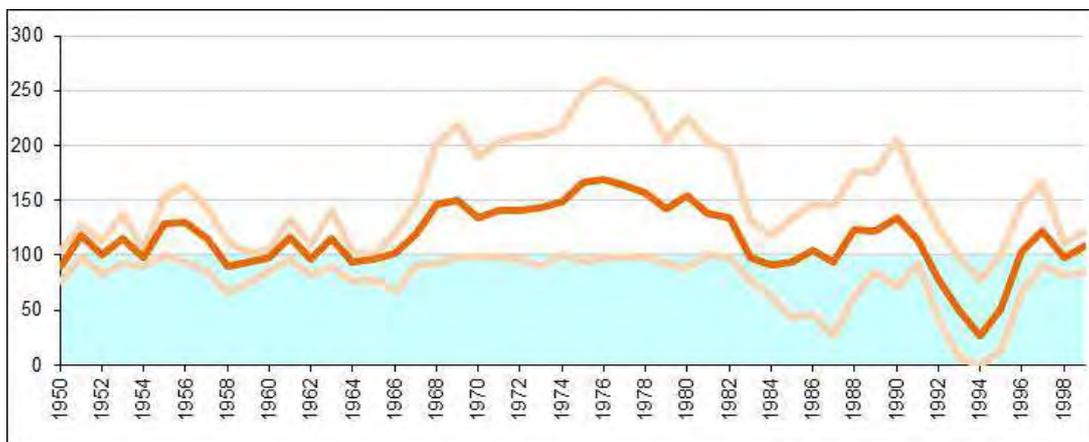


Figure 80. Annual time-series resulting from the seasonal time-series in Figure 79

7.5.6.2 Activity 25: Calibrate model using all dry, all wet and combined dry and wet scenarios

The median of the present day scenario should be in the region of 100% (see value indicated under average of scenario row P in Figure 79). The present day scenario is calibrated by each specialist by adjusting the response curves input in each indicator so that in the overall response of the indicator, the median of the present day scenario is between or close to 95% and 105% (close to 100%).

Hydrology data from three fictitious scenarios are also included in the DSS. The 'all' wet scenario includes values from the wettest years throughout the time series so that it appears as though the river has wet years throughout. The 'all dry' scenario includes values from the driest years throughout the time series and the 'combined wet and dry' scenario includes values from the wettest years for half of the time series and for the driest years flow for the remaining half of the time series.

The specialists now calibrate the response curves for each of their indicators by using the 'all wet', 'all dry' and 'combined' scenarios. For example, it would be expected that the abundance of riffle rapid dwelling fish species would increase in the 'all wet' scenario and decrease drastically in the 'all dry' scenario.

8 PHASE 10: SCENARIO PREDICTIONS OF CHANGE, MOKOLO RIVER, SITE 4

8.1 Introduction

The process followed in the DRIFT-DSS method on which the DRIFT-Arid DSS is based uses scenarios that are chosen by the team after consultation with DWA and stakeholders in the catchment. The hydrology for each of the scenarios is then simulated using a hydrological model (in this case MIKE SHE was used). The model produces simulated daily flows as an output for each scenario and these daily flows are used to determine eco-hydrological indicators such as number of days with no surface flow, longest period of inundation of Flood Zone 2, etc. Each of the geomorphological indicators, hydraulic indicators and biotic indicators react to the hydrological indicators and also react to each other. The socio-economic indicators can also react to the ecosystem indicators (Figure 81).

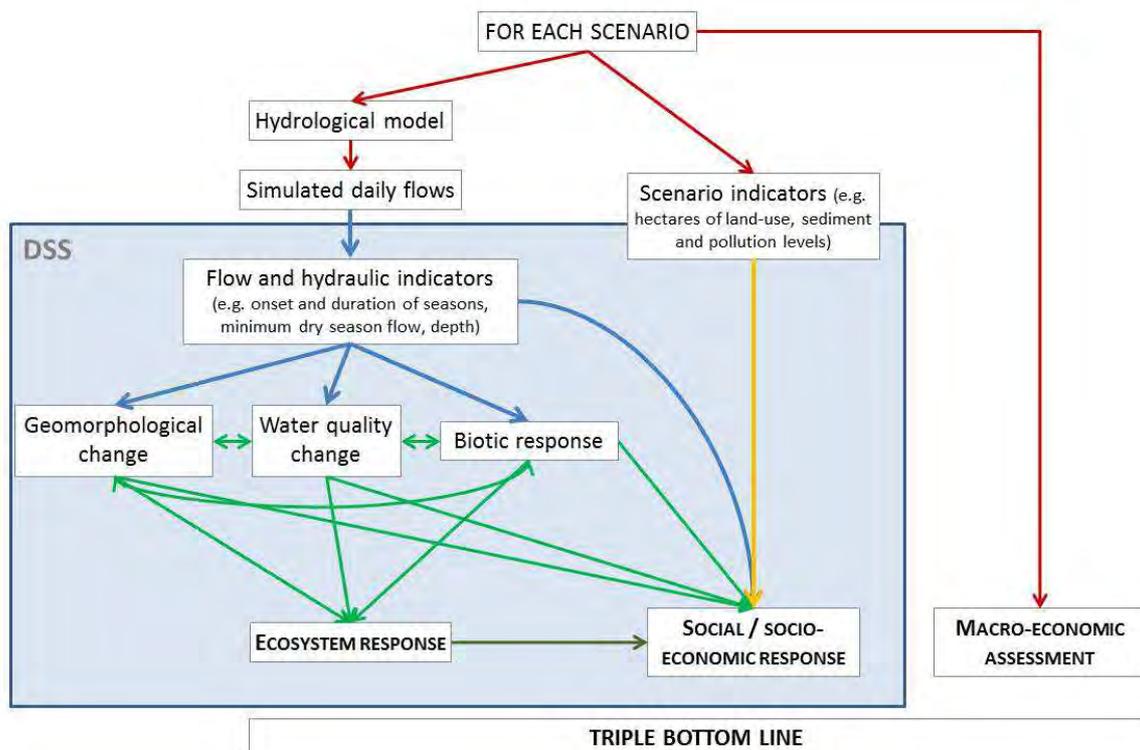


Figure 81. DRIFT-Arid method and DSS flow of information

The DRIFT DSS makes use of the indicators which are identified in each discipline to describe the status of the ecosystem and its users, for the Present Day and any scenario of interest. These indicators need to be linked to changes in flow or water depth, etc. Biophysical indicators would describe how ecosystems could change from the present state under different scenarios. The resulting socio-economic changes due to the change in ecosystem services are then identified. Socio-economic indicators also need to be river-linked indicators and they also reflect changes in the river ecosystem.

Knowledge of each indicator and how it reacts to the other indicators is used by each specialist to draw a Response Curve that captures their best available understanding. A Response Curve describes how a responding indicator responds to a driving indicator.

Severity Ratings that are grouped into five categories (see Table 8) are used in the Response Curves to describe relative change in indicators from Present Day Median values and are entered into the DRIFT DSS data-entry sheets (Figure 9). These data sheets are then used to configure the DSS (set up its 'brain'). It is now ready to predict the impacts of any flow scenario chosen.

It is important to note that the main aim of the project was to test the DRIFT-Arid method on the semi-permanent Mokolo River. To reduce complexity in the report it was decided to **only present the results from Site 4** here. All the Response Curves for site 4 are included in the individual specialist reports available on CD. The Response Curves and results of the scenarios for Sites 1 and 4 are also included in the copy of the DSS which is available from the WRC.

8.2 Recap of scenario information

The five scenarios chosen for the Mokolo River were:

Scenario 1 (PD)	Present Day
Scenario 2 (Natural)	Natural
Scenario 3 (Game Farming)	Sites 1-3: Agriculture converted to game farms Sites 4-5: No further development
Scenario 4 (ExtWater)	Sites 1-3: No further development Sites 4-5: Interbasin transfer of water from Crocodile River to Mokolo Basin, in order to supply expanding power plants, mining and towns
Scenario 5 (Combined)	All of the changes (i.e. agriculture to game farm at sites 1-3, mining, etc. expansions at sites 4-5).

8.3 Recap of Site 4 information

Only scenario results for site 4 are presented here. Site 4 is situated 36 km downstream of the Mokolo Dam in the Limpopo Water Management Area, quaternary catchment A42G. The site is in a confined section of the mainstem of the Mokolo River in the Waterberg (6.01) ecoregion and falls in a lowland river geomorphological zone (see Appendix B: Plate 4).

The river at this point is significantly wider than upstream of the dam with a wandering alluvial low flow channel pattern within a straighter macro-channel. Pools, alluvial, sand bars, reeds lining pools, single thread, and islands are present (van der Waal and Rowntree, 2010). There was no floodplain at the site. A rocky bluff formed the left hand bank of the channel, with steep slopes coming down to the channel edge. A shallow gradient alluvial fan formed the right hand bank. Upstream and downstream terraces that may have been flooded during extreme events bound the channel (Rowntree and van der Waal, 2012).

The marginal zone at this site is very narrow (50-80 cm) and is dominated by *Phragmites* and *Cynodon dactylon* (dominant grass species). The lower bank has a steep slope with large boulders in some areas and is mostly dominated by trees and shrubs. The upper bank is distinguished from the terrestrial zone by structure. It has almost the same species composition but trees in the upper bank are larger than those in the terrestrial zone (Kemp, 2012).

The main impact at this site is the Mokolo Dam, which has a large impact on the magnitude and frequency of flood events and on the sediment load. Increased low flow releases would have the effect of encouraging reed growth and enhancing channel stability. The bed of this river reach is

highly mobile and the course of the wandering channel is liable to change from one flood event to the next.

8.4 Results from MIKE-SHE (surface and groundwater flow and depth)

Given the nature of the scenarios defined, and of the hydrological modelling, the following summarises the flow and associated water availability at this site for these scenarios:

- There is little difference between PD and the expansion/external water (ExtWater) scenario, i.e. the water brought in from the Crocodile River is not modelled to reach the Mokolo River either as a result of releases from the dam, or as return flows from mining or agriculture (Figure 82). However, the ExtWater water scenario does improve the availability of water for irrigation, and supply to mining and power production.
- There is little difference between the Natural, GameFarm and Combined scenarios, i.e. changing from irrigation to game farming above the dam is modelled to produce much higher releases from the dam than are released currently, and the change to game farming dominates flows in the resulting Combined scenario (Figure 82).

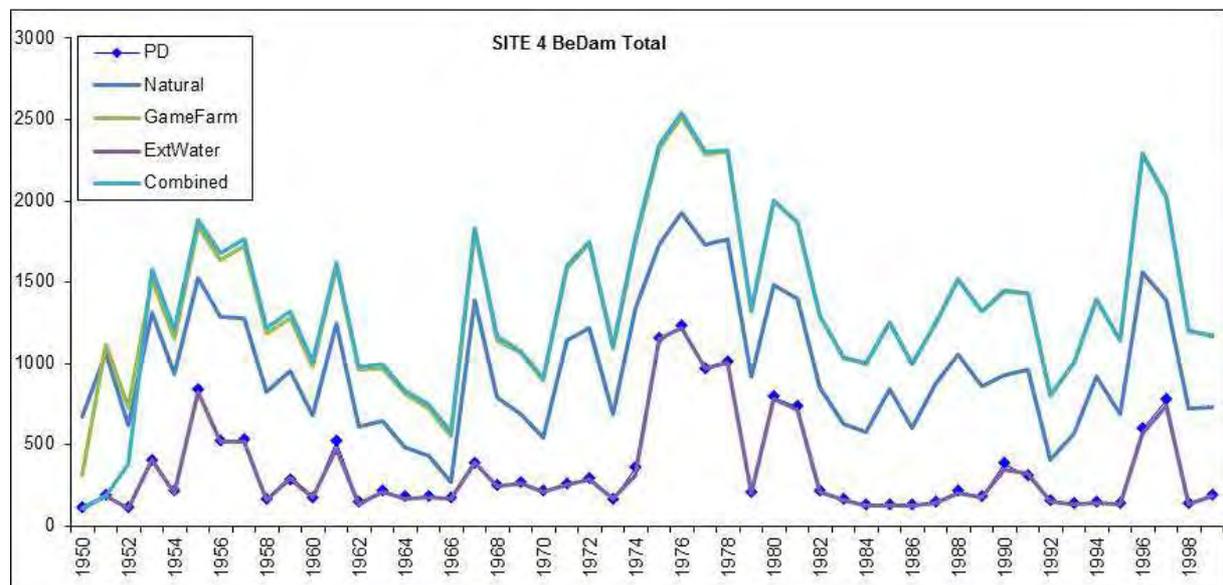


Figure 82. Total annual volume of surface flow (MAR) at site 4 on the Mokolo River from 1950-2000.

8.5 Activity 26: Evaluate impact of chosen scenarios on each indicator and combined indicators for each discipline

8.5.1 Geomorphology scenario output

The outcome of running the five scenarios is illustrated in Figure 83 and Figure 84. The results for the ten Geomorphology indicators for Site 4 are shown in Figure 83a-j. In all scenarios the low flow channel width (b), low flow channel depth (c), geomorphic pool depth (d) and pool length (e) responded synchronously in response to increased or decreased flood events. The feedback between low flow channel depth and the number of floods inundating flood zone 1 (FZ1) can be seen in (j). FZ1, as expected, was the most responsive to changes in channel width (f), with a varied response between scenarios. The extent of the other flood zones varied little for all scenarios through time.

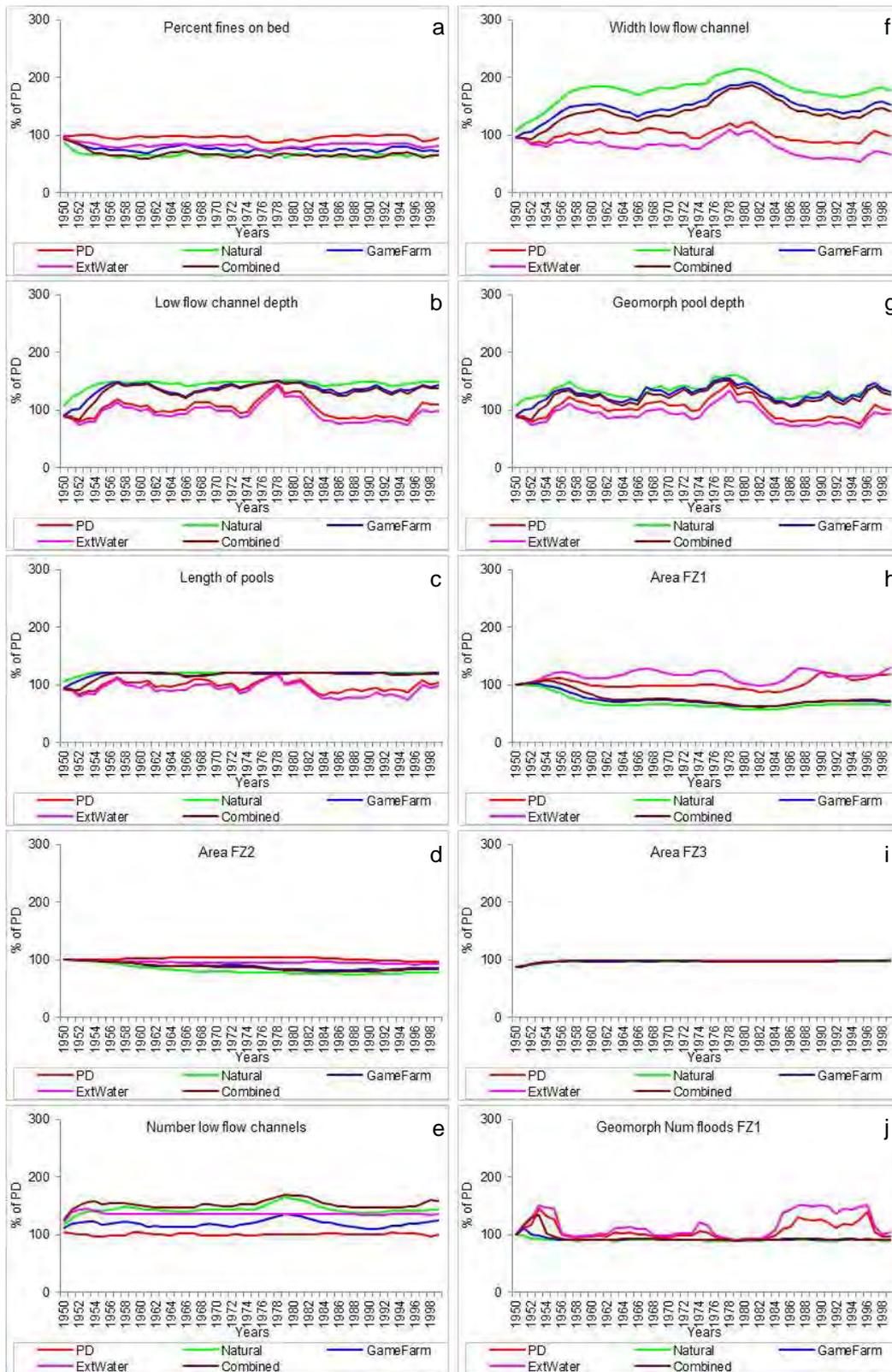


Figure 83. Geomorphology output for the five scenarios for ten indicators at Site 4

The summary results for fluvial geomorphology at Site 4 under the five scenarios indicate some change in integrity (Figure 84). The site was in a B/C category in the PD scenario and improved to an A/B (natural to largely natural) category in terms of fluvial geomorphology for the GameFarm and

Natural scenarios. The ExtWater scenario, where an interbasin transfer from the Crocodile River to the Mokolo River, further development in the mining, Lephalale town and new Medupi Power station is included, had the largest impact.

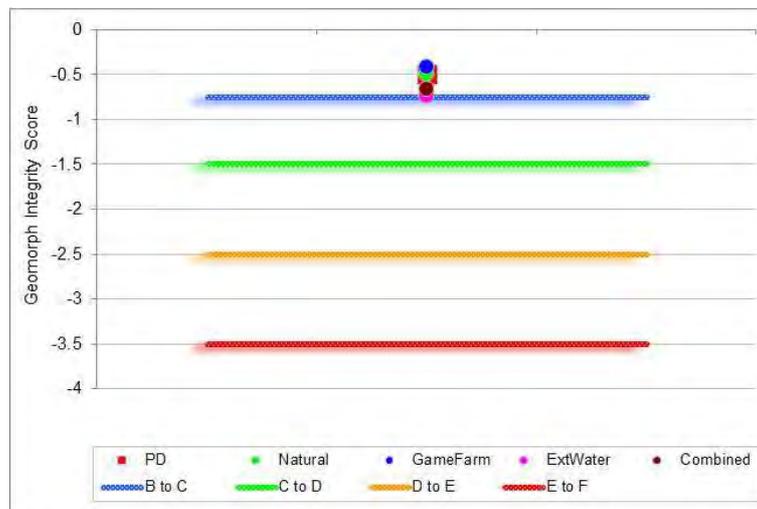


Figure 84. Integrity scores for geomorphology at Site 4

8.5.2 Water Quality scenario output

A summary from the DRIFT-Arid DSS model based on the response curves drawn for the different water quality constituents is provided in Figure 85. Note that in some of Figure 85's graphs ExtWater (pink line) is above the '300% of PD' mark and not shown on the graph.

The results from the different water quality constituents for the different scenarios indicate that impacts on water quality will be small should the area revert back to natural conditions or game farming at Sites 1 to 3. The ExtWater and Combined scenarios have a significant impact on water quality.

There is an anomaly in that one would expect GameFarm to have a greater impact on water quality than Natural. The integrity results (Figure 86) do not show this probably due to the fact that different veld types were used (see Section 6.8.1.2 for explanation) in the MIKE SHE model resulting in much higher runoff in GameFarm compared to Natural. PD and Natural were very similar as one would expect, but the Game Farming scenario results in a higher integrity score.

ExtWater would be expected to have similar results to Combined, but because of the above mentioned hydrological modelling input where different veld types were used in the scenarios, there is a significant difference in the water quality integrity score between these two scenarios.

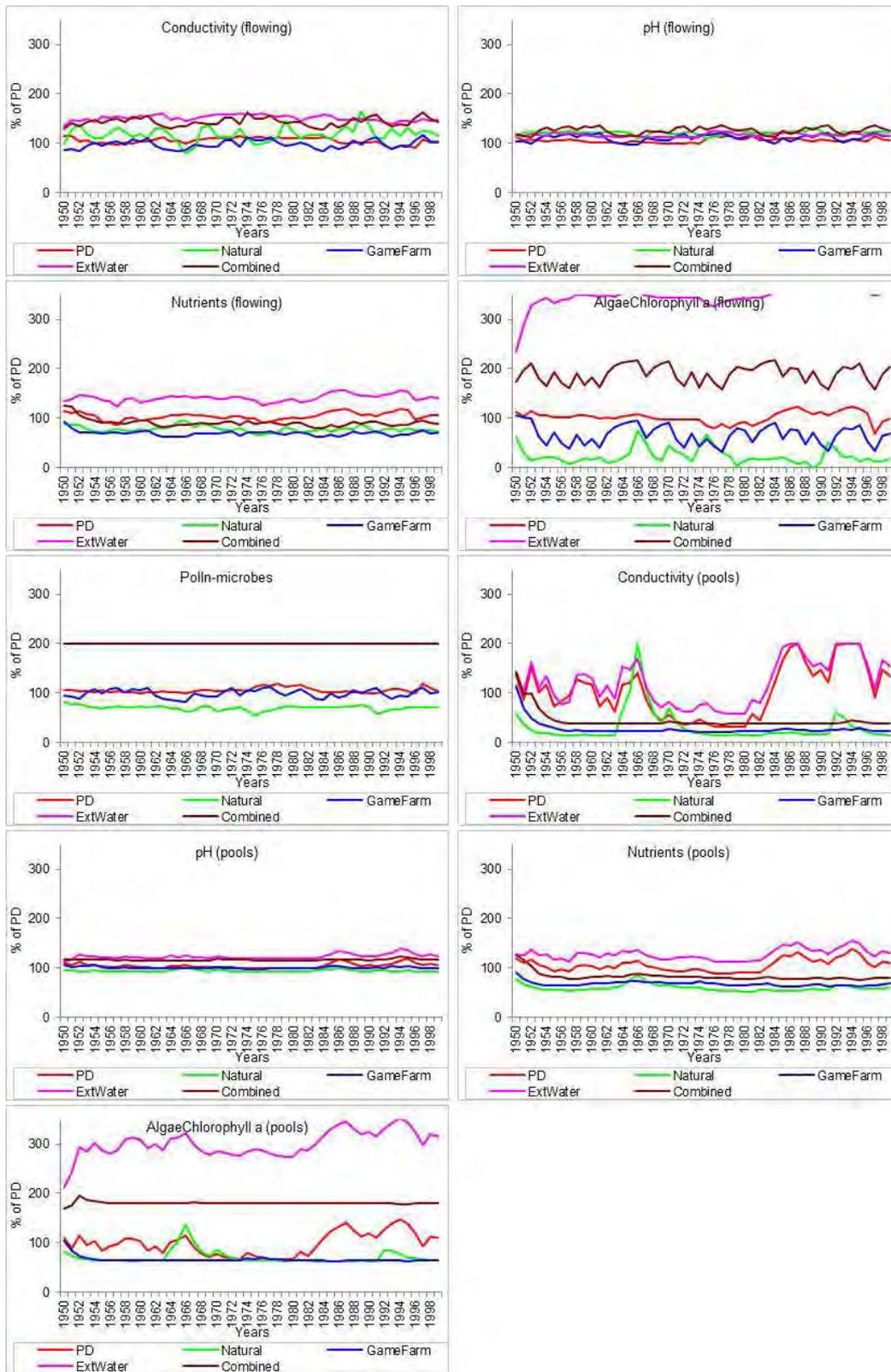


Figure 85. Summary of the water quality responses for the scenarios at Site 4

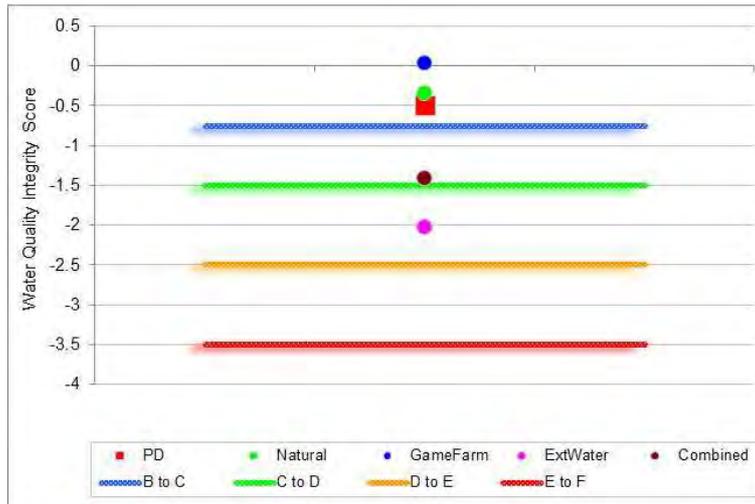


Figure 86. Integrity scores for water quality at Site 4

Natural would have less pollution input compared to PD. PD water quality status of the Mokolo River is mostly in a B to BC category (largely natural to moderately modified), and under Natural the category is closer to an A category.

GameFarm should result in less pollution than PD, but more pollution than under Natural (higher numbers of game than natural as well as increased tourist operations will lead to an increased pollution, in turn resulting in deterioration in water quality).

ExtWater, where additional water is imported from the Crocodile River, could have a detrimental impact on the water quality of the Mokolo River as the water quality of the Crocodile River is very different from that of the Mokolo (higher TDS and nutrient concentrations). The impacts of the water quality of the Crocodile River on the water quality of the Mokolo River will be attenuated as one move downstream. This scenario is also associated with expanded mining, etc. that could also result in deterioration in the water quality of the Mokolo River.

Combined would result in the water quality impact from the Crocodile River water and further development in the town (Lephalale), mines and power stations being mitigated by the improving water quality from upstream as a result of irrigation being replaced by game farming.

8.5.3 Vegetation scenario output

The four response indicators present at Site 4 responded differently to the four scenarios, compared to PD (Scenario 1).

Both the Aquatic and Marginal Vegetation showed a significant increase in abundance for the **ExtWater** Scenario. This was expected since aquatic and marginal vegetation would have a positive response to the higher nutrient load that is associated with the ExtWater Scenario. The Natural, Combined and GameFarm scenarios will result in a decrease in abundance in the Aquatic Vegetation.

Both of these two indicators are the most sensitive to a change in flow conditions, compared to the lower and upper bank response indicators, with the aquatic vegetation as the most sensitive to a change in flow conditions.

What is however difficult to explain, is the fact that the vegetation abundance of all the Marginal, Lower Bank and Upper Bank indicators under the Natural Scenario indicates a decrease in abundance. It was expected that the trend in abundance would rather be closer to PD, or at least closer to the trend that could be seen in the GameFarm Scenarios. It is possible that this phenomena could be linked to the fact that Acocks's Vegetation Landcover was used instead of Mucina and Rutherford's vegetation data, during the calibration of the vegetation (See discussion on 6.8.1.2: Vegetation).

The vegetation on the lower bank is expected to behave more dynamically. Although such a trend is reflected in the up and down curves on the Lower Bank Vegetation graph, compared to PD, the overall abundance is lower than PD. The GameFarm and Combined Scenarios followed that same trend over the 50 year period, while the Natural Scenario again showed lower vegetation abundance. The ExtWat scenario didn't deviate much from PD, compared to the trend followed by the Natural Scenario on the Aquatic and Marginal Vegetation response indicator graphs.

Except for response of the Upper Bank vegetation in the Natural Scenario in the Upper Bank vegetation, the other scenarios have a lesser effect on the abundance of the Upper Bank Vegetation compared to PD. The floods that occurred in 1976 could explain the temporary decrease in vegetation abundance on the upper banks of the Mokolo for the Combined Scenario.

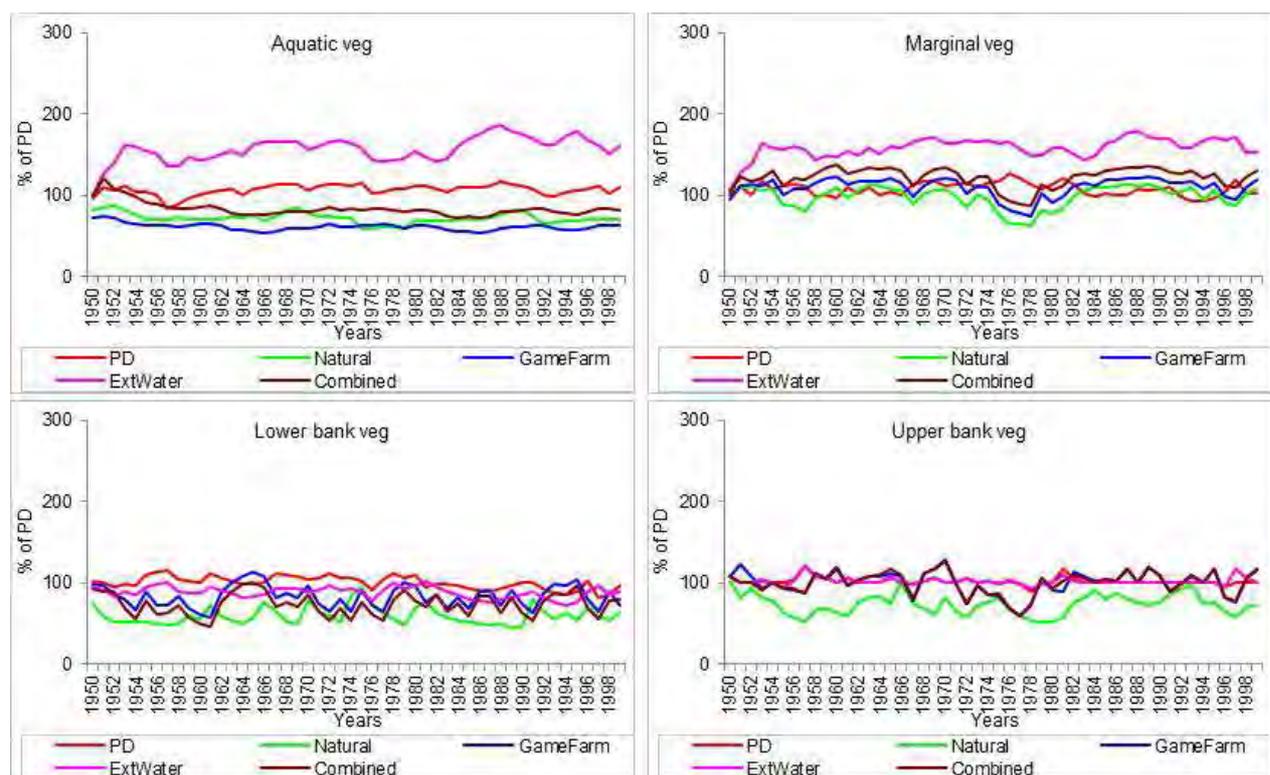


Figure 87. Summary of the vegetation responses for the scenarios at Site 4 (note that the indicator Floodplain vegetation was “switched off” at this site)

According to Figure 89, the ExtWater Scenario would have the highest negative impact on the integrity for the riparian vegetation at site 4. This could be a result of the significant increase in abundance in the aquatic and marginal vegetation response indicators under the ExtWater conditions?

Both the Marginal-, Lower Bank- and Upper Bank Vegetation response indicators for the GameFarm and Combined Scenarios, didn't deviate significantly from PD, resulting in their associated close proximity to PD in Figure 89.

According to the integrity scores, the Natural Scenario would be favourable for the riparian vegetation, although the vegetation abundance for most of the response indicators showed a decrease under the Natural Scenario.

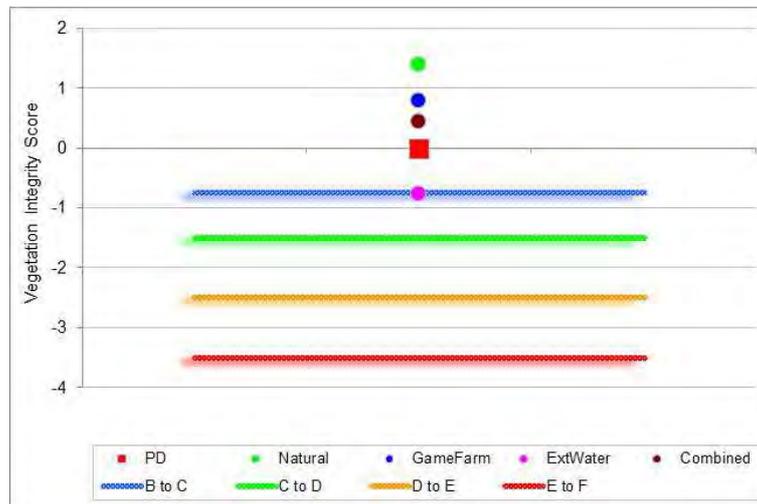


Figure 88. Integrity scores for vegetation at Site 4

8.5.4 Macro-invertebrate scenario output

The abundance of riffle and rapid; pool; aquatic and marginal macro-invertebrate families was used as indicators of change under the five scenarios chosen in the Mokolo River at Site 4.

Scenario 1: Present day (PD)

Under PD, the river is impacted due to regulation of flow as a result of the Mokolo Dam. This has resulted in longer periods of no flow at the site when compared to natural. The habitat, flow and water quality would therefore be impacted on. Some macro-invertebrate families present at the site under PD conditions are flow, water quality and habitat sensitive such as Tricorythidae, etc. The integrity score adjusted for PES is -1.083 (riffle, rapid and rocky interpools macro-invertebrate abundance), -1.047 (pools and open sandy beds macro-invertebrate abundance) and -0.871 (aquatic and marginal vegetation macro-invertebrate abundance) which is an indication that some change has occurred, from natural, but the change in abundance is negligible (Figure 89 and Table 47).

The macro-invertebrate PES for this scenario is in a **B** (80%) category and this site is largely natural at present (Figure 90).

Scenario 2: Natural

Under Natural, no Mokolo Dam is present which means that there was no flow regulation and habitat, flow and water quality sensitive invertebrates would have been present at the site. No change from PD was however noted in the macro-invertebrate family abundance at this site except for the aquatic and marginal vegetation families (60-79% abundance retained compared to PD abundance; Figure 89 and Table 47) which would decrease in abundance probably due to a decrease in nutrients and an associated decrease in algal growth and other vegetation at the site.

The macro-invertebrate PES for this scenario is in an **A/B** (91.5%) category and this site will therefore be close to natural if this scenario is chosen (Figure 90).

Scenario 3: Game Farming

The GameFarm scenario would result in an improved quality of water entering and leaving the Mokolo Dam and therefore an improvement in water quality at Site 4. There would also be more flow downstream of the Mokolo Dam if releases reflected the increased inflow (less irrigation upstream would result in more flow downstream) into the dam. No change in abundance of macro-invertebrates is envisaged for riffle, rapid and rocky interpools and the pools and sandy bed macro-invertebrates and 80-100% abundance is retained in the aquatic and marginal vegetation families (Figure 89 and Table 47).

The macro-invertebrate PES for this scenario is in an **A/B** (101%) category and this site will therefore be close to natural if this scenario is chosen (Figure 90).

Scenario 4: External Water

There should be no increased flow downstream of the Mokolo Dam as a result of this water transfer in ExtWater. The water quality of the Crocodile River is poorer than that of the Mokolo River and if it is transferred to the Mokolo Dam it will have a negative influence on the water quality of the dam and also of the water being released from the dam to Site 4. This would negatively impact on the abundance of macro-invertebrates at this site especially the abundance of the more sensitive riffle, rapid and rocky interpools families of which only 20-40% abundance will be retained (Figure 89 and Table 47).

The macro-invertebrate PES for this scenario is in a **C** (69.7%) category and this site will therefore be moderately modified if this scenario is chosen (Figure 90).

Scenario 5: Combined

More flow is expected under the Combined scenario and it should be more or less the same as in the GameFarm scenario. The change in abundance of macro-invertebrate families under Combined would be negligible for the riffle, rapid and rocky pool families as well as for the aquatic and marginal vegetation families. A small change is expected in the pools and sandy bed families as abundances would increase by 1-25% of PD due to the pools being larger and holding water for longer periods (Figure 89 and Table 47).

The macro-invertebrate PES for the Combined scenario is in an **A/B** (111%) category and this site will therefore be largely natural to natural if this scenario is chosen (Figure 90).

Table 47. Summary of DRIFT-Arid DSS results for Macro-invertebrates at Site 4 for 5 scenarios

Scenario	Average abundance (% PD)	Integrity score Adjusted for PES	Severity of change
Indicator	Riffle, Rapid and Rocky interpools macro-invertebrate abundance		
Present Day	98.6	-1.08	None to negligible
Natural	112.5	-0.17	None to negligible
Game Farming	136.4	0.82	None to negligible
External Water	57.6	-3.45	Moderate to large (20-40% abundance retained)
Combined	117.1	0.12	None to negligible
	Pools and open sandy bed macro-invertebrate families abundance		
Present Day	99.2	-1.05	None to negligible
Natural	151.2	1.14	None to negligible
Game Farming	132.4	0.72	None to negligible
External Water	110.0	-0.38	None to negligible
Combined	171.4	1.45	Negligible (1-25% gain)

Scenario	Average abundance (% PD)	Integrity score Adjusted for PES	Severity of change
Aquatic and marginal vegetation macro-invertebrate families abundance			
Present Day	105.9	-0.87	None to negligible
Natural	78.5	-2.25	Low (60-79% abundance retained)
Game Farming	93.6	-1.37	Negligible (80-100% abundance retained)
External Water	104.9	-0.72	None to negligible
Combined	116.2	0.08	None to negligible

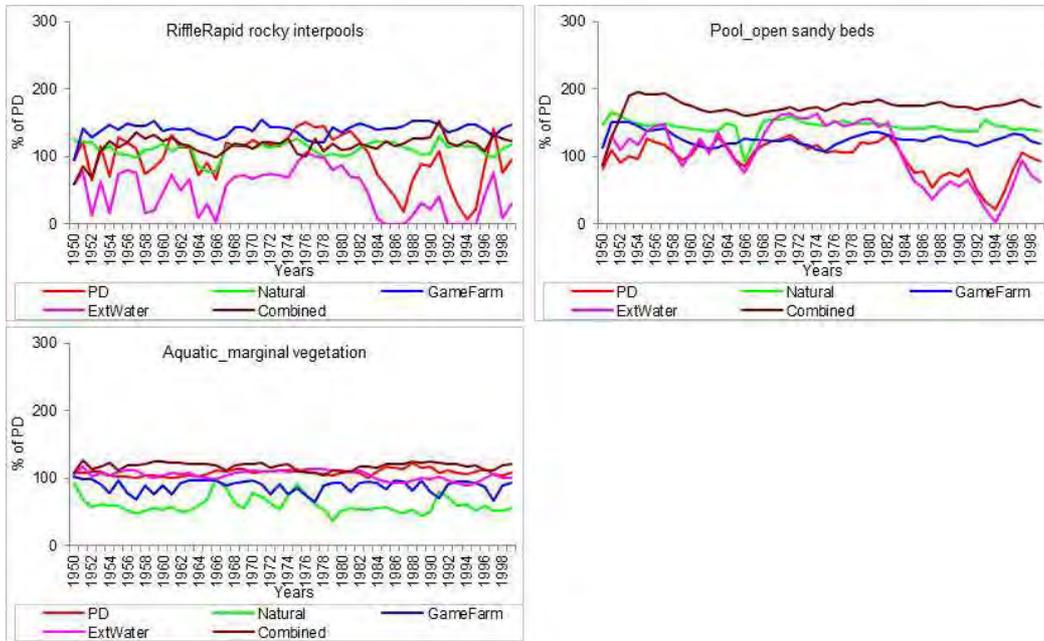


Figure 89. Riffle, Rapid, Pool, Aquatic and Marginal Vegetation macro-invertebrate family abundance at site 4 in the Mokolo River for 5 scenarios

Summary of scenario predictions for macro-invertebrates

An increase in macro-invertebrate integrity from PD is expected under the Natural, GameFarm and Combined Scenarios. The ExtWater scenario would have the largest impact (negative) probably due to the deterioration in water quality and associated decrease in the abundance of sensitive macro-invertebrate families (Figure 90).

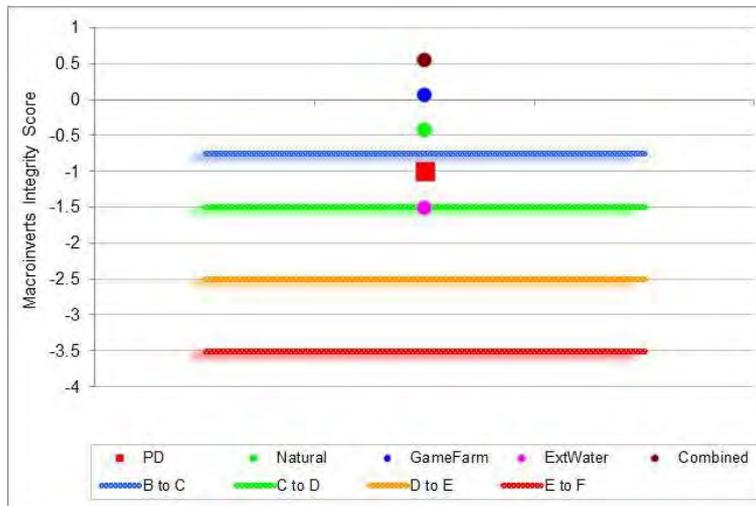


Figure 90. Summary integrity of macro-invertebrates in the Mokolo River at Site 4 for five scenarios

8.5.5 Fish scenario output

Three fish indicators were applied at Site 4 under the five scenarios chosen for the Mokolo River, namely: Rapid/riffle dwelling species, Deep pool dwelling species and Shallow pool dwelling species.

Rapid/Riffle dwelling species

The fish assessment indicated that the present ecological state of the fish community is moderately to largely modified (61.3%; PES Category C/D) at Site 4, mainly due to a reduction in fast-flowing habitats (Fast-deep and Fast-shallow). This is mainly the result of flow modification and regulation due to the upstream presence of the Mokolo Dam and a relatively large number of weirs and gauging stations in the river channel. The impact of these anthropogenic adaptations is most severe for the rapid/riffle dwelling species which are strongly associated with flow-sensitive habitats. The further extraction of water from the river under Scenarios 4 and 5 is, therefore, expected to increase the negative impact on this indicator group. It is evident from Figure 92 that this is indeed the case for Scenario 4 (Extwater; see Figure 92), but strangely not for Scenario 5 (Combined) where the abundance of rapid/riffle species is expected to increase despite the additional extraction of water from the river. Species from this indicator group are expected to be more abundant under Scenario 2 (Natural) and 3 (Game farming). This is however not reflected in Figure 92 with the abundance of rapid/riffle species under Scenario 2 (Natural) being less than for present day (Scenario 1). It, therefore, appears as if surface flow over rapid/riffle habitats increased under present day conditions. This could be the effect of regular low flow releases from the dam at present.

Deep pool dwelling species

Species from the deep pool dwelling species indicator group are strongly associated with Slow-deep habitats and cover types such as substrate, aquatic vegetation and the water column. Both the abundance and quality of deep pools are expected to be influenced by, amongst other, the flood regime (both the magnitude and frequency of floods). The presence of the Mokolo Dam is, therefore, expected to have a large effect on the magnitude and frequency of floods under the present day scenario (Scenario 1), which is reflected in Figure 92. Scenario 4 (Extwater) is predicted to have the greatest negative impact on the abundance of deep pool dwelling species and the implementation of this scenario could result in a large decline of deep pool species during a series of drier years.

Shallow pool dwelling species

The Shallow pool dwelling species indicator group comprises of species that are predominantly associated with slow-flowing, shallow habitats and aquatic vegetation cover. These are also species that would move onto the floodplains during high flows and flood conditions. From Figure 92 it is evident that the altered flow regime under present day conditions (Scenario 1) is having a negative effect on their abundance. The greatest negative impact is expected to occur under Scenario 4 (Extwater). The implementation of this scenario could hold grave consequences for species from this indicator group, especially during a series of drier years. It is not clear why the abundance of shallow pool dwelling species are predicted to soar under Scenario 5 (Combined) as the impacts under this scenario include the additional extraction of water from the Mokolo Dam.

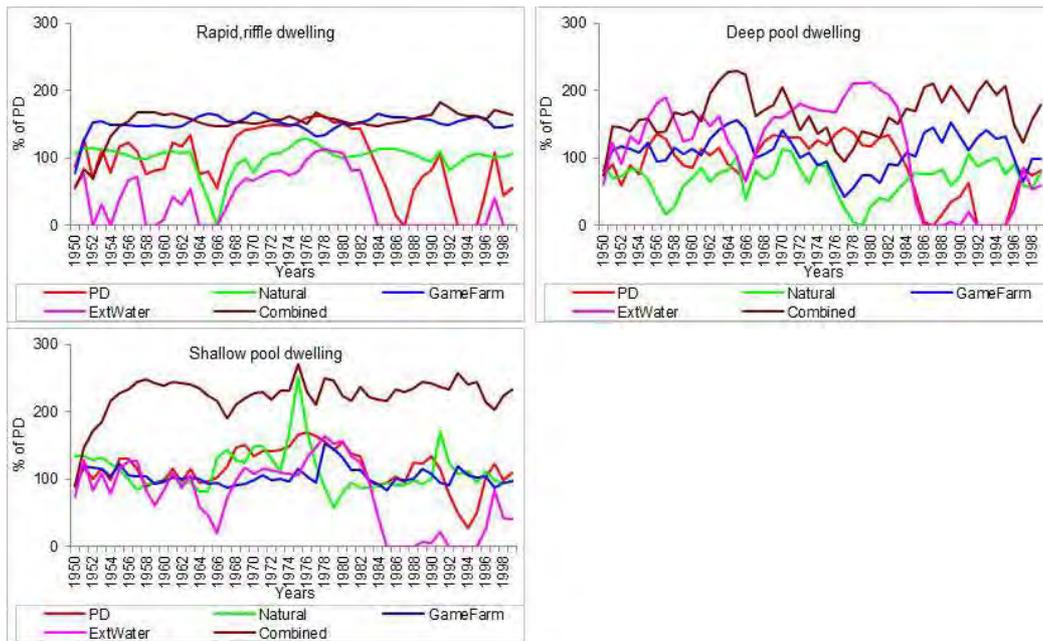


Figure 91. Summary of the fish responses for the scenarios at Site 4

Fish community integrity is predicted to increase markedly under Scenarios 3 (Game farm) and 5 (Combined; see Figure 93). The PES is expected to increase from a C/D to a B/C under Scenario 3 and even higher under Scenario 5. It is not clear why such a large increase in PES is anticipated for Scenario 5 as conditions under this scenario are expected to be detrimental to the fish community instead of favourable. Scenario 4 (Extwater) is predicted to have a negative impact on the integrity of the fish community. The PES is predicted to decrease from a C/D to a D/E category under this scenario, mainly due to an anticipated loss of flow-sensitive habitats, a deterioration of environmental conditions in the pools, especially during periods of surface flow intermittence, and a reduction in the flooded areas due to a reduction in the magnitude and frequency of floods.

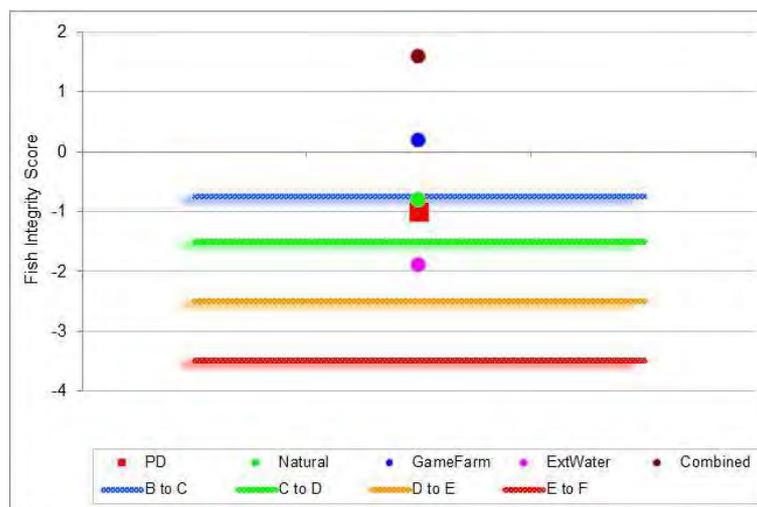


Figure 92. Integrity scores for fish at Site 4

8.5.6 Socio-economic scenario output

For socio-economics, the results from Site 4 and Site 5 are combined as the area below the dam forms a socio-economic unit (above the dam, Sites 1, 2 and 3 are combined for socio-economics). The results from the DRIFT-Arid DSS for each scenario are presented in Table 48.

The indicators to measure the change in well-being of the population in the Mokolo River catchment were:

- Employment (number of jobs from farming, mining and power production)
- Household income (average income calculated from the numbers employed in each sector)
- Tourist numbers
- Incidence of diarrhoea among children under five
- The incidence of pesticide poisoning
- The impact of floods and droughts

The number of people employed (and consequently income) were calculated using standard figures for employment per hectare and employment per megawatt power produced (crops: 0.087/ha, game: 0.007/ha, mining: 0.6/MW). These were calculated for the combination of land-use and mining activities under each scenario.

Scenario 1: PD

Using only the three employment activities represented in the scenarios, approximately 2700 people would be employed under the PD scenario, with total earnings of about R23 mill. These and all other indicators are represented as approximately 100% of PD for the PD scenario (Table 48 and Figure 93).

Scenario 2: Natural

No employment, household income or tourism will occur under the Natural scenario. While the incidence of diarrhoea and pesticide poisoning should also be returned as 0% of PD, a shortcoming in the DSS meant that these two indicators did not go all the way to zero (greater than zero values arose from links to other indicators, namely, microbial pollution and ecosystem integrity). The impacts of floods and droughts are predicted to be less under Natural (Table 48 and Figure 93). Overall Natural impacts social well-being of the population downstream of the Mokolo Dam negatively when compared to PD.

Scenario 3: GameFarm

No change from present day in agricultural employment and household income per hectare is predicted for this Game Farm. Tourist numbers would increase and the incidence of diarrhoea, pesticide poisoning and impact of floods and droughts would decrease (Table 48 and Figure 93). Overall this scenario would improve the social well-being of the population downstream of the Mokolo Dam when compared to PD.

Scenario 4: ExtWater

There would be some increases in employment and household income under ExtWater. Due to the increase in mining, power stations and pollution, fewer tourists would visit the area (the extent of the impact has probably been overestimated). There would be an increase in diarrhoea due to increase in population in Lephalale and associated areas and an increase in pollution from this and mining and power production. Pesticide poisoning would also increase and the impacts of floods and droughts would be exacerbated (Table 48 and Figure 93). Overall, ExtWater would negatively impact social well-being of the population downstream of the Mokolo Dam when compared to PD.

Scenario 5: Combined

Employment downstream of the Mokolo Dam shows a slight increase with an associated increase in household income under Combined (the same as ExtWater). A slight increase in tourist numbers is predicted under Combined (due to the increased game farming). Because of the ExtWater components of this scenario, pesticide poisoning and incidence of diarrhoea would increase. The impact of floods and droughts would decrease (Table 48 and Figure 93) (ameliorated by the increase in game farming). Overall Combined would improve the social well-being of the population downstream of the Mokolo Dam when compared to PD.

Table 48. Summary of DRIFT-Arid DSS results for Socio-economics downstream of the Mokolo Dam for four scenarios relative to the PD scenario

	Abundance score (% PD)	Social well-being score	Severity of change relative to PD
Scenario 1 – Present Day (PD)			No change from PD
Scenario 2 – Natural			
Employment	0	-5	No employment
Household income	0	-5	No hh-income
Tourist numbers	0	-5	No tourism
Incidence of diarrhoea among children under five	8.38	5	81-100% decrease
Incidence of pesticide poisoning	21.1	4.6	81-100% decrease
Impact of floods and droughts	65	2.03	26-67% improvement
Scenario 3 – Game Farming			
Employment	100	0	No change
Household income	100	0	No change
Tourist numbers	178	2.5	68-250% gain in numbers
Incidence of diarrhoea among children under five	71.8	1.6	21-40% decline
Incidence of pesticide poisoning	95.1	0.3	Slight improvement
Impact of floods and droughts	17.5	4.8	251-500% improvement
Scenario 4 – External water (ExtWater)			
Employment	121	1.31	20% increase
Household income	129	1.62	21-40% increase
Tourist numbers	17	-4.81	61-80% loss in numbers
Incidence of diarrhoea among children under five	224	-2.97	68-250% increase
Incidence of pesticide poisoning	154	-2.20	26-67% increase
Impact of floods and droughts	114	-0.95	Slight increase
Scenario 5 – Combined			
Employment	121	1.31	20% increase
Household income	129	1.62	21-40% increase
Tourist numbers	122	1.37	Increase in numbers
Incidence of diarrhoea among children under five	205	-2.80	68-250% increase
Incidence of pesticide poisoning	40.5	3.45	60% decrease
Impact of floods and droughts	30.5	4.02	251-500% improvement

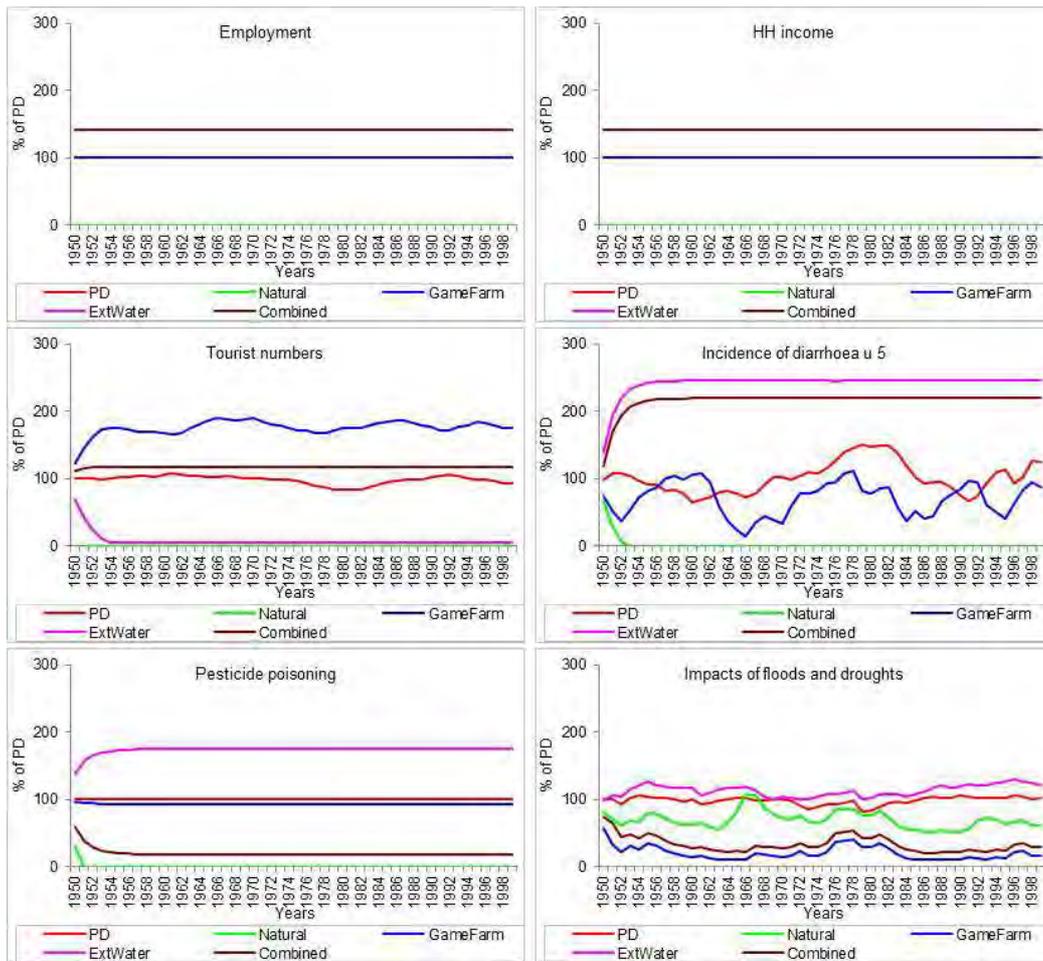


Figure 93. Impact on socio-economic indicators downstream of the Mokolo Dam

Summary of social wellbeing of population downstream of the Mokolo Dam:

Based on the above analysis, in terms of social well-being, GameFarm and Combined appear to be the most beneficial in terms of increasing the socio-economic well-being of the population in the Mokolo River basin. The least beneficial scenario is ExtWater (Figure 94).

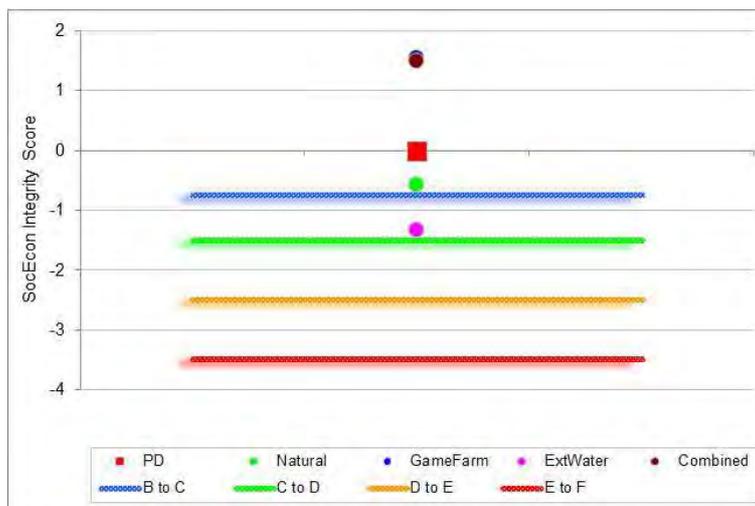


Figure 94. Summary integrity of Socio-economic indicators downstream of the Mokolo Dam in the Mokolo River for five scenarios

8.6 Activity 27: Evaluate overall impact of chosen scenarios on catchment

Summary of scenario predictions

The DRIFT-Arid DSS uses the integrity scores from each of the disciplines to determine the overall ecosystem integrity of the site under the different scenarios (Figure 95). It is worth noting once again that, given the problems with hydrological modelling and scenario definition, these are hypothetical results only, and **no conclusions should be drawn from them regarding the actual performance of the different scenarios.**

An increase in integrity is noted in all scenarios except in ExtWater where integrity is quite severely negatively impacted (dropping a category from overall B to overall C, bordering D (Figure 95).

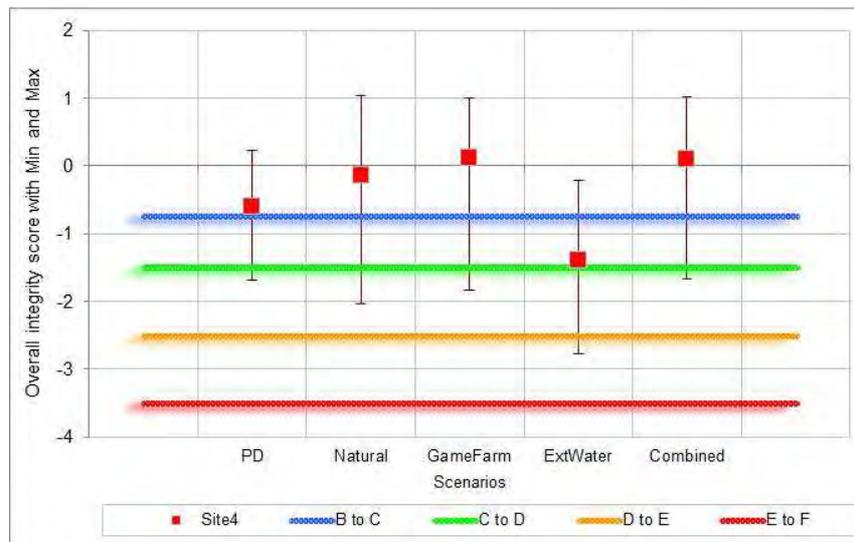


Figure 95. Overall integrity at Site 4 on the Mokolo River (ecosystem integrity only)

Figure 96 compares ecosystem integrity and social well-being for the five scenarios. Relative to PD, GameFarm and Combined would have positive impacts on both Integrity and on Well-being (note: the Integrity and Well-being scales are not comparable: one cannot say that GameFarm impacts are greater on Well-being than on Integrity, but one can say that both are positive). ExtWater would have negative impacts on both, and Natural would benefit the ecosystem at the expense of social well-being.

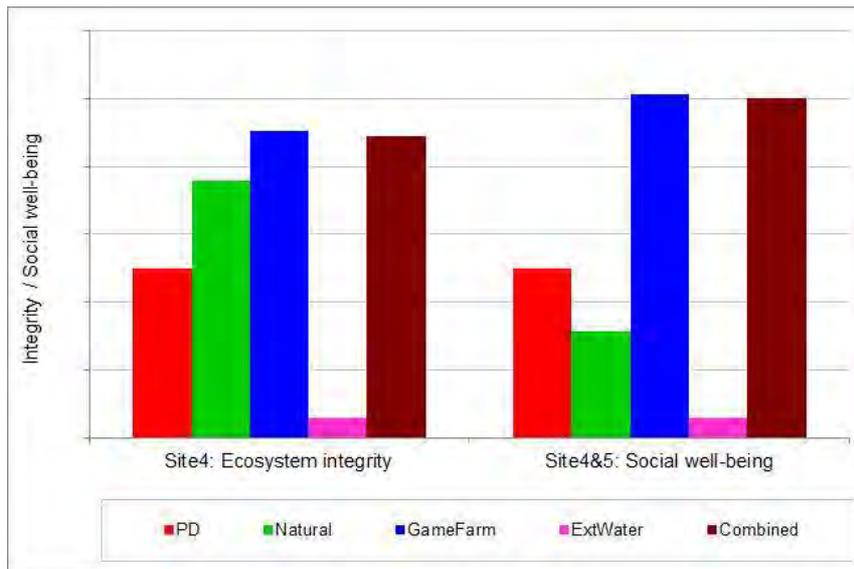


Figure 96. Comparison of impacts of the scenarios on the ecosystem and on socio-economics (note these are not on comparable scales)

8.6.1.1 Excluding “linked indicators”

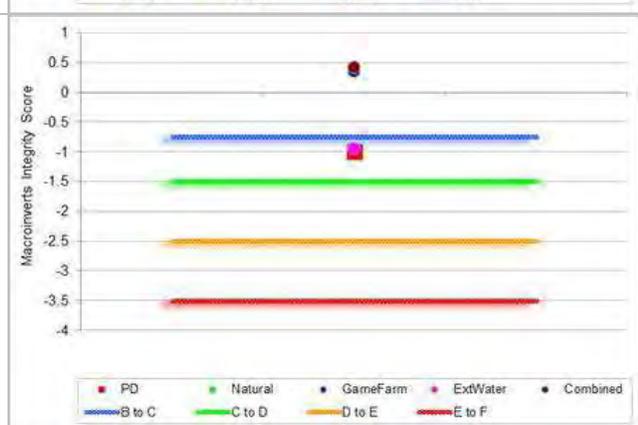
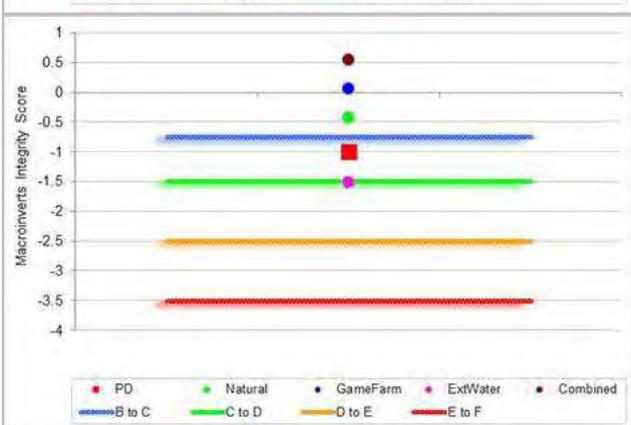
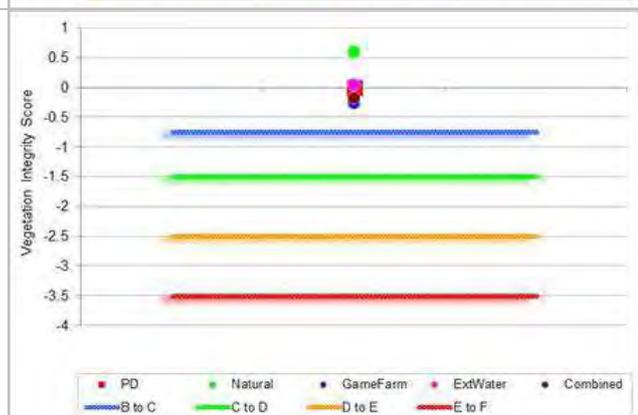
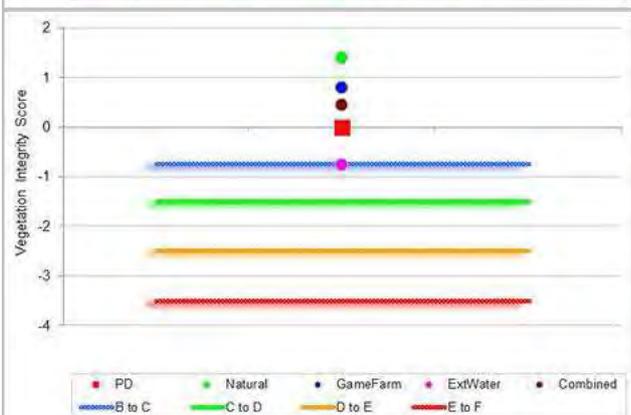
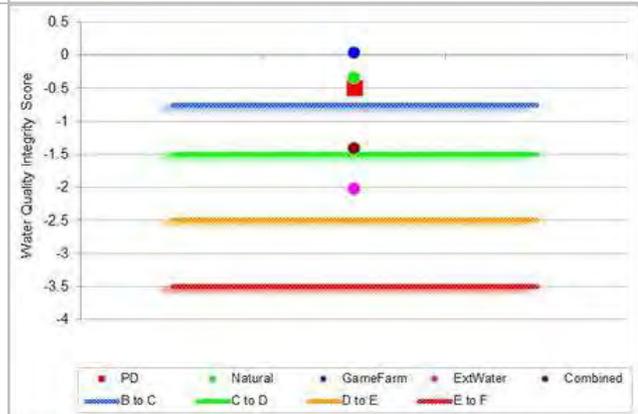
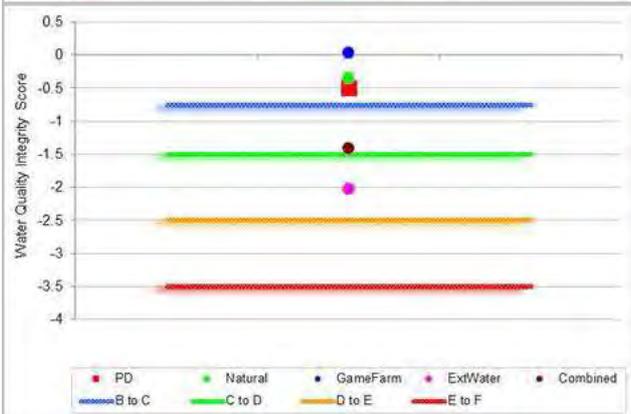
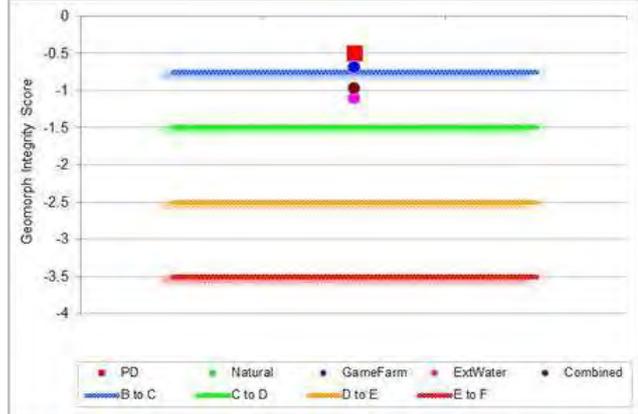
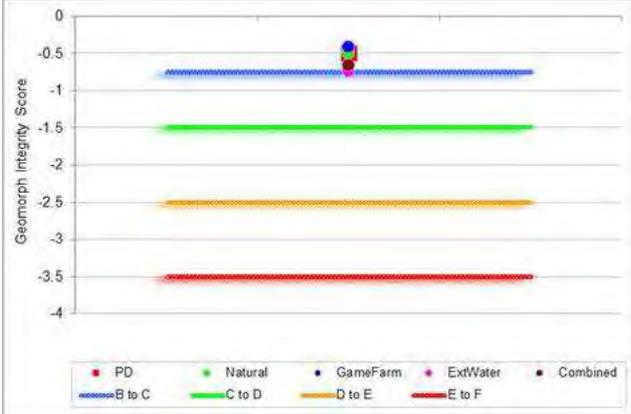
Although a proper sensitivity analysis was not undertaken, a quick comparison was made of the results if links to indicators other than flow (and hydraulics and scenario indicators) were excluded from the analysis (apart from for socio-economics, where links to non-flow indicators were always permitted). Note that this is not an entirely realistic test, as if only links to flow had been permitted for disciplines other than socio-economics, different flow indicators might have been selected. In one case (macro-invertebrates in marginal vegetation), there were no links to flow, so with this test, the indicator did not change at all (stays at 100% PD for all scenarios, all seasons). Nevertheless, it was felt to be of interest to compare the possible effects of ignoring ecosystem links.

Figure 97 shows the discipline level integrity scores with (left) and without (right) ecosystem links. In general, apart from geomorphology and water quality, the scenarios are more differentiated when ecosystem links are included (left). In other words, in these cases, the inclusion of ecosystem links has improved or increased the differentiation between scenarios.

In the case of water quality there were no links to non-flow indicators. In the case of geomorphology, the links to non-flow indicators (mostly vegetation) were *intended* to dampen the effects of flow (e.g. vegetation serves to stabilise banks, therefore will reduce the effects of floods as compared to floods where vegetation is reduced). Therefore the results without ecosystem indicators show too severe effects on the geomorphology indicators (right).

With links to flow and other ecosystem indicators

With links only to flow



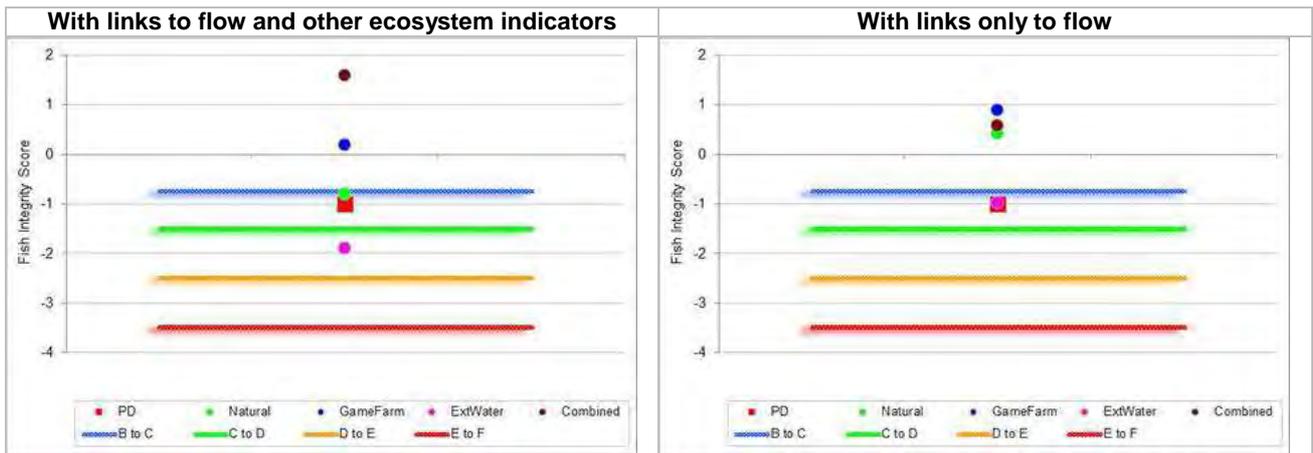


Figure 97. Comparison of results with links to flow and other ecosystem indicators (left) and with only links to flow (right) (Mokolo River, Site 4)

Figure 98 shows the overall comparison for Site 4, the reduced differentiation between scenarios in terms of ecosystem integrity being again apparent. However, the lower ecosystem integrity of Combined carries through to a low score for Well-being, so that GameFarm would more obviously be preferred.

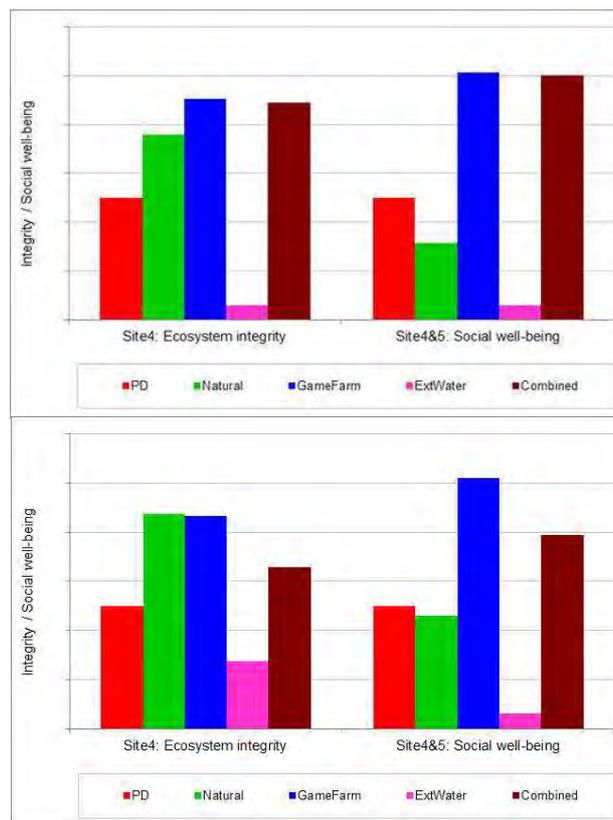


Figure 98. Comparison of overall results with links to flow and other ecosystem indicators (left) and with only links to flow (right) (Mokolo River, Site 4) (Social well-being still includes links to other than flow indicators)

9 EVALUATION OF THE DRIFT-ARID METHODOLOGY

9.1 Introduction

The Arid-proto method developed on the Seekoei River (Seaman et al., 2010; see section 3.3) was tested using the Mokolo River as case study. The Arid-proto method was adjusted as the project on the Mokolo River progressed. An evaluation of the adjusted DRIFT-Arid method (see section 4) will be discussed for each phase of the method indicating where the method differed from the Arid-proto method and if the adjusted method was successful or not.

9.2 PHASE 1 and 2: Initiate and setup the EWR study.

Determining the degree of perenniality is considered to be a vital step in the DRIFT-Arid method as it was found in a previous study (Seaman et al., 2010) as well as in the Mokolo River case study that each type of a non-perennial river would need to be approached differently. For semi-permanent rivers, such as the Mokolo River, the perennial EWR methods could be used with success but for the ephemeral rivers, such as the Seekoei River, these methods could often not be used (Seaman et al., 2010).

The appointment of different specialists for the different types of rivers was also evident. In the Mokolo River study it was found that soil scientists contributed valuable data that was needed for the integrated groundwater surface water modelling. They however should be included in the study team for all types of rivers if integrated hydrological modelling is to be part of all methods. In episodic rivers macro-invertebrate and fish specialists would probably not be included in the team and the inclusion of vegetation, mammal (wildlife) and terrestrial insect specialists would become more important (Table 49). It was also evident from the studies on the Seekoei River as well the Mokolo River that all specialists included in the non-perennial river teams should have particular experience working in these rivers and the vegetation specialist should have specific knowledge of the riparian zone and not just vegetation in general. A hydraulic specialist should be included in all studies although the traditional hydraulic approach used in EWR studies would have to be adjusted in non-perennial rivers. Hydraulic input is especially needed for cross sections, specifically for pools, as this is crucial to the accurate integrated groundwater surface water modelling and for determining the mean and range of values from the daily time series of hydrological data for the indicators related to pool depth and volume, etc.

Table 49. Specialist disciplines and methods to be included in the EWR determination for a range of river types

River type	Perennial		Non-perennial	
	Perennial	Semi-permanent	Ephemeral	Episodic
Groundwater	Yes	Yes	Yes (very important)	Yes (very important)
Surface water	Yes	Yes	Yes	Yes
Hydraulics	Yes	Yes	Yes	Yes
Fluvial and Catchment Geomorphology	Yes (GAI)	Yes (GAI)	Yes (adjusted GAI)	Yes (adjusted GAI)
Soil scientists	Probably	Yes	Yes	Yes
Water Quality	Yes (PAI)	Yes (PAI)	Yes (adjusted PAI)	Yes (adjusted PAI)
Riparian Zone Vegetation	Yes (VEGRAI)	Yes (VEGRAI)	Yes (adjusted VEGRAI)	Yes (adjusted VEGRAI)
Macro-invertebrates	Yes (MIRAI)	Yes (MIRAI)	Yes (adjusted MIRAI, adjusted OKASS or alternative pool method)	No
Fish	Yes (FRAI)	Yes (FRAI)	Yes (adjusted FRAI)	No

River type	Perennial		Non-perennial	
	Perennial	Semi-permanent	Ephemeral	Episodic
Specialist discipline				
Socio-economics	Yes	Yes	Yes	Yes
Wildlife	Probably	Yes	Yes	Yes
Terrestrial insects	No	No	No	Yes

9.3 PHASE 3: Delineate the catchment and describe its hydrology

The catchment delineation method followed in the adjusted DRIFT-Arid method is similar to the resource delineation method used in the Intermediate Reserve for the Mokolo River (DWA, 2008b), but extra activities such as the delineation of Runoff Potential Units (RPUs) and the combination of the NRUs and MRUs to delineate homogenous catchment response units have been included.

In the Arid-proto method (Seekoei River study) the Combined Response Units (CRUs) were created by superimposing the RPUs with information from the Hydrological Model and the Habitat Integrity Assessment. A problem identified when delineating the CRUs was that the data for the RPUs (by fifth order catchment) and the hydrological model (by quaternary catchment) were at different scales and it was therefore difficult to integrate the two (Seaman et al., 2010).

RPUs were specifically included in the Arid-proto method for catchments where there is very few hydrological data. Available catchment data such as the vegetation cover, soil type, slope and rainfall intensity then acts as a surrogate for gauging weir data and is used to determine areas where runoff is expected to be high or low. They are therefore deemed necessary and need to be included in the DRIFT-Arid method.

To solve the problem of scale a GIS approach was used in the DRIFT-Arid method to determine the CRUs for the Mokolo River catchment. The process followed is described below:

NRU determination:

- The RPUs were delineated (using the method described in Seaman et al., 2010) and digitised.
- Instead of the original hydrological data by quaternary catchment as suggested in the Arid-proto (Seaman et al., 2010) homogenous hydrological (surface and groundwater) units were delineated by the hydrologist and geohydrologist using desktop catchment information. The specialists were instructed to delineate units in the catchment which would be homogenous in terms of the surface flow, groundwater contribution, groundwater depth, etc. These homogenous units were then digitised by the GIS specialist. This solved the scale problem as the units identified were not based on quaternary catchment scale.
- The ecoregion level II, geomorphological zones and macro-reaches in the catchment were also digitised.
- The RPUs, homogenous hydrological units, ecoregion level II, macro reaches and geomorphological zones were then overlain to identify the NRUs. The NRUs would then represent units in the catchment that are homogenous in terms of natural characteristics such as runoff, climate, rainfall, geomorphological features, flow, groundwater depth, vegetation, habitat and geology, etc.

MRU determination: The same GIS process was followed to identify the MRUs:

- The water quality specialist was asked to identify homogenous water quality units (WQRUs). The catchment is already impacted on and it is difficult to know what the natural water quality would have been in the catchment. It was therefore decided by the team that water quality as it is at

present represents the management impact on the river and should be included in the MRUs. The WQRUs were digitised.

- The habitat integrity also represents the human impact on the river and is then also included in the MRUs. The habitat (riparian and instream) integrity units were digitised.
- The socio-economic specialist was also asked to determine homogenous units in terms of social and economic aspects in the catchment and this was digitised.
- The WQRUs, Habitat Integrity Units and Socio-Economic Units were overlain and MRUs were identified. The MRUs would then represent homogenous units in terms of management impacts (dams, weirs, abstraction, landuse, towns, development, etc.).

CRU determination: The NRUs and MRUs were then overlain to determine the CRUs.

Evaluation: The process worked well and the team easily identified the CRUs in the catchment. The process however needs a competent GIS specialist to be included in the team.

9.4 PHASE 4: Engage Stakeholders

The stakeholder engagement process followed the steps as set out in Seaman et al. (2010). Due to budget constraints however only one field excursion was possible and there was a strong reliance on secondary data for the socio-economic study triangulated by qualitative data obtained from key informant interviews. While qualitative data yields rich in-depth data, quantifiable empirical data obtained through a community survey is possibly a better fit for inclusion into a model that relies on the output of quantifiable data.

Evaluation: The socio-economic specialist could provide most of the information and data needed to determine the socio-economic indicators for the project and to give background information to determine the future scenarios for the catchment. She however emphasised that a more comprehensive stakeholder process is needed to fully incorporate the socio-economic aspects into the EWR determination process. In non-perennial rivers the stakeholder process is extremely important as it provides additional information and data for specialists to use in catchments where data are scarce. Although the stakeholder process is very expensive it is a necessity in any study on non-perennial rivers

9.5 PHASE 5: Site and indicator selection

Site selection: The site selection process in the prototype DRIFT-Arid method was based on a desktop analysis of the catchment, a macro-reach analysis and a field visit. It was decided that a more comprehensive method was needed to determine the most important sites that represent the various homogenous units in the river.

In the adjusted DRIFT-Arid method the CRUs identified by the team were ranked in terms of importance (relevance for their specific discipline) by each specialist. The ranking was combined (see Table 25 and section 5.3.5.4) and the most important CRUs were determined. The number of most important CRUs chosen, where sites are to be selected, depends on the budget available for the study. For the Mokolo River study 5 sites were chosen and these sites were then verified during a field visit in April 2010. Unfortunately the river was in flood at the time of the field visit and it was difficult to determine if the sites were ideal or not.

Evaluation: The site selection method chosen for the adjusted DRIFT-Arid method worked well and is scientifically sound as all aspects of the catchment (natural and management) are included as well as most of the requirements for all specialists involved in the study. The fact that all the specialists, and

not just the biologist, hydraulician or hydrologist, had a valuable contribution to make to site selection was regarded as a positive step in this method. This approach to site selection also relates to the approach followed in the Water Resource Classification System (Dollar et al., 2007) where nodes are identified in each Integrated Water Resource Unit (IWRU).

Indicator selection: Each specialist on the team went through a thorough investigation (see individual specialist reports available on CD included) to determine relevant indicators for their disciplines. A workshop where all specialists listed their particular requirements with regards to driver indicators (hydrology, hydraulics, and geomorphology) was regarded as a necessity in the project. These driver indicators were then evaluated by the hydrologist and geomorphologist and they then provided a summary list of what they could provide in terms of data available. Unfortunately the hydrological modellers were only involved in the project at a later stage and they indicated that they needed to be involved from the start as they could then give input into what type of data for indicators is possible from the model and what not. In a future project it would be advisable to involve the modellers from the beginning.

Specialists were allowed to provide an exhaustive list of indicators for their as the aim of the project was to test the method. In an actual EWR study it is recommended that a more concise list of indicators should be used. Dr. Alison Joubert also evaluated each indicator with the specialists to make sure they would provide the type of information needed for the DRIFT DSS.

Evaluation: The process to determine indicators for the different disciplines still needs research and after further studies on different types of non-perennial rivers a generic list of indicators could possibly be developed.

9.6 PHASE 6: Complete Specialist studies and choose scenarios

9.6.1 Specialist studies

Data for each discipline was collected during a field visit in April 2010. Only one field visit was possible due to budget constraints. The river was in flood at the time of the field visit and the specialists had problems collecting data using the standard sampling methods prescribed for a EWR study.

Evaluation: The geomorphologists needed to use an inflatable boat to access the channel due to the high flow. The current speed hampered the surveying of the channel because firstly it was difficult to remain in one position and secondly the current pushed the survey-staff downstream at an angle. Despite these difficulties the surveyed transects give a satisfactory picture of the dimensions, shape and complexity of the different channels. Deep floodwaters covered and obscured the lower channel features hampering the identification of morphological features in the field. In no cases could the channel bed be observed due to the high water depth. Its dimensions were assessed from the cross-section surveys and the bed material from probing the bed with the end of a survey staff. A field visit during a dry period would have added to the accuracy of data collected.

Data from the water quality samples taken in a flooded river need to be used with caution due to the dilution effect and would not provide a true reflection of the current water quality at the sites studied.

The vegetation specialist found it difficult to identify the various riparian vegetation zones and samples of vegetation for identification could not always be taken due to the high water level.

The sampling method recommended for macro-invertebrates namely SASS5 (Dickens and Graham, 2002) specifically cautions against sampling in flooded rivers as most invertebrates could be swept downstream and the sample would not be representative of the present invertebrate community. Access to the main channel was often not possible due either to the long stretch of floodplain which was inundated, or the depth and high flow in the main channel that made SASS sampling near impossible.

Effective fish sampling was also difficult due to high flow and most of the samples were taken in the flooded areas, which were more accessible than the fast flowing main channel.

The specialists (water quality, geomorphology, vegetation, macro-invertebrate and fish) needed to supplement their field data with data from the Intermediate Reserve study (DWA, 2008a) and other relevant reports in order to provide information for the indicators chosen and to determine the PES for each site.

More than one field visit should always be part of a EWR determination in a non-perennial river as it is almost impossible to find an ideal sampling period in these rivers which are often flooded or dry.

9.7 PHASE 7: Choosing scenarios

Five scenarios were chosen by the team for the Mokolo River Catchment namely:

- Scenario 1 Present Day
- Scenario 2 Natural
- Scenario 3 Sites 1-3: Agriculture converted to game farms
Sites 4-5: No further development
- Scenario 4 Sites 1-3: No further development
Sites 4-5: Power, mining and interbasin transfer expansion
- Scenario 5 All of the changes
(i.e. agriculture to game farm sites 1-3, mining, etc. expansions sites 4-5).

Evaluation: It is important to consider the direction of change implied by the scenarios. The scenarios chosen in the Mokolo River study all implied *more* water available than currently. It would have been more illuminating to have at least one where more water was abstracted from the river or groundwater. The expansion scenario had very little impact on the river as the water from the interbasin transfer was modelled to be transferred directly to the town, power stations and mines and no water was returned to the Mokolo River either directly or via return flows (although this was not anticipated when choosing this scenario).

The scenarios were also chosen before the hydrological modellers were included in the team and they indicated that it would be preferable that modellers are part of the team when scenarios are chosen. They could provide valuable input into what the model could provide data for and what type of data are needed to simulate the hydrology for a particular scenario. It would also be preferable that the scenarios guide the modelling as different aspects need to be included for different types of scenarios.

When a scenario such as the expansion scenario with an interbasin transfer is envisaged specific data, on where the water will be used and how, where it will be released and how much, etc. is needed for the hydrological simulation of the scenario. When scenarios are chosen, the team therefore needs to know what type of data are needed for each scenario and then to check if the data are available.

9.8 PHASE 7: (Activity 19): Hydrological simulation of scenarios using Groundwater/Surface water interaction modelling

DHI were appointed to simulate the hydrology for each of the scenarios chosen. The MIKE SHE model first had to be calibrated and a conceptual model of the Mokolo River catchment was then developed. The model was run to provide data for the present day scenario and then for the other four scenarios at each of the five sites.

Evaluation: The following is an evaluation of the MIKE SHE Mokolo River modelling project outcomes. The evaluation is organized by project phase.

9.8.1 Characterization & Conceptualization

The model had difficulty simulating non-perennial conditions and peak flows at some of the gauges as well as depths that reflected field measurements. The model's inability to simulate these responses can be largely attributed to known data gaps. The data gaps that had the greatest influence include:

- **Irrigation** – Although some data are available on annual irrigation rates from surface water and groundwater sources, it was not possible to correlate irrigation rates and sources to actual irrigation areas. This by itself could explain why the model was unable to simulate non-perennial conditions at some gauges.
- **Mokolo Dam operation scheme** – No direct outflows from the Mokolo Dam were available. The only indirect information on outflows was a stream gauge several kilometres downstream of the dam. The lack of direct outflow measurements and information on the dam operation significantly hinders the calibration of the dam storage dynamics and of the model's ability to simulate flow conditions downstream of the dam.
- **Subsurface aquifer data** – Basic subsurface aquifer data were unavailable, including aquifer depths, properties, and transient water level observations. This significantly hinders the calibration of groundwater flow and groundwater-surface water interaction. In particular, the stream-aquifer interactions are important in the reserve determination method.
- **Soils** – Basic soils data are available, but this needs to be correlated with the subsurface aquifer data when it becomes available.
- **Topography** – The available topography data are relatively coarse, which is suitable for a regional integrated model. However, the available topography resolution is insufficient for the creation of appropriate cross-sections to describe the surface water flows and levels.
- **Climate** – Ultimately, use of daily climate data must be evaluated during model calibration to assess whether it adequately simulates surface runoff and infiltration/recharge to groundwater. Ideally, it is always better to use sub-daily rainfall and aggregate up if needed. This is however an unrealistic requirement in South Africa as such data are very difficult to obtain.

The limitations of the input data translate directly into uncertainty associated with the conceptualization, calibration, and scenario results.

It must however be noted that the Mokolo River is a data rich system with more data available than most of the non-perennial rivers in South Africa. This therefore poses the question if the MIKE-SHE model would be capable of modelling these data poor systems.

9.8.2 Calibration

The calibrated model largely reproduced the long-term, regional-scale flow behavior observed in the Mokolo catchment. However, the system is sensitive to irrigation and near-stream vegetation, soils and sub-surface properties, all of which were poorly defined.

Particularly in the groundwater, the lack of observations and field data means that the simulated groundwater response is only generally correct. The network of dikes and faults probably compartmentalizes the regional groundwater flow system, which cannot be simulated in the current model. This may partly explain the difficulty in simulating non-perennial flows, since groundwater baseflow is likely a local process.

The calibrated model also had difficulty simulating some peak flow responses. This can be attributed to the lack of sub-daily precipitation data and the lack of information associated with instream weirs and farm dams.

9.8.3 Future Scenarios

The model generally reproduced the expected direction of changes in flow associated with the scenarios. However, the absolute magnitudes as well as the relative magnitudes of change were less certain given uncertainties in model inputs and the difficulties with non-perennial conditions.

Differences in the initialization of each of the scenarios make exact comparisons difficult. For example, in one of the scenarios different numerical convergence parameters had to be used to make the simulation stable, which affected the results. Also, the scenarios suggest that the removal of the Mokolo Dam impacts the catchment flow for more than 50 years afterwards.

In particular the scenarios showed that

- Changes in the vegetation associated with conversion of irrigated land to game farming (in Scenarios 3 and 5) significantly increased the mean flow simulated at the sites upstream of the Mokolo Dam (simulated values for these scenarios were 200 to 800% more than PD/Baseline). Increases in maximum flow were even higher (simulated values up to 70 times PD/Baseline maximum flow).
- The change to Game Farming resulted in larger changes compared to those for Natural. The changes were larger because modified native vegetation (Acocks veldtypes using ACRU method to determine LAI) was used in the Game Farming and Combined scenarios. Whereas, in the Natural scenario, the existing (Mucina and Rutherford, 2006) vegetation was used, based on MODIS LAI. The modified native vegetation (GameFarm and Combined scenarios) uses much less water than the natural vegetation in Natural. This was a shortcoming of the modelling, rather than a realistic result of the differences in scenarios. Furthermore, the significantly different response to vegetation (Natural vs. Game Farming and Combined) demonstrates how sensitive a fully integrated model can be to changes in vegetation parameters.
- The ExtWater scenario had virtually no effect on the selected indicators. This is a limitation of the way the scenario was defined, relative to the indicator locations and difficulties in knowing how the expansion scenario should be implemented.

The flow conditions downstream of the Mokolo Dam are strongly controlled by releases from the dam. Given the lack of data associated with operating rules and strategies, the simulated changes downstream of the dam are only indicative of potential changes. Different strategies or rules would significantly impact the results.

9.8.4 Lessons learnt by DHI

- It is critical that the hydrological modelling team is involved early in the project. The current project had been underway for several years before DHI became involved. Although this was unavoidable in the current project, it resulted in significant lost opportunities for data collection, coordination and communication.

- The data sources used in the models must be clearly documented. This includes metadata, date stamps, origins, etc. This will save considerable time in researching and assessing the data quality and its relevance for calibration. A matrix can be developed for data input to keep track of large datasets
- Clear deadlines for data provision need to be communicated to the team and enforced. There is a significant effort involved in re-interpreting data and re-calibrating the models if new data are provided late in the project.
- The Mokolo River is close to perennial with a large dataset and this makes modelling difficult as inaccurate data could be compounded in the model and produce inaccurate results. Rivers closer to non-perennial with less data would be easier to model but calibration is difficult if not impossible if gauging data are not available. In systems with sparse data, modeller could use climate data as a surrogate for gauge data.
- There is likely a paucity of data for most catchments in South Africa. The resulting uncertainty in the results is likely to be high. This favours the development of multiple conceptual models that all match the observations reasonably well. The different conceptualizations can then be ranked in terms of their ability to reproduce observed conditions. The range of results from the models that are equally well calibrated is a measure of the uncertainty in the results.
- If the project needs to have data on hydraulics with a high level of accuracy then the right kind of data, right quantity versus quality and right locations and frequency of data must be collected.
- Riparian zone data not included in the model could result in the model showing more flow in river than was the case in reality as the riparian zone would absorb a lot of the water. Model results are very sensitive to vegetation as well as soil and this is something that needs to be looked at in more detail.
- Surface and groundwater boundaries do not match. Surface water boundaries are easier to estimate than groundwater boundaries and assumptions need to be made as to where groundwater boundaries are.
- Poor irrigation data and data that is not verified and possibly much less than actually used in a catchment would result in more water in river and difficulty in producing zero or low flows in the model.
- The model cannot distinguish between subsurface and surface flow and so at very low flows it is difficult to reproduce zero flow periods. There is always flow in the system although the flow is probably in the alluvium and not actual surface flow.
- Water extracted illegally from the riverbed (out of the alluvial aquifer) would impact on flow in the river in the model output as the amount of water removed by illegal abstractions are not known.
- In arid/semi-arid environments, it is usually necessary to use 'event-level' rainfall because rainfall events are typically short (<1 hour), intense and localized. If soils are generally permeable (e.g. sandy), then it is possible to use daily data to simulate integrated flows, as most rainfall will infiltrate. However, if the rainfall rate exceeds the capacity of the soil to infiltrate water, daily rainfall data can promote infiltration at the expense of the surface runoff generated during short, high intensity events that are averaged-out over a day. Ultimately, use of daily climate data must be evaluated during model calibration to assess whether it adequately simulates surface runoff and infiltration/ recharge to groundwater. Ideally, it is always better to use sub-daily rainfall and aggregate up if needed.
- Building a conceptual model is one of the most important steps in setting up a model. Inadequate model structure (conceptualization) is far more detrimental to the accuracy of the output than the actual data limitations and causes uncertainty in the model output. In data limited areas the modeller would need to develop multiple conceptualizations in order to find one which is most suited to the observed system structure.
- The Modeller should first use a sub catchment to calibrate the model and then go on to the larger basin.

- The calibration strategy should carefully consider the needs of the ecological DSS. That is, the strategy needs to include the hydrological and hydraulic indicators used in the DSS, along with the available data. In particular, the strategy needs to consider the:
 - **Available calibration data** prior to the start of modelling, including spatial distribution and length of record. If appropriate calibration data are unavailable (e.g. depth to water table beneath the river) then the early identification of the missing data could motivate for its collection.
 - **Appropriate calibration target locations, types and values.** Instead of the traditional discharge and water level targets, the indicators themselves could become critical calibration targets. For example, if non-perennial conditions are a critical indicator, then the annual period of non-perennial flow could be a calibration target.
 - **Priority of the calibration targets.** The indicators chosen by the team need to be prioritised and the modeller can then make sure the model produces accurate information for the most important indicators. It is generally not feasible to calibrate a model that reproduces disparate responses equally well. For example, it is challenging to create a model that is very well calibrated to river peak flows, river low flows and groundwater levels. The different targets must be prioritized based on the intended use of the model. Prioritizing the hydraulic indicators would effectively prioritize the hydraulic calibration targets.
 - **Appropriate accuracy of the calibration.** The accuracy of the calibration is fundamental to the modelling effort required. It may be that a high-level of calibration accuracy is not required to produce the same ecological response results. If the ecological DSS response is not very sensitive to the exact model results, then considerable time, effort and money could be saved in the modelling. Similarly, if the ecological results were sensitive to the difference between two responses, then only the differences need to be accurate (which is generally easier to simulate accurately).
- The calibrated model largely reproduces the long-term, regional-scale flow behaviour observed in the Mokolo catchment. Particularly in the groundwater, the lack of observations and field data means that the simulated groundwater response is only generally correct. The network of dikes and faults probably compartmentalizes the regional groundwater flow system, which cannot be simulated in the current model. This may partly explain the difficulty in simulating non-perennial flows, since groundwater base flow is likely a very local process.
- The calibrated model has difficulty simulating some peak flow responses. This can be attributed to the lack of sub-daily precipitation data and the lack of information associated with instream weirs and farm dams.
- Scenarios chosen must be carefully designed. Scenarios that simulate the required response are not always easy to design. There is a need to pre-evaluate scenario responses and adjust the final scenarios accordingly. In this project, such a design/evaluation process would have identified that indicators were insensitive to the expansion scenario (scenario 4). The scenario could then have been adjusted or changed accordingly to ensure a reliable response. This would also have identified early on issues with the vegetation definition in the natural (2) versus the game farming (scenario 3) and combined (scenario 5) scenarios. The pre-evaluation of the scenarios could be done on a shorter simulation, or a simpler model setup.
- Datasets used in the various scenarios should be the same, i.e. different vegetation base data were used for the Game Farm and Natural scenarios in this project which proved to be a problem when output was compared.
- Modelling uncertainty should be propagated to the DSS. In any modelling project, there is inherent uncertainty. Some of this uncertainty can be quantified through formal analysis (sensitivity analysis, multiple conceptual models, etc.). The uncertainty in the hydrological responses should be communicated to the DSS team as a range of expected values. The range of expected values could be incorporated into the DSS to determine if the DSS outcomes are

sensitive to the range of hydrologic uncertainty. If so, then this could motivate for additional data collection in the catchment to reduce the model range. This could also motivate for changes to the DRIFT methodology or the ecological DSS to make it more robust, with respect to the expected uncertainty of the hydrologic modelling.

- Focus on change in hydrology rather than a specific state (actual real time results as this is only possible at high confidence when considerable amounts of data are available). MIKE SHE model predicts a change in a system rather than a specific state. It is very difficult to simulate real systems flow data when input data are not accurate or verified.
- Ultimately the calibration approach is dictated by available data, complexity of flow conditions (natural and anthropogenic) and required accuracy needed for ecological assessment. It is important to appreciate that if the integrated hydrologic flow model is unable to provide the level of accuracy required by the ecological DSS assessment, more data must be collected to reduce model calibration error and predictive uncertainty.

9.9 PHASE 8: Knowledge capture

In the Arid-proto method a simple method was used for knowledge capture where the team identified links between the driver and responding indicators and drew responses for them in Excel. The specialists drew the response curves without having the actual driving indicator data available. A scale from -5 to +5 was used to indicate an increase or decrease in the driving indicator and the response (also on a scale from -5 to +5) was then drawn on a graph.

In DRIFT-Arid a more structured method of knowledge capture is followed and the DSS (using Excel functions and VBA macros) helps to integrate inputs, outputs and results. Response curves are drawn directly into Excel spreadsheets and data on the input flow and hydraulic indicators are available to the specialists. Being able to view the input range (x-axis values of the response curves) and the resulting time series allowed for more accurate predictions of change. The linked indicator data (for indicators other than flow and hydraulics) is however not available and specialists rely on dummy data (i.e. a standard range from 0 to 250% for the x-axis) to draw the initial response curves, and no response is reflected in the time-series. Once the specialists have completed the initial response curves, the DSS is run. The data files are returned to the specialists (with the linked indicator x-axis data, and time-series of linked indicators values now available) and they can alter their responses if needed. The process is easier for the specialists to use than the Arid-proto method as they can view the time-series results of their response curves and interactively adjust as required.

9.10 PHASE 9: Scenario analysis

The change in driving indicators relate to a change in the responding indicators in each of the scenarios chosen by the specialists. In the Arid-proto method problems were experienced with the output of the hydrological analysis that could not provide data for the delivery of sediment to catchment and floods which were two of the driving indicators chosen. The analysis started with PD indicated as "0" and predictions of change to each of the driving indicators was made in relation to PD. Several problems were identified namely:

- Indicators needed to be weighted but this was done subjectively although expert opinion was used.
- The number of indicators used affected the final value of the response as those responding indicators with more drivers had a lower value than those with fewer drivers.

In the DRIFT-Arid method the MIKE SHE model was used and although the output was not realistic in terms of real data it did provide a daily time series of flow, depth, groundwater depth, baseflow and groundwater (subsurface) flow beneath the river that could be used to calculate the flow and hydraulic indicators (a value for each indicator for each year) as well as the medians, ranges and standard

deviations. This resolved the problem of input values for the driving indicators experienced in the Arid-proto method.

In the Arid-proto method, the particular approach to scoring, weighting and aggregating (Seaman et al., 2010), resulted in aggregated results for indicators with more drivers being “diluted” relative to those with less drivers. In the DRIFT-Arid method and DSS the effects of driver indicators are **additive**. This means that specialists need to be sure that they include the relevant drivers “evenly” for all their indicators, so as not to under-report effects.

Specialists also needed to calibrate their responses as part of the DRIFT-Arid method. This step was not included in the prototype method. To calibrate the responses specialists needed to use an all wet, all dry and combined wet/dry scenario. However not all specialists were aware that they needed to complete this step and this resulted in some anomalies in response curve output when results were used by other specialists. This can however be avoided in follow up studies and it is emphasised that this step should be communicated to the specialists involved.

9.11 PHASE 10: Evaluate scenarios

In the Arid-proto method ecosystem integrity was not determined but specialists drew abundance response curves and then indicated the direction of change (away (-) or toward (+) natural). Thus, a situation could arise, in the scenario analysis, where several “aways” and “towards” would cancel each other out and no change in integrity would be recorded. The team were uncomfortable with this, and attempted to resolve it by cancelling out positive and negative ratings of equal value and then using the remaining ratings to determine the direction of change. For more details on this please see Seaman et al., 2010 Chapters 5 and 6.

A similar approach is followed in the DRIFT-Arid method, where specialists indicate whether a change in abundance is a change toward (+) or away from (-) natural (see Figure 76). This is then used to determine the integrity scores for each discipline (on a scale from -5 to +5). (Note that in DRIFT-Arid and DRIFT a further adjustment is made to the integrity scores, whereby at the discipline level, they are adjusted relative to PES, so that an A condition (natural) has an integrity score of 0, and any integrity change is negative relative to that).

Thus, as in Arid-proto, moves towards and away from natural can cancel each other out. This is, in fact, regarded as a realistic reflection of the result of certain parts of an ecosystem improving, while others decline, although some parts of the ecosystem might be more important in determining the resulting ecosystem integrity than others, both at the discipline level and at the site level. For example, at the discipline level, at a certain site, a particular group of fish or a fish species might be more important for overall integrity of fish in the ecosystem than another. By the same token, at the site level, for argument’s sake, water quality might be more important for overall site level ecosystem integrity than, for example, geomorphology. For this reason, in both DRIFT-Arid and DRIFT, indicators can be weighted when they are aggregated to find overall discipline level integrity, and disciplines can be weighted when they are aggregated to find overall site level integrity.

While the “cancelling out” of improvements and deteriorations in integrity are considered appropriate up to a point, there may be a need (included in some previous version of DRIFT-Excel) for a “veto” whereby if the integrity of any, or one in particular, part of the ecosystem falls below a certain level, a large improvement in another (which would be unlikely to occur if the system had been properly modelled) can no longer counterbalance the negative impact.

9.12 PHASE 11: Outputs

The output required by the DWA for the management of the EWR for rivers is in the form of a Reserve template and it includes two hydrological parts namely:

- The bulk amount of water needed for the Ecological Reserve and how much is needed at different assurance levels. This includes maintenance high flows, maintenance low flows, drought low flows and drought flood flows as a monthly percentage of MAR at a point and as monthly volumes of water in million cubic metres, and
- Transforming the information into flows that can be monitored and managed. This is done by providing monthly flow duration curves, each with an accompanying natural flow duration curve. The Reserve flow is then determined by calculating what the natural flow would have been on a particular day and then reading off the equivalent percentile value on the Reserve flow duration curve (King and Pienaar, 2011).

The DRIFT-Arid DSS and the Hydrological model used (in this case MIKE SHE) can provide a summary of the hydrology expected under each scenario as well as the ecological and socio-economic consequences of these scenarios. These can be provided in a visual format and as excel spreadsheets and stakeholders can see in which PES category the site or river would be under each scenario. The stakeholders and the DWA then need to decide which scenario would be acceptable.

In the MIKE SHE (or any other integrated surface and groundwater hydrological model used) model output one could determine what the natural flow should be at each point in the river. The maintenance flows needed, can then be also determined for each point on the river.

There are however big challenges in determining accurate flow conditions in a non-perennial flow system. The level of accuracy depends heavily on the calibration of the system. And of course this depends strongly on quantity and quality of available data (input stresses like climate, or pumping, hydrogeological framework and system response data like streamflow, or groundwater level variations in time) and the complexity of the system, both of which strongly influence the degree to which an integrated system can be calibrated. As in the case of the Mokolo system model, non-perennial conditions were not reproduced at a high level during calibration – for a variety of reasons. With more data, more time and a clearer understanding of the subsurface aquifer system better results could certainly have been obtained. Data will however always be limited in all catchments and this won't allow development of highly accurate models (of any type) especially in non-perennial flow systems (more challenging to simulate low-/no-flow conditions than perennial systems) (Purchas pers. comm.).

Given data limitations and their impacts on model calibration and the DWA's objective an option would be to:

- a. Compile best available dataset and create functional databases.
- b. Develop MSHE model (or any other integrated hydrological model) of the basin using this dataset.
- c. Calibrate the integrated hydrological model of the basin to the extent possible. Use 30-50 year continuous climate datasets (as in Mokolo), or from NASA GLDAS2 datasets available globally (and over all of South Africa) to develop long-term baseline/present day simulations (as was done in the Mokolo) of historic conditions.
- d. Develop a Natural condition scenario where all development is taken out of the model to compare against Baseline (developed basin) to produce best possible estimate of hydrologic/hydraulic change in flow system.
- e. Determine environmental reserve needed.
- f. Using the MSHE (or any other integrated model) scenarios and assess the impacts of individual permits, or collective permits on system hydrology (either Natural or Baseline) and determine whether

percent change to system hydrology/hydraulics is acceptable for environmental reserves. These simulations could be set up with limited training (doesn't require advanced skills needed to calibrate).
g. If real-time data is needed, there are ways to automatically update the calibration of the model that can be prepared within a more formal decision support system framework (Prucha pers. comm.).

If the standard perennial approach, for output to the DWA, is used two sets of data would probably need to be provided to the DWA in non-perennial rivers – one for wet years and one for dry years. It would however be very difficult to manage the rivers with this type of data as it would be near impossible to predict if the year is going to be wet or dry and which of the datasets need to be used.

A solution to the output has not been determined in this project and would need the input from leading hydrologists, geohydrologists, hydrological modellers as well as staff involved in actual implementation to provide a solution. A possible solution is to setup a real time hydrological model such as MIKE SHE and then to implement the Ecological Reserve on a day to day basis but this would need highly specialised modellers to run.

10 LESSONS LEARNT IN INTEGRATED GROUNDWATER AND SURFACE WATER MODELLING AND IN THE DRIFT-ARID DSS.

10.1 Introduction

The field of Environmental Water Requirements (EWRs) for non-perennial rivers is relatively new in South Africa. Various methods such as DRIFT (Brown et al., 2008 and 2008a), Ecoclassification (Kleynhans and Louw, 2007) and HFSR (O Keeffe et al., 2002) have all been developed and tested in South Africa from the 1990s and the team used the knowledge and years of experience captured in these methods to guide them in determining which of these could be used in rivers with highly variable flow and long periods of no-flow. Dr. Jackie King, one of the co-founders of the DRIFT method was involved as an advisor to the team for this project and with her extensive knowledge of method development in South Africa and the world, she suggested that the team start by using the DRIFT method. This method leans itself to being suitable for use in a variety of river types and can easily be adjusted as the team gain experience and knowledge in non-perennial rivers. One of the main reasons this method was recommended was that it starts at present day (PD) and this is the period where specialists have the most data and experience. Most of the other methods start at using natural as the reference condition and in non-perennial rivers this is difficult to determine as there is very few historical data available on these rivers.

The Mokolo River case study was initiated specifically to test the Arid-proto method for non-perennial rivers, which was developed using the non-perennial Seekoei River as a case study. The DRIFT method (which was used as a guide) includes choosing indicators (measureable units that indicate change) in each discipline as well as possible scenarios (future developments in the catchment). A hydrological model is used to produce a daily time series of flow data for the present day as well as for each of the scenarios in the catchment being studied. This information is then used to determine values (mean and standard deviation, etc.) for the flow and hydraulic indicators chosen by the team.

For the Mokolo River case study an integrated surface and groundwater hydrological model – MIKE SHE was used to produce a daily time series of flow data. The output from this model was then used to determine the values for each flow and hydraulic indicator chosen. These values were entered into the DRIFT-Arid DSS which is an excel based model used to combine all the experience and knowledge from experts into an organised structured setup. It allows information to be captured and predictions made in an orderly and transparent fashion. The intention of the DSS is to model biophysical and socio-economic changes in relation to changes in a river (e.g. changes in river flow). This is interpreted and operationalised by describing river flow on the basis of flow indicators, and biophysical and socio-economic changes on the basis of relevant indicators. The DRIFT-Arid DSS (based on the original DRIFT-DSS) was designed to store the specialist-created response curves of flow-indicator relationships, and to use these to predict the ecological and social outcomes of any development driven change in a non-perennial river system.

This chapter will highlight the lessons learnt by the team and modellers in the use of the MIKE SHE model and the DRIFT-Arid DSS model in the Mokolo River.

10.2 Lessons learnt in the integrated groundwater and surface water model (MIKE SHE)

DHI were appointed by the team to model the integrated groundwater surface water hydrology of the Mokolo River. It must be stated that DHI were not part of the project from the beginning and that Dr. Ingrid Dennis was originally tasked with the hydrological modelling for the project. Dr. Dennis resigned

from the team in 2010 and after consultation with various hydrologists in South Africa DHI was appointed.

10.2.1 Lessons learnt by the team

- Objectives of the study need to be talked through carefully with the modeller (especially if the modeller is not acquainted with EWR studies). Need to establish what output level of accuracy is needed as this influences the data required for the model. Data needs would rely on the specific objectives. If high accuracy of predictions is needed then more data as well as higher level of accuracy are needed.
- The modeller needs to be part of the field excursion and also needs to sit with the team when data are being organised so that guidance can be provided as to what type of data are needed. The Geographer/Data co-ordinator/GIS specialist and modeller should work together in the early stages of modelling in order to accumulate all data before calibration starts and also to verify data for usefulness and accuracy.
- Need to include time in the budget to collect data and organise them before the modelling begins.
- There is a considerable body of hydrological data available in South Africa but these data are difficult to access as it is mostly in the hands of private consultants or in reports at the various government departments. A Central Data Storage Facility is needed in the country where data are stored, verified and interpreted, this would minimise time and budget needed for EWR studies in South Africa.
- It is difficult to apply a complex hydrological model in a situation where there are limited data both as input to a distributed model and to calibrate the model. The model assumes certain processes that may not be true for the particular system.
- Response curves could be drawn for channel complexity, longitudinal connectivity and lateral connectivity that were related to simple hydrological variables such as flow variability and flow discharge that themselves would not need to be precisely quantified.
- A geological model of the catchment is essential to accurate groundwater modelling of the catchment being studied. This information is also needed for the subsurface flow modelling in the MIKE SHE model. MIKE SHE has the capability of linking with ArcView and a geological editor has been developed in ArcView that supports the interpretation of borehole and geophysical data into a consistent geological model, and finally, the model is easily evaluated and exported for further use in the numerical model. This can then be accessed by the MIKE SHE model (DHI, 2012). Although this is possible, it is time consuming and outside the scope of this project. It is however recommended if the MIKE SHE model is to be used in future.
- Several cross-sections per site (at least 3 per pool and through riffle rapid area as well) should be included for more accurate hydraulics modelling.
- Leaf Area Index (LAI) data with time are critical to modelling especially for natural vegetation as some data already exist for crops but very little for natural vegetation.
- Root depth of riparian vegetation is an important dataset needed.
- A meeting with the hydrology modeller needs to be held after the calibration phase is completed so that team can decide if they are satisfied with the output in terms of accuracy of data and this was not done successfully in this project.

10.3 Lessons learnt in the DRIFT-Arid DSS model

Dr. Alison Joubert used the DRIFT DSS to provide an indication of the integrity of each discipline as well as a combined integrity output for each scenario chosen by the team at sites 1 and 4 on the Mokolo River. The team identified the following aspects which need attention in the DSS model output and structure.

- Only one person (Dr. Alison Joubert – modeller and co-creator) in South Africa can run the DSS. The DSS is not static, it evolves with each project or river and this makes it difficult for anyone else to run. This poses a problem where more than one EWR has to be completed at the same time. Training courses are needed.
- The DSS needs to be streamlined which is currently being done as part of a different project. (However, although the “coded” version being created is necessary, it remains useful to have the Excel-VBA based version “on hand” as it is flexible and allows changes to be made and tried out with easy access to results);
- Specialists need to work together to identify indicators and links (are the relevant indicators for one specialist being supplied by another?).
- The number of indicators and links chosen needs to be prioritised and of minimal size, so that only the most important are included. More than “usual” were allowed in this project as it was specifically done to test a method and was not an actual EWR study.
- It is possible that a different set of indicators will be relevant depending on whether the river system is in a flowing state or an isolated pool or dry state. Alternatively, a different set of response curves might be relevant, where the same indicators are relevant, but the responses to inputs will be different depending on which state prevails. This was identified as a possible need for the water quality indicators, but seemed to be dealt with by the DSS as described in Chapter 7.
- It might be advisable for all indicators to have a link to a hydrological or hydraulic indicator as this should make calibration easier.
- A positive aspect of the DSS is that indicators can be switched on and off to test sensitivity, and off when not needed at a site.
- The data or information from the driving indicators should be provided to the team before the response curves are drawn. Note however, that non-flow input indicators are not available until the specialist dealing with that input has completed the response curves. Therefore, specialists cannot initially, interactively assess the time-series resulting from all responses, only that resulting from flow indicators, which may be a small subset of all the linked indicators, or there may be no flow indicators relevant at all. This means that the specialists complete their flow indicator response curves and a first estimate response curve based on a hypothetical range for other indicators. The specialist can only view the overall time-series once all the information has been fed back through the DSS.
- The workshop process becomes complex as a result of linked indicators and feedback loops.
- A facility should be included in the DSS where if something is altered, it, as well as the changes to the links are indicated (perhaps colour coded) so that one can see the result of the change.
- Calibration should be done using an all wet (flood) scenario (wet scenario is where a series of very wet years are artificially put together), and an all dry scenario (where a series of very dry years are artificially put together) as well as a combined wet and dry scenario (half wet and half dry) and not using the actual scenarios chosen (only some specialists had access to these calibration scenarios prior to the workshop).
- In systems where the community is not directly reliant on the river such as in the Mokolo River, modelling socio-economic consequences is less direct. Areas of different landuses were used and directly linked to the social indicators, this required some ad hoc adjustment to the DSS, which need to be formalised.
- For geomorphology there will be long periods in a year when there is insignificant change and short periods during peak flows when change is possible. These can be coarsely approximated as four seasons can be used in the DSS, allowing for short periods of “activity”.
- Thresholds and response time are two of the key problems when developing response curves for geomorphic change. While individual response curves allow for thresholds, it is possible that the threshold effect is reached only when a number of the links reach specific thresholds (i.e. the

threshold might be a synergistic combination). For example, if peak discharge reaches X AND sediment load reaches Y AND bank vegetation reaches Z, then a single thread channel may change to a braided channel, while this might not happen when individual inputs reach any of these thresholds.

- The questions regarding lag period in the DSS model input files are difficult to answer and clearer instructions are needed for this.
- A weakness of the DSS used in the Mokolo study is that it was overly complex and end users were not always aware of how the dynamic aspects of the system worked. For example, what is the difference between a lingering and a lag effect?
- The DSS should encourage communication between specialists but in practice during a workshop each specialist is absorbed in their tasks. Outside of workshops geographic distance hindered effective communication.
- A positive aspect of the DSS is that if a specialist has data for a specific year they can use these to check if the response obtained in the DSS coincides with the actual data.

10.4 Concluding remarks

MIKE SHE: One of the criticisms against using an integrated groundwater surface water model such as MIKE SHE is that it is data intensive. This is possibly correct but the model can be run with a minimum of data producing a lower confidence output which is also true for any hydrological model. The reality is that there is a large body of data available in South Africa but it is not always accessible. Some of the lessons learnt and problems identified in this project were related to data availability and accuracy.

DRIFT-Arid DSS: More workshops with the team need to be included during the data input phase of the DSS and an iterative process should be followed. The DSS needs to be streamlined and made more user friendly so that it can be run by other modellers as well.

11 CONCLUSIONS

The research in the current (WRC 1798) and the previous related EWR projects (Rossouw et al., 2005 and Seaman et al., 2010) have contributed considerably to the knowledge on the ecological functioning of non-perennial rivers and the testing of a method to determine the EWR for non-perennial rivers.

The DRIFT-Arid method developed in this project is an adapted version of DRIFT which was developed by Southern Waters for use in perennial rivers and is one of the standard methods used in South Africa to determine the EWR of rivers. A first attempt at using an integrated surface and groundwater hydrology model was included in the project. Hydrology is one of the main drivers of DRIFT-Arid method and the importance of groundwater in non-perennial rivers was emphasised in the previous two WRC projects (Rossouw et al., 2005 and Seaman et al., 2010).

11.1 Ecological functioning of a non-perennial river

The results from the previous EWR project (Seaman et al., 2010) indicated that most of the methods used to determine the PES, developed for use on perennial rivers, were not suitable for use on the ephemeral Seekoei River. The main constraints were difficulty in determining reference conditions, the highly variable flow regime and the generalist nature of the biota that were resilient to change in flow and habitat.

In the current project each specialist investigated the use of current perennial methods to determine the PES for their particular discipline and found that in the Mokolo River, a semi-permanent river which is close to a perennial, most methods were applicable (with some adjustments) but these methods now need to be tested on an episodic river.

11.2 Hydrological modelling

One of the main constraints identified in the previous EWR project (Seaman et al., 2010) was the difficulty in modelling the hydrology of non-perennial rivers (specifically the ephemeral Seekoei River) due to a shortage in gauging weir data and the absence of a suitable hydrological model for integrated surface and groundwater modelling.

DHI were appointed to use MIKE SHE (an integrated surface and groundwater model) to model the hydrology of the Mokolo River in the current project. The use of an integrated surface and groundwater hydrology model for a whole catchment was a first in non-perennial rivers in South Africa although an attempt was made in the Intermediate Reserve (DWA, 2010) to model a section of the Mokolo River using integrated hydrology.

Several problems were identified in applying the MIKE SHE model to the Mokolo River catchment namely:

- It was difficult to calibrate the model to periods of no-flow, likely due to a combination of irrigation issues (lack of accurate data), topographic resolution/accuracy and also because the model cannot distinguish between surface and groundwater flow so cannot pinpoint times of cessation of surface flow. DHI therefore had to post process the data obtained from the MIKE SHE model to produce the zero flows observed in the gauging weir data.
- The calibrated model largely reproduced the long-term, regional-scale flow behaviour observed in the Mokolo catchment. Particularly in the groundwater, the lack of observations and field data meant that the simulated groundwater response was only generally correct. The network of dikes and faults probably compartmentalizes the regional groundwater flow

system, which cannot be simulated in the current model. This may partly explain the difficulty in simulating non-perennial flows, since groundwater base flow is likely a very local process.

- The model generally reproduced the expected direction of changes in flow associated with the scenarios chosen. However, the absolute magnitudes as well as the relative magnitudes of change were less certain given uncertainties in model inputs and the difficulties with non-perennial conditions.

It is however important to remember that the absolute accuracy of models is not the issue, it is if they are able to improve our understanding of the catchment hydrology and the related management decisions that need to be made. Model output is also a result of the quality, quantity and accuracy of data input (Dallas and Rivers-Moore, 2012).

The results from the MIKE SHE model could be used in a non-perennial river and it has the advantage of being a real time model which can be improved as data are collected. An approach that would be possible is to first develop a simple, non-data intensive integrated model (MIKE SHE LIGHT) using easily obtainable data and then to increase complexity if and where needed.

An important output of the MIKE SHE modelling of the Mokolo River catchment was the identification of data gaps and the implications of this for reliable modelling. It also highlighted the type of data that should be prioritised in the data collection process. The sensitivity of the integrated model to vegetation (especially riparian vegetation characteristics), subsurface and soil data emphasises the need for more studies in these disciplines.

In data-scarce rivers it would be easier to model the hydrology than in a data rich system where data are inaccurate, but calibration is difficult if not impossible if gauging data are not available. In systems with sparse data, the modeller could use climate data as a surrogate for gauge data.

A recurring theme in all projects where hydrology is modelled is the lack of accurate data. This needs to be addressed and in South Africa where functioning gauging weirs are scarce alternative methods need to be developed to collect data on flow.

11.3 EWR method used

The original DRIFT method developed by Southern Waters can be used in semi-permanent and ephemeral rivers with some adjustments of which the most important are:

- The catchment delineation method followed in the DRIFT-Arid method is similar to the resource delineation method used in the Intermediate Reserve for the Mokolo River (DWA, 2008b), but extra activities such as the delineation of Runoff Potential Units (RPUs) and the combination of the NRUs and MRUs to delineate homogenous catchment response units have been included.
- The addition of new flow (and hydraulic) indicators added which are relevant for non-perennial systems such as Onset of hydro wet season after a period of wet river bed, etc.
- The creation of weighted (as opposed to un-weighted) lag periods, such that more recent results have a greater influence than those further in the past (now also incorporated in the original DRIFT method); and
- The creation of links within disciplines (now also incorporated in the original DRIFT method).

The choice of indicators by each specialist was streamlined and a more efficient method was developed by the specialists with the help of Dr. Jackie King and Dr. Alison Joubert.

Another adaptation that was considered concerned the possibility of creating a two-state model (or a state and transition model), given that a different set of indicators will be relevant depending on whether the river system is in a flowing state or an isolated pool or dry state. Alternatively, a different

set of response curves might be relevant, where the same indicators are relevant, but the responses to inputs will be different depending on which state prevails. Although this did not appear to be required as DRIFT-Arid was able to accommodate the modelling of both states in an integrated system, it might be interesting for further research.

It is envisaged that DRIFT-Arid and the DRIFT-Arid DSS will evolve from its current state as the underlying conceptual understanding of the functioning of non-perennial systems evolves and is tested on other rivers (specifically episodic rivers).

12 RECOMMENDATIONS

In King and Pienaar (2011) the lack of funding for fundamental research on the ecological functioning of rivers in South Africa is emphasised. The application for water use licences and the pressure placed on the DWA to award these licences has resulted in rapid methods being developed which need to rely on current knowledge in the country. Perennial rivers have been studied intensively but very few studies on the ecological functioning of non-perennial rivers have been completed in South Africa. Very few functioning gauging weirs are present in non-perennial rivers probably due to the fact that water from these rivers has not been used in the past as variability is high and assurance of supply is very low. With the increase in population and demand for food, etc. farmers are now turning to these rivers to supply water for irrigation, livestock, etc. and the DWA are receiving licence applications for abstractions from these rivers. Methods used to determine the Ecological Reserve needed in perennial rivers are not suitable for use on non-perennial rivers as was found in the previous two WRC studies (Rossouw et al., 2005 and Seaman et al., 2010). One of the main reasons for this is a lack of data (ecological and hydrological) and this was also found in the current study.

A recurring theme throughout the current project results has been that data are needed – to improve the hydrological modelling; to improve methods used for the PES determination in each discipline and to improve the selection and hydrological simulation of scenarios, etc.

Fundamental research is needed on non-perennial rivers and developing a method to determine the EWR for these rivers will not be successful until a reasonable amount of basic data are collected on a variety of non-perennial rivers in South Africa. It is often said that we need to move on and use the data that we have but in non-perennial rivers this is not always possible. Studies completed on non-perennial rivers (Lamprecht, 2009; Seaman et al., 2010) has also highlighted the fact that data cannot be extrapolated from one non-perennial river to the next even when they are situated in the same ecoregion and geomorphological zone.

The aim of the current project was to test the Arid-proto method developed on the Seekoei River on another non-perennial river to determine if the method would work on a range of non-perennial rivers or if it needed to be adjusted. The Mokolo River was chosen as a test river and the Arid-proto method was applied. Several adjustments had to be made which resulted in an adjusted DRIFT-Arid method. This method now needs to be tested on other non-perennial rivers specifically an episodic river and additional data needs to be collected to improve the method further.

Some findings and recommendations from the current study will be discussed in this chapter.

12.1 Pool dynamics

Pools act as refugia in non-perennial rivers and the presence of these pools is critical to the functioning of the river. An alternative method to determine the EWR for non-perennial rivers based on pools could be developed. Abstraction from pools needs to be regulated and this can only happen if the dynamics of pools are better understood. Fundamental studies in all disciplines on different types of pools (permanent and temporary) are needed.

Questions that need to be answered relate to the value of pools in non-perennial systems and systems without pools also need to be addressed in terms of value. What kind of objectives or basic management rules need to be defined to protect non-perennial systems? How can non-perennial systems be integrated into catchment management planning?

12.2 Data availability

One of the major setbacks in this project was the availability of data. Although the Mokolo River is a data rich system and data are probably available it was not always possible to find the data and data were not always accurate.

A data base should be housed either at the DWA or the WRC where all raw data from projects are made available to users. Each project funded by taxpayer money should be made available to the public. Data from projects completed by private consultants (funded by taxpayer money) should also be kept at a central store in the DWA or WRC and raw data collected in these projects should be housed on the database. A fee could be included in the projects to cover costs of administration, etc. This would save a large amount of money for both institutions as it often happens that new data needs to be collected for a project because the data already collected (by similar projects or in the same catchment) is not available. It is very difficult and time consuming to try to find data for EWR studies and it is in the interest of all that this data become readily available. Users could be given passwords and databases could be protected by copyright if needed.

12.3 Irrigation and abstraction data

Several versions of irrigation data were obtained from the DWA and irrigation boards in the Mokolo Catchment and the databases did not correspond.

Accurate (georeferenced) data on the source for irrigation (groundwater – springs, alluvial aquifer, surface water – river, farm dams, pools, etc.) as well as accurate abstraction amount is needed to enable accurate hydrological modelling.

12.4 Present ecological state (PES) determination

In each of the disciplines specific constraints and challenges (see section 2.3) have been identified when using the current perennial methods to determine the PES.

Studies are needed in each discipline in non-perennial rivers where the link between habitat and flow availability is determined. For most of the disciplines the variability in habitat and flow available has led to generalist animals and plants that are able to survive the conditions. These generalists are not sensitive to flow and habitat alteration in the same sense that sensitive species are in perennial rivers. Studies need to determine what the critical stage in habitat and flow change is before these generalist species are affected.

12.5 Geomorphology

12.5.1 Data collection

- The geomorphologist needs to describe the present state of the river and also to be able to reconstruct historical change. Once the site location has been finalised, good quality historical aerial imagery of each site needs to be acquired. This imagery is useful to a number of specialists, in particular the geomorphologist and riparian botanist. A decision must be made as to who will acquire this data and how it will be disseminated.
- Time spent in the field is critical to an effective study. Observing the river in flood provided useful insight into channel processes, but it is imperative that sites are visited at low flow condition so that the channel morphology can be observed and sediment samples taken from all relevant morphological units.

- Site plans of the channel morphology and key habitats should be drawn in consultation with all specialists during fieldwork and before other specialists do their sampling.
- Cross-sections must be surveyed at each site to indicate the morphological features and their relationship to instream and riparian habitats. The surveyor and geomorphologist (who can be the same person) must work closely with the ecological specialists to identify key habitats. The number of cross-sections will depend on how they will be used subsequently (to develop response curves or as input to a complex hydraulic model).
- Sediment samples should be taken to represent the different morphological units across the transect(s). In gravel-bed rivers the size distribution is measured in the field, in sand bed rivers samples should be collected and taken back to the laboratory for analysis. In some cases it may be necessary to take additional samples at points away from the transect to typify sediment that is readily transported through the channel.
- A GAI field form should be completed.

12.5.2 Indicators

Too many geomorphological indices were used, but all were not taken up by the ecologists. They were selected as having ecological significance, but in many cases it was difficult to develop a sensible flow related response curve. Fewer indicators, for which established empirical relationships with flow have been developed, should be chosen. It would be necessary for the ecological specialists to draw their own inferences as to how these changes would impact on habitat for their suite of species.

Recommended indicators are as follows:

- Channel complexity is a measure of habitat diversity. Thoms (2006) has developed a relationship between channel complexity and hydrological indices of flow variability or predictability.
- Channel capacity is a measure of channel size that is a direct function of channel forming discharge. It is calculated as the product of width x depth. Expansion or contraction of the channel will affect the extent of available habitat either instream or riparian.
- The width-depth ratio is a measure of channel shape. It depends on bed mobility and bank strength. In the marginal zone vegetation has a significant impact on the width-depth ratio. Channels become narrower and deeper as the stabilizing effect of vegetation increases. Changes to the width-depth ratio will have a direct impact on at-a-station hydraulic geometry.
- A change in the channel type (cobble, gravel, sand) represents a state change with significant ramifications for habitat. Not only will the channel bed be different, but the width-depth ratio and channel complexity are also likely to change. Changes in channel type are related more to sediment processes than flow. Armouring below a dam due to sediment trapping is one example. A shift towards a sand bed river due to extensive catchment erosion would be another.

12.5.3 General procedure

Time must be given for effective interaction between specialists. Reducing the number of indicators is one way to find this extra time. Recommendations for interaction procedures are as follows.

In the field

Specialists must work together as far as is possible. Time should be set aside in the evenings for feedback.

In the workshop

Sufficient time should be allowed at the start of the workshop for specialist feedback on indicators. Each specialist should provide a clear description of their indicators followed by discussion with other specialists as to possible inter component relationships and feedback

loops. The outcome of this session should be a conceptual model of links and feedback loops that is constructed by all specialists.

Between workshops

Sustaining contact between specialists between workshops is difficult. Circulating and reading specialist reports is time consuming and may not be catered for in the budget. One possibility would be to have a website where all reports are accessible and for the project manager to direct specialists to certain reports that are most relevant to them. A blog site is an effective way of encouraging feedback.

12.6 Riparian vegetation

Data on vegetation in South Africa is readily available but very little data is available specifically for the riparian zone across the range of non-perennial rivers. These riparian zones are also of utmost importance as they act as longitudinal refugia for biota in periods of no-flow and drought. Riparian vegetation is often the only ecological indicator left that can be used to determine the present state of non-perennial rivers, where there is extended no flow periods and neither fish and nor macro-invertebrates can be used as response indicators.

The application of more remotely sensed data is limited due to the low resolution of e.g. SPOT data. **LAI** data also needs to be included as a source of information on potential transpiration rates. The use of LAI data seems promising after discussions with DHI. **Root depths and densities** for specific riparian species do not currently exist and root depth and density plays an extremely important role in modelling the response of riparian species to a change in groundwater levels. Several individual projects that could provide data and a better understanding on the applicability of LAI, root depth and densities, as well as the **critical wilting point** for different riparian vegetation species will be very valuable in our understanding of the functioning of non-perennial systems. More information on the most appropriate **key indicator species** in the different riparian zones also needs to be researched.

12.7 Macro-invertebrates

Alternative methods for sampling and interpreting bioassessment data need to be developed for non-perennial rivers. Of key importance is the factoring of hydrological phase into the interpretation of data and the generation of interpretative guidelines specifically for non-perennial rivers. These guidelines should take into account the higher proportion of generalist taxa that have low to moderate sensitivity weightings.

Given the substantial differences observed within non-perennial river sites, which range from pool-phase only to pool- plus flow-phases, consideration needs to be given to developing a method that takes these differences into account. The potential for developing a method based solely on pools, which are the most common and widespread habitat type in these arid and semi-arid regions, should be investigated. Pools may function as refuges for lentic invertebrate taxa, and serve as a source for colonisation once inundation begins. Pools differ in their degree of permanence, groundwater contribution, available substrate and biotopes. Classification of pools in a manner that takes into account such factors will facilitate the development of a typology for pools. Sampling of a range of pools of different types, such that spatial and temporal trends are identified and quantified, would enable the developing of a reference assemblage, as well as related interpretative guidelines (Watson and Dallas, 2013).

12.8 Fish

The existing Fish Response Assemblage Index (Kleynhans, 2007) was successfully applied to determine the PES of the Mokolo River fish community. The suitability of this index in ephemeral rivers might need further consideration and a validation process might be needed. Alternatively, an alternative approach for assessing the PES of ephemeral rivers with species-poor, generalist-dominated fish communities might be investigated.

Continued research on the fish communities of ephemeral rivers is crucial for the further development of methodologies to determine the environmental water requirements of non-perennial rivers. The pressure to develop non-perennial water resources is expected to increase in future and a greater understanding of the effects of high flow variability on fish communities, and other aquatic communities, would greatly enhance confidence in the results produced by DRIFT-Arid.

12.9 Indicators that need to be included in all levels of EWRs

Event hydrology, groundwater-surface water interactions, sediment transport processes and vegetation, drive channel dynamics in non-perennial systems. Hydrology, geomorphology and vegetation therefore should form the basis of a EWR at any level. There may not be fish in an episodic system, and macro-invertebrates may not be observed during no-flow conditions, but there will always be channel morphology that is the integrated response to past flows, and deep rooted vegetation will be sustained through dry periods (Rowntree and van der Waal, 2012).

12.10 Digitising of river network

A review of the river network compared to the 21 m DEM and aerial imagery obtained from the DWA (and ESRI world file imagery) indicated problems with the original river shape file for the Mokolo River. The trace and resolution of rivers was not very accurate (please see page 2-28 in Prucha and Graham, 2012). As a result of the first problem, stream profiles, critical to modelling surface flow successfully, could not be accurately estimated from the 21 m DEM (original streambeds cut across hillsides) without re-tracing most of the network.

The DWA or the WRC should engage in a project to improve the digitisation of South African rivers.

12.11 The way forward

The DRIFT-Arid method now needs to be tested on various non-perennial rivers especially episodic rivers where data are scarce. An alternative method to determine the management rules for these rivers, possibly using pools, also needs to be investigated.

Due to the data (hydrological and ecological) shortage and inaccurate data available in non-perennial rivers we need a rapid method to follow until more reliable data are available. A fast approach to determine the EWRs in non-perennial rivers needs to be developed. It would be advisable to proceed with a MIKE SHE (or other hydrological integrated model) LITE where less data are needed. Intensive research to understand non-perennial rivers should be done in parallel with the development of the model. Scientists/researchers are learning to meet the requirements of a hydrological model but perhaps the modellers should also be prepared to fit their models to the data available. Any hydrological model needs to include soil data and the models need to accommodate SA conditions (hanging wetlands (above the river as well as above the groundwater level), slope and seepage). The model should also include the vadose layer and this could possibly be included in at local scale. The vadose layer makes a huge contribution to riverflow, etc. Hydrological models need to focus more on groundwater in the riparian zone and need to identify dominant hillslopes within a landtype and to determine how this contributes to riverflow.

It is important that future projects need to focus on testing the DRIFT-Arid method on other non-perennial rivers and not focus on developing and testing surface and groundwater interaction modelling as such. The integrated hydrological modelling should be a separate project, which keeps the current team, or future teams, involved in the development of an EWR method for non-perennial rivers informed.

Another option in place of the comprehensive/intermediate DRIFT-Arid method is a rapid DRIFT-Arid LITE where a countrywide assessment is done to identify non-perennial rivers and how they are adapting to development. It would probably be necessary to study rivers in different ecoregions, etc. This can be used to look at the impact of scenarios on similar rivers. We could possibly then develop very coarse rules on how non-perennial rivers react to development and this could then help predict how a river would react to a specific type and scale of development.

Several projects to collect data for the individual disciplines are needed such as projects to determine the LAI and wilting point of natural riparian vegetation. Pool dynamics needs to be researched. Hydrocensus and geological logs are needed together with accurate abstraction rates for rivers where EWRs are to be determined.

13 REFERENCES

- African Development Bank. 2009. Executive summary of South Africa: Environmental Impact Assessment for the Medupi Power Plant Project of Eskom. Report by the African Development Bank for the Department of Environmental Affairs. Pretoria.
- Allanson BR, Hart RC, O'Keeffe JH and Robarts RD. 1990. *Inland waters of southern Africa: an ecological perspective*. Kluwer Academic Publishers, London.
- Angliss MK. 2002. A Biomonitoring survey of the Mogol (Mokolo) River Catchment (Limpopo). Report for Limpopo Department of Environmental Affairs. Limpopo.
- ASTM. 2002. D 5979-96. American Society for Testing and Materials, Standard Guide for Conceptualization and Characterization of Ground-Water Systems. American Society for Testing and Materials (ASTM) International.
- Avenant MF. 2010. Challenges in using fish communities for assessing the ecological integrity of non-perennial rivers. *Water SA* 36(4): 397-405.
- Barker CH. 2010. Catchment Geomorphology. Runoff Potential Unit Determination. Report for Centre for Environmental Management as part of WRC Project K5/1798. Water Research Commission. Pretoria.
- Bowmaker AP, Jackson PBN and Jubb RA. 1978. Freshwater fishes. In: Werger MJA and Van Bruggen AC (Eds.). *Biogeography and ecology of southern Africa*. Junk, The Hague. Pp. 1181-1230.
- Bramblett RG and Fausch KD. 1991. Fishes, macro-invertebrates, and aquatic habitats of the Purgatoire River in Piñon Canyon, Colorado. *The Southwestern Naturalist* 36(3): 281-294.
- Brandl G. 1996. The geology of the Ellisras area. Council for Geoscience. 1:250 000 Geological Series, Explanation, (2326). ISBN 1-875061-17-7, Department of Mineral and Energy Affairs. South Africa.
- Brown C, Pemberton C, Birkhead A, Bok A, Boucher C, Dollar E, Harding W, Kamish W, King J, Paxton B and Ractliffe S. 2006. In support of water resource planning – highlighted key management issues using DRIFT: A case study. *Water SA* 32(2): 181-192.
- Brown CA and Louw D. 2011. Tools and procedures for Resource Directed Measures. In: King JM and Pienaar H. 2011. *Sustainable use of South Africa's inland waters*. WRC Report No. TT 491/11. Water Research Commission. Pretoria.
- Brown CA, Joubert AR, Pemberton CW, Greyling AJ and King JM. 2008. DRIFT user manual. Volume 2: Biophysical Module for predicting overall river condition in small to medium sized rivers with relatively predictable flow regimes (incorporating updates to the DRIFT database). Water Research Commission. Pretoria.
- Brown CA, Joubert, AR, Pemberton, CW, Greyling, AJ, and King, JM. 2008. DRIFT USER MANUAL V2.0: Biophysical Module for predicting overall river condition in small to medium sized rivers with relatively predictable flow regimes. (Incorporating updates). Southern Waters. South Africa.
- Brown, CA, Joubert, AR, Beuster J, Greyling A and King JM. 2013. DRIFT: DSS software development for integrated flow assessments: Final report and user manual. Southern Waters. South Africa.
- Bull LJ and Kirkby MJ. 2002. "Dryland River Characteristics and Concepts". In Bull LJ and Kirkby MJ. (eds.) 2002. *Dryland Rivers Hydrology and Geomorphology of Semi-Arid Channels*. Wiley and Sons Ltd., Chichester.
- Busari O. 2008. Groundwater in the Limpopo Basin: occurrence, use and impact. *Environment, Development and Sustainability* 10: 943-957
- Chow VT. 1959. *Open channel hydraulics*. New York: McGraw-Hill.
- Chutter FM. 1967. Hydrobiological studies of the Vaal River. National Institute for Water Research. CSIR Special Report Water 38. CSIR. Pretoria.

- Chutter FM. 1994. The rapid biological assessment of stream and water quality by means of the macro-invertebrate community in South Africa. In: Uys MC. (Ed.). 1994. Classification of rivers and environmental health indicators. Proceedings of a joint South African/Australian Workshop. February 7-14 1994, Cape Town, South Africa. WRC Report No: TT 63/94. Water Research Commission, Pretoria.
- Dallas H and Rivers-Moore N. 2012. Water temperatures and the ecological reserve. WRC Report No. 1799/1/12. Water Research Commission. Pretoria.
- Dallas HF. 1995. An evaluation of SASS4 (South African Scoring System) as a tool for the rapid bioassessment of water quality. MSc thesis. University of Cape Town. Cape Town.
- Dallas HF. 2007. River Health Programme. South African Scoring System (SASS) data interpretation guidelines. Prepared for the Institute of Natural Resources and Department of Water Affairs and Forestry. Pretoria.
- Dallas HF. 2009. Wetland monitoring using aquatic macro-invertebrates. Technical Report 5/2009. Prepared for the Biokavango Project, Harry Oppenheimer Okavango Research Centre. University of Botswana. The Freshwater Consulting Group. University of Cape Town. Cape Town. South Africa.
- DHI (Danish Hydraulic Institute) 2012. GIS and water resource modelling at DHI. Online: <http://www.cwr.utexas.edu/gis/gishyd98/dhi/mikeshe/Mshebody.htm>
- Davies BR, Thoms MC, Walker KF and O'Keeffe JH. 1994. Dryland rivers: their ecology, conservation and management. In: Calow P and Petts GE (eds.). *The Rivers Handbook* (volume 2). Blackwell Scientific. Oxford.
- Demarcation Board. 2006. Municipal Profiles. Online: <http://www.demarcation.org.za>
- Dennis I. 2010. Groundwater Assessment of the Mokolo River catchment. A report to the Centre for Environmental Management for the WRC project no K5/1798. University of the Free State. Bloemfontein.
- Dickens CWS and Graham PM. 2002. The South African Scoring System (SASS) Version 5. Rapid Bioassessment Method for Rivers. *African Journal of Aquatic Science* 27: 1-10.
- Digout D. 2002. Map of aridity zones in Africa based on information provided by the World Meteorological Organization (WMO), UNEP and Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC). Online: <http://www.aridareas.co.za/characteristics.html>
- DOH (Department of Health). 2008. Statistical notes. Department of Health. Pretoria.
- Dollar ESJ, Brown CA, Turpie JK, Joubert AR, Nicolson CR and Manyaka SM. 2007. The development of the Water Resource Classification System (WRCS). Volume 1. Overview and 7-step classification procedure. CSIR Report No. CSIR/NRE/WR/ER/2006/0187A/C. Department of Water Affairs and Forestry. Pretoria.
- Du Preez L. and Rowntree KM. 2006. Assessment of the geomorphological Reference Condition: an application for Resource Directed Measures and the River Health Programme. WRC Report no. 1306/1/06. Water Research Commission. Pretoria.
- DWA (Department of Water Affairs). 2008. Intermediate Reserve Determination Study for Selected Water Resources (Rivers, Groundwater and Wetlands) in the Limpopo Water Management Area, Mpumalanga. Mokolo River System: EcoClassification Report – Volume 1: Prepared by Water for Africa and Clean Stream Biological Services. Louw, MD and Koekemoer S (eds.). Report No. 26/8/3/10/14/008. Department of Water Affairs. Pretoria.
- DWA. 2008a. Intermediate Reserve Determination Study for the Surface and Groundwater Resources in the Mokolo Catchment, Limpopo Province: EcoClassification Report – Volume 2. Prepared by Water for Africa and Clean Stream Biological Services. Louw, MD and Koekemoer S (eds.). RDM Report no. 26/8/3/10/14/008. Department of Water Affairs. Pretoria.

- DWA. 2008b. Intermediate Reserve Determination Study for Selected Water Resources (Rivers, Groundwater and Wetlands) in the Limpopo Water Management Area, Mpumalanga. Mokolo River System: Resource Unit Delineation: Prepared by Clean Stream Biological Services and Water for Africa. Kotze PJ and Louw MD (eds.). Report no. 26/8/3/10/14/006. Department of Water Affairs. Pretoria.
- DWA. 2010. Intermediate Reserve Determination Study for the Surface and Groundwater Resources in the Mokolo Catchment, Limpopo Province: Ground Water – Surface Water Interaction Report. Authored by Rivers for Africa eFlows consulting. Report No: 26/8/3/10/12/013. Department of Water Affairs. Pretoria.
- DWA. 2010a. Rivers Database. Online: <http://www.riv.co.za/Rivers/Application/Login.aspx?ReturnUrl=%2fRivers%2fApplication%2fDefault.aspx>
- DWAF (Department of Water Affairs and Forestry). 1992. Yield Analysis of the Hans Strydom Dam. Report No. A400/00/0192. Department of Water Affairs. Pretoria.
- DWAF. 2007. The Mokolo River Catchment – Validation of existing Lawful Water Use: Study Report. Department of Water Affairs and Forestry. Pretoria.
- DWAF. 2001. Limpopo WMA Water Resources Situation Assessment Report. Report No. PWMA01/000/00/0301. Department of Water Affairs. Pretoria.
- DWAF. 2004. Internal Strategic Perspective: Limpopo Water Management Area: Prepared by Goba Moahloli Keeve Steyn (Pty) Ltd. in association with Tlou & Matji (Pty) Ltd and Golder Associates (Pty) Ltd. On behalf of the Directorate: National Water Resource Planning. Report No. P WMA 01/000/00/0304. Department of Water Affairs and Forestry, Pretoria.
- Gaigher IG, Hamman KCD and Thorne SC. 1980. The distribution, conservation status and factors affecting the survival of indigenous freshwater fishes in the Cape Province. *Koedoe* 23:57-88.
- Gaigher IG. 1969. Aspekte m.b.t. die ekologie, geografie en taksonomie van varswatervisse in die Limpopo- en Incomatirivier sisteem. Unpublished Ph.D. dissertation, Randse Afrikaanse University, Johannesburg.
- GoogleEarth. 2010. Maps. Online: www.maps.google.co.za
- Graham DN. and Butts MB. 2005. Flexible Integrated Watershed Modelling with MIKE SHE. In: Singh VP and Frevert DK. (eds.). 2005. *Watershed Models*. CRC Press.
- Hamilton SK, Bunn SE, Thoms MC and Marshall JC. 2005. Persistence of aquatic refugia between flow pulses in a dryland river system (Cooper Creek, Australia). *Limnology and Oceanography* 50(3): 743-754.
- Harrison AD and Elsworth JF. 1958. Hydrobiological studies of the Great Berg River; Part 1. General description of chemical studies and main features of the flora and fauna. *Transactions of the Royal Society of southern Africa* 35(3):125-226.
- Hughes DA and Hannart P. 2003. A desktop model used to provide initial estimate of the ecological instream flow requirements of rivers in South Africa. *Journal of Hydrology* 270: 167-181.
- Hughes DA. 2008. Hydrological information requirements and methods to support the determination of environmental water requirements in ephemeral river systems. WRC Report No. KV 205/08. Water Research Commission. Pretoria.
- Kaiser-Hill K-H. 2002. Site-Wide Water Balance Model Report for the Rocky Flats Environmental Technology Site. Golden Colorado.
- Kemp M. 2012. Vegetation specialist report. Specialist Report for Project WRC K5/1798. Water Research Commission. Pretoria.
- King JM and Pienaar H. 2011. Sustainable use of South Africa's inland waters. A situation assessment of Resource Directed Measures 12 years after the 1998 National Water Act. WRC Report no. TT 491/11. Water Research Commission. Pretoria.
- King JM, Brown CA, Paxton BR and February RJ. 2004. Development of DRIFT, A scenario-based methodology for Environmental Flow Assessments. WRC Report no. 1159/1/04. Water Research Commission. Pretoria.

- Kingsford RT and Thompson JR. 2006. Desert or dryland rivers of the world: an introduction. In: Kingsford R (ed.). *Ecology of desert rivers*. Cambridge University Press. Cambridge.
- Kingsford RT, Georges A and Unmack PJ. 2006. Vertebrates of desert rivers: meeting the challenges of temporal and spatial unpredictability. In: Kingsford R (ed.). *Ecology of desert rivers*. Cambridge University Press. Cambridge.
- Kleynhans CJ and Louw, MD. 2007. Module A: EcoClassification and EcoStatus determination in River EcoClassification: Manual for EcoStatus Determination (version 2). Joint Water Research Commission and Department of Water Affairs and Forestry Report. WRC Report No. TT329/08. Water Research Commission. Pretoria.
- Kleynhans CJ and Louw MD. 2007a. River reach demarcation, delineation and site suitability. Appendix A in: Department of Water Affairs and Forestry (DWAF), South Africa. 2007. Comprehensive Reserve Determination Study for Selected Water Resources (Rivers, Groundwater and Wetlands) in the Inkomati Water Management Area, Mpumalanga. Sabie and Crocodile Systems: Resource Unit Delineation. Report no. 26/8/3/10/12/006. Department of Water Affairs and Forestry, Pretoria.
- Kleynhans CJ, Louw MD and Graham M. 2008. Module G: EcoClassification and EcoStatus determination in River EcoClassification: Index of Habitat Integrity (Section 1, Technical manual). Joint Water Research Commission and Department of Water Affairs and Forestry report. WRC Report No. TT 377-08. Water Research Commission. Pretoria.
- Kleynhans CJ, Louw MD and Moolman J. 2008a. Module D (Volume 2): Reference Frequency of Occurrence of Fish Species in South Africa: Manual for EcoStatus Determination (Version 2). Joint Water Research Commission and Department of Water Affairs and Forestry Report. WRC Report No. TT331/08. Water Research Commission. Pretoria.
- Kleynhans CJ, McKenzie J and Louw MD. 2007a. Module F: Riparian Vegetation Response Assessment Index (VEGRAI) in River EcoClassification: Manual for EcoStatus Determination (Version 2). Joint Water Research Commission and Department of Water Affairs and Forestry Report. WRC Report No. TT333/08. Water Research Commission. Pretoria.
- Kleynhans CJ, Thirion C, Moolman J and Gaulana L. 2007b. A Level II River Ecoregion classification System for South Africa, Lesotho and Swaziland. Report No. N/000/00/REQ0XXX. Resource Quality Services. Department of Water Affairs and Forestry. Pretoria. South Africa.
- Kleynhans CJ, Thirion C and Moolman J. 2004. A Level 1 and II River Ecoregion classification System for South Africa, Lesotho and Swaziland. Draft Report No. N/0000/00/REQ0104. Resource Quality Services. Department of Water Affairs and Forestry. Pretoria. South Africa.
- Kleynhans CJ. 1984. Die verspreiding en status van sekere seldsame vissoorte van die Transvaal en die ekologie van sommige spesies. Unpublished D.Sc. dissertation. University of Pretoria. Pretoria.
- Kleynhans CJ. 1996. A qualitative procedure for the assessment of the habitat integrity status of the Luvuvhu River (Limpopo system, South Africa). *Journal of Aquatic Ecosystem Health* 5: 41-54.
- Kleynhans CJ. 1999a. The development of a fish index to assess the biological integrity of South African Rivers. *Water SA* 25(3): 265-278.
- Kleynhans CJ. 1999b. R7: Assessment of Ecological Importance and Sensitivity. In: Resource Directed Measures for protection of Water resources: River Ecosystems. Department of Water Affairs and Forestry. Pretoria.
- Kleynhans CJ. 2003. National Aquatic Ecosystem Biomonitoring Programme: Report on a National Workshop on the use of Fish in Aquatic System Health Assessment. NAEBP Report Series No.16. Institute for Water Quality Studies. Department of Water Affairs and Forestry. Pretoria. South Africa.

- Kleynhans CJ. 2007. Module D (Volume 1): Fish Response Assessment Index in River EcoClassification: Manual for EcoStatus Determination (Version 2). Joint Water Research Commission and Department of Water Affairs and Forestry Report. WRC Report No. TT330/08. Water Research Commission. Pretoria. South Africa.
- Kolm KE. 1993. Conceptualization and Characterization of Hydrologic Systems: International Ground-Water Modelling Center Technical Report 93-01. Colorado School of Mines. Golden Colorado.
- Kotze P. 2008. Fish specialist report. In: DWA. 2008a. Intermediate Reserve Determination Study for the Surface and Groundwater Resources in the Mokolo Catchment, Limpopo Province: EcoClassification Report – Volume 2. Prepared by Water for Africa and Clean Stream Biological Services. Louw, MD and Koekemoer S (eds.). RDM Report no. 26/8/3/10/14/008. Department of Water Affairs. Pretoria.
- Lamprecht E. 2009. Data extrapolation from macro-invertebrate communities in the Upper Orange River catchment area, South Africa. Is it viable? Unpublished Thesis, Masters in Environmental Management. University of the Free State. South Africa.
- Larned ST, Datry T, Arscott DB and Tockner K. 2010. Emerging concepts in temporary-river ecology. *Freshwater Biology* 55: 717-738.
- Leigh C and Sheldon F. 2008. Hydrological changes and ecological impacts associated with water resource development in large floodplain rivers in the Australian tropics. *River Research and Applications* 24(9): 1251-1270.
- Louw MD, Kleynhans CJ and Thirion C. 2005. Chapter 1: EcoClassification. In: EcoStatus Manual. WRC Report No. KV 168/05. Water Research Commission. Pretoria.
- LTSS (Land Type Survey Staff). 1989. Memoirs of the Agricultural Natural Resources of South Africa. Department of Agriculture and Water Supply. Pretoria.
- MacKay H. 2001. Groundwater and ecosystems. Online: http://www.africanwater.org/ag_eco_groundw.htm.
- Midgley DC, Pitman WV and Middleton BJ. 1994. Surface Water Resources of South Africa 1990 – Volume 1. Appendices and Book of Maps. WRC Report No. 298/1.1/04. Water Research Commission. Pretoria.
- Mucina L, and Rutherford, MC. (eds.) 2006. *The vegetation of South Africa, Lesotho and Swaziland*. Strelitzia 19. South African National Biodiversity Institute, Pretoria
- Mucina L, Rutherford MC and Powrie LW. (eds.). 2005. Vegetation Map of South Africa, Lesotho and Swaziland. 1: 1 000 000 Scale sheet maps. South African National Biodiversity Institute. Pretoria. ISBN 1-919976-22-1.
- NASA LP DAAC (NASA Land Processes Distributed Active Archive Center). 2001. Leaf Area Index – Fraction of Photosynthetically Active Radiation 8-Day L4 Global 1km. ASTER L1B. USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota. Online: https://lpdaac.usgs.gov/products/modis_products_table/mcd15a2
- Neuman SP and Wierenga PJ. 2003. A Comprehensive Strategy of Hydrogeologic Modelling and Uncertainty Analysis for Nuclear Facilities and Sites. NUREG/CR-6805. U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research Washington. DC 20555-0001. Washington.
- OKAKOM. 2011. The Permanent Okavango River Basin Water Commission. *Cubango-Okavango River Basin Transboundary Diagnostic Analysis*. Maun. Botswana.
- O'Keeffe JH, Hughes DA and Tharme RE. 2002. Linking ecological responses to altered flows, for use in environmental flow assessments: The Flow Stressor-Response method. *International Association of Theoretical and Applied Limnology* 28:84-92.
- Ollif WD. 1960. Hydrobiological studies of the Tugela River system. *Hydrobiologia* 14:281-392.
- Partridge TC, Dollar ESJ, Moolman J and Dollar LH. 2010. The geomorphic provinces of South Africa, Lesotho and Swaziland: A physiographic subdivision for earth and environmental scientists. *Transactions of the Royal Society of South Africa* 65 (1): 1-47.

- PRB (Population Reference Bureau). 2007. World Population Data Sheet 2007. Washington: Population References Bureau.
- Prucha RH and Graham D. 2012. Integrated hydrologic flow model of the Mokolo River Basin, South Africa. Specialist report for Centre for Environmental Management. University of the Free State. For WRC Project K5/1798. Water Research Commission. Pretoria.
- Prucha RH. 2002. A Conceptual and Modelling Framework for Investigating Recharge in Arid/Semi-Arid Environments. Ph.D. Dissertation. Department of Civil Engineering. University of Colorado, Boulder. Colorado.
- Refsgaard JC, van der Sluijs Højberg AL and Vanrolleghem PA. 2007. Uncertainty in the environmental modelling process – A framework and guidance. *Environmental Modelling & Software* 22:1543-1556.
- RHP (River Health Programme). 2006. State-of-Rivers Report. The Mokolo River System. Department of Environmental Affairs and Tourism. Pretoria.
- Rosgen D. 1996. *Applied River Morphology*. Wildland Hydrology Books. Pagosa Springs. CO.
- Rossouw L. and Vos AT. 2010. Water Quality Component of testing a prototype Environmental Water Requirement methodology on the Mokolo River. Specialist report as part of the WRC project K5/1798. Water Research Commission. Pretoria. .
- Rossouw L and Vos AT. 2008. Water Quality Specialist Report. In: Seaman MT, Avenant MF, Watson M, King J, Armour J, Barker CH, Dollar E, du Preez PJ, Hughes D, Rossouw L and van Tonder G. 2010. Developing a method for determining the environmental water requirements for non-perennial Systems. WRC Report No. TT 459/10. Water Research Commission. Pretoria.
- Rossouw L, Avenant MF, Seaman MT, King JM, Barker CH, du Preez PJ, Pelser AJ, Roos JC, van Staden JJ, van Tonder GJ and Watson M. 2005. Environmental water requirements in non-perennial systems. WRC Report No. 1414/1/05. Water Research Commission. Pretoria.
- Rowntree KM and van der Waal B. 2012. Fluvial geomorphology specialist report. Specialist Report for Project WRC K5/1798. Water Research Commission. Pretoria.
- Rowntree KM and du Preez L. 2008. Integrative River Science. In: Brierley G and Fryers K. (eds.). 2008. *River Futures: An Integrative Scientific Approach to River Repair*. Island Press.
- Rowntree KM and Wadeson RA. 1998. A geomorphological framework for the assessment of instream flow requirements. *Aquatic Ecosystem Health and Management* 1: 125-141.
- Rowntree KM and Wadeson RA. 1999. A Hierarchical Geomorphological Model for the Classification of Selected South African Rivers. WRC Report No 497/1/99. Water Research Commission. Pretoria.
- Rowntree KM, Wadeson, RA and McGregor GK. 1996. Geomorphology. In: Brown C, Eekhout S and King JM (eds.). 1996. National Biomonitoring programme for Riverine Ecosystems: Proceedings of spatial framework workshop. NPB Report Series No. 2. Institute for Water Quality Studies. Department of Water Affairs and Forestry. Pretoria. South Africa.
- Rowntree KM, Wadeson RA and O’Keeffe J. 2000. The development of a geomorphological classification system for the longitudinal zonation of South African Rivers. *South African Geomorphology Journal* 82(3): 163-172.
- RSA (Republic of South Africa). 1970. Report on the Mogol River Government Water Work (Wildebeesfontein Dam). WP N – 70. Department of Water Affairs. Pretoria.
- SAIRR (South African Institute of Race Relations). 2009. South Africa Survey 2008/2009. Institute of race relations. Pretoria.
- Schulze R and Maharaj M. 2007. 50 years of daily hydroclimatic data per quaternary catchment in South Africa. University of KwaZulu-Natal. School of Bioresources Engineering and Environmental Hydrology. On CD-ROM.
- Schulze RE and Horan MJC. 2007. Soils: Hydrological Attributes. In: Schulze RE (ed.). 2007. South African Atlas of Climatology and Agrohydrology. WRC Report No. 1489/1/06. Water Research Commission. Pretoria.

- Seago CJ, de Jager FGB and McKenzie RS. 2005. Rainfall data analysis. Draft report compiled by WRP Consulting Engineering (Pty) Ltd, DMM Development Consultants CC and Golder Associates Africa (Pty) Ltd, in association, as part of the Updating the Hydrology and Yield Analysis in the Mokolo River catchment study for the Department of Water Affairs and Forestry. Directorate National Water Resource Planning. Pretoria.
- Seaman MT, Avenant MF, Watson M, King J, Armour J, Barker CH, Dollar E, du Preez PJ, Hughes D, Rossouw L and van Tonder G. 2010. Developing a method for determining the environmental water requirements for non-perennial systems. WRC Report No. TT 459/10. Water Research Commission. Pretoria.
- Skelton PH. 2001. *Freshwater fishes of southern Africa*. Struik Publishers. Cape Town
- South Africa Municipalities. 2010. City Population. Online: <http://www.citypopulation.de/SouthAfrica.html>
- Stejn E. 2008. Investigation into the reliability of the discharge records of selected gauging stations in a few non-perennial rivers in RSA. Report by Department of Water Affairs and Forestry, Northern Cape Province for Centre for Environmental Management as part of a WRC project K5/1798. Water Research Commission. Pretoria.
- Taylor JC, Harding WR and Archibald GM. 2005. A Methods Manual for the Collecting, Preparation and Analysis of Diatom Samples. Version 1.0 July 2005. Water Research Commission, Pretoria.
- Thirion C. 2008. Module E: Macro-invertebrate Response Assessment Index in River Ecoclassification: Manual for Ecstatus Determination (version 2). Joint Water Research Commission and Department of Water Affairs and Forestry Report. WRC No TT 332/08. Water Research Commission. Pretoria.
- Thirion C and Uys M. 2008. Macro-invertebrate data for the Intermediate Reserve Determination Study for Selected Water Resources (Rivers, Groundwater and Wetlands) in the Limpopo Water Management Area, Mpumalanga. Mokolo River System: EcoClassification Report: Specialist Appendices. Department of Water Affairs. Pretoria.
- Thoms MC and Sheldon F. 2002. An ecosystem approach for determining environmental water allocations in Australian dryland river systems: the role of geomorphology. *Geomorphology* 47: 153-168.
- Thoms MC. 2006. Variability in riverine ecosystems. *River Research and Application* 22: 115-121.
- Unmack PJ. 2001. Fish persistence and fluvial geomorphology in central Australia. *Journal of Arid Environments* 49: 653-669.
- Uys MC and O'Keeffe JH. 1997. Simple words and fuzzy zones: early directions for temporary river research in South Africa. *Environmental Management* 21(4): 517-531.
- Uys MC. 1997. The ecology of temporary streams in the Eastern Cape. Unpublished MSc. Thesis. Rhodes University. Grahamstown.
- Van der Waal B. and Rowntree K. 2010. Macroreach analysis of the Mokolo River. Specialist document prepared for the Centre for Environmental Management as part of WRC project K5/1798. Geography Department. Rhodes University. South Africa.
- Van Tol J and le Roux P. 2012. Hydropedological data for the Mokolo River catchment. Specialist report to Centre for Environmental Management for WRC project K5/1798. Water Research Commission. Pretoria.
- Vermeulen PD, Bester M, Cruywagen L-M and van Tonder GJ. 2009. Scoping level assessment of how water quality and quantity will be affected by mining method and mining of the shallow Waterberg coal reserves west of the Daarby fault. Report to the Water Research Commission. Pretoria.
- Wadley R. 2009. Geology, mining and risk explained. Online: http://www.chroniclesa.co.za/index.php?option=com_content&view=article&id=377:geology-mining-and-risk-explained&catid=35:conservancy-news&Itemid=74

Watson M and Dallas HF. (2013). Bioassessment in ephemeral rivers: constraints and challenges in applying macro-invertebrate sampling protocols. *African Journal of Aquatic Science* 38(1): 35-51

14 APPENDICES (ALL)

Appendix A: Ecoregion attributes (taken from Kleynhans et al., 2004)

Main Attributes		Limpopo Plain 1.02
Terrain Morphology: Broad division		Plains; low relief; Plains; moderate relief; Lowlands, Hills and Mountains; moderate and high relief; Closed Hills, Mountains; moderate and high relief.
Terrain Morphology		Plains; Slightly undulating plains; Slight irregular plains; extremely irregular plains (almost hilly) (limited); Moderately undulating plains; Lowlands with parallel hills; Lowlands with mountains; High mountains
Vegetation types (dominant types in bold) (Primary)		Sweet Bushveld
Altitude (m a.m.s.l.)		500 to 1300
MAP (mm)		300 to 500
Coefficient of variation (% of annual precipitation)		25 to 39
Rainfall concentration index		60 to >65
Rainfall seasonality		Early to mid summer
Mean annual temp (°C)		18 to 22
Mean daily max temp (°C) February		24 to 32
Mean daily max temp (°C) July		18 to 24
Mean daily min temp (°C) February		16 to 19
Mean daily min temp (°C) July		2 to 7
Median annual simulated runoff (mm) for quaternary catchment		<5 to 40; (40 to 60; 80 to 100 limited)
Main Attributes		Limpopo Plain 1.03
Terrain Morphology: Broad division		Plains; low relief; Plains; moderate relief; Lowlands, Hills and Mountains; moderate and high relief (limited)
Terrain Morphology		Plains; Slightly undulating plains; Slight irregular plains Lowlands with parallel hills
Vegetation types (dominant types in bold) (Primary)		Mixed Bushveld; Waterberg Moist Mountain Bushveld; Kalahari Plains Thorn Bushveld
Altitude (m a.m.s.l.)		700 to 1300
MAP (mm)		300 to 600
Coefficient of variation (% of annual precipitation)		25 to 34
Rainfall concentration index		60 to >65
Rainfall seasonality		Early to mid summer
Mean annual temp (°C)		18 to 22
Mean daily max temp (°C) February		28 to 32
Mean daily max temp (°C) July		18 to 24
Mean daily min temp (°C) February		16 to 19
Mean daily min temp (°C) July		2 to 5
Median annual simulated runoff (mm) for quaternary catchment		<5 to 60
Main Attributes		Waterberg 6.01
Terrain Morphology: Broad division		Table-lands; moderate and high relief
Terrain Morphology (Primary)		Table-lands (mountain and hill plateaux)
Vegetation types (dominant types in bold)		Waterberg Moist Mountain Bushveld; Mixed Bushveld; Mopane Bushveld
Altitude (m a.m.s.l.)		900 to 1700
MAP (mm)		300 to 700
Coefficient of variation (% of annual precipitation)		25 to 34
Rainfall concentration index		60 to >65
Rainfall seasonality		Early to mid summer
Mean annual temp (°C)		14 to 22
Mean daily max temp (°C) February		24 to 32
Mean daily max temp (°C) July		16 to 22
Mean daily min temp (°C) February		12 to 19
Mean daily min temp (°C) July		0 to 5
Median annual simulated runoff (mm) for quaternary catchment		<5 (limited); 10 to 100

Main Attributes	Waterberg 6.02
Terrain Morphology: Broad division	Plains; low relief (limited); Lowlands, Hills and Mountains; moderate and high relief
Terrain Morphology (Primary)	Plains (limited) Lowlands with hills
Vegetation types (dominant types in bold)	Mixed Bushveld; Waterberg Moist Mountain Bushveld
Altitude (m a.m.s.l.)	900 to 1700
MAP (mm)	400 to 600
Coefficient of variation (% of annual precipitation)	20 to 34
Rainfall concentration index	60 to >65
Rainfall seasonality	Early to mid summer
Mean annual temp (°C)	16 to 20
Mean daily max temp (°C) February	24 to 30
Mean daily max temp (°C) July	16 to 22
Mean daily min temp (°C) February	14 to 17
Mean daily min temp (°C) July	2 to 3
Median annual simulated runoff (mm) for quaternary catchment	20 to 60
Main Attributes	Western Bankenveld 7.02
Terrain Morphology: Broad division	Plains; moderate relief
Terrain Morphology (Primary)	Moderately undulating plains
Vegetation types (dominant types in bold)	Waterberg Moist Mountain Bushveld
Altitude (m a.m.s.l.)	1100 to 1500
MAP (mm)	400 to 700
Coefficient of variation (% of annual precipitation)	25 to 29
Rainfall concentration index	60 to >65
Rainfall seasonality	Early to mid summer
Mean annual temp (°C)	14 to 20
Mean daily max temp (°C) February	24 to 28
Mean daily max temp (°C) July	16 to 22
Mean daily min temp (°C) February	14 to 17
Mean daily min temp (°C) July	2 to 5
Median annual simulated runoff (mm) for quaternary catchment	60 to 100
Main Attributes	Western Bankenveld 7.03
Terrain Morphology: Broad division	Closed Hills, Mountains; moderate and high relief
Terrain Morphology	Low Mountains
Vegetation types (dominant types in bold)	Waterberg Moist Mountain Bushveld; Mixed Bushveld
Altitude (m a.m.s.l.)	900 to 1700
MAP (mm)	400 to 700
Coefficient of variation (% of annual precipitation)	20 to 29
Rainfall concentration index	60 to >65
Rainfall seasonality	Early to mid summer
Mean annual temp (°C)	16 to 20
Mean daily max temp (°C) February	24 to 30
Mean daily max temp (°C) July	16 to 22
Mean daily min temp (°C) February	14 to 19
Mean daily min temp (°C) July	2 to 5
Median annual simulated runoff (mm) for quaternary catchment	20 to 80
Main Attributes	Bushveld Basin 8.05
Terrain Morphology: Broad division	Plains; low relief; Closed Hills, mountains; moderate and high relief (limited)
Terrain Morphology (Primary)	Slightly undulating plains; Hills (limited)
Vegetation types (dominant types in bold)	Mixed Bushveld, Clay Thorn Bushveld; Waterberg Moist Mountain Bushveld (limited)
Altitude (m a.m.s.l.)	900 to 1500
MAP (mm)	400 to 700
Coefficient of variation (% of annual precipitation)	25 to 29
Rainfall concentration index	60 to >65
Rainfall seasonality	Early to mid summer
Mean annual temp (°C)	16 to 20
Mean daily max temp (°C) February	26 to 32
Mean daily max temp (°C) July	18 to 22
Mean daily min temp (°C) February	14 to 17
Mean daily min temp (°C) July	2 to 3
Median annual simulated runoff (mm) for quaternary catchment	20 to 40 (limited); 40 to 100

Appendix B: Photo plates of five sites sampled on the Mokolo River

Site 1:



Plate 1: Images from Site 1. From top left to bottom right: overhead view of river above site showing floodplain on the far side; the main channel with dense pool and dense reed growth; flood zones 1 (at edge of deep water) and 2 (from foot of bank extending under water); same as previous, looking upstream; flood zone 3; flood debris in trees on flood zone 3 (Source: Rowntree and van der Waal, 2012).

Site 2:



Plate 2: Images from Site 2. Top left to bottom right: abandoned channel, flood zone 3 to right; flood zone 3; flood zone 2; flood zone 1; the main channel looking upstream and downstream, note dense reeds on islands in mid-channel, trees in distance are on islands or the far bank (Source: Rowntree and van der Waal, 2012).

Site 3:

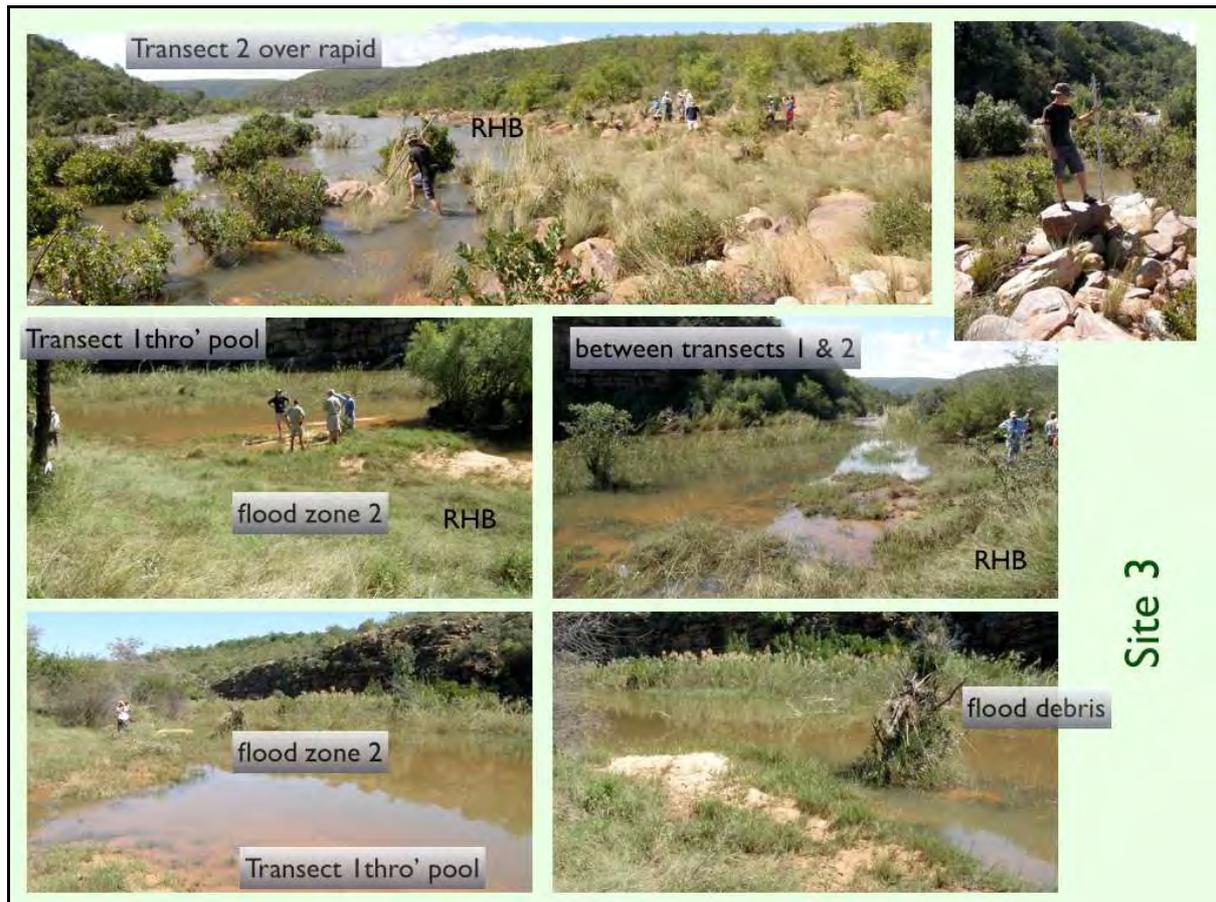


Plate 3: Images from Site 3. Top left to bottom right: the downstream rapid; boulders on edge of rapid comprising flood zone 2; flood zones 1 (under water) and 2 (exposed) at side of pool; as for previous, steep rock wall on left hand bank of channel is visible; same again looking upstream; flood debris in bush on flood zone 1 (Source: Rowntree and van der Waal, 2012).

Site 4:



Plate 4: Images from Site 4. Top left to bottom right: top row – aerial views of the river looking downstream and upstream; looking across the river towards the alluvial fan; flood zones 1 (flooded) and 2 (out of water); general view across river from flood zone 3 on wooded hillslope (Source: Rowntree and van der Waal, 2012).

Site 5:

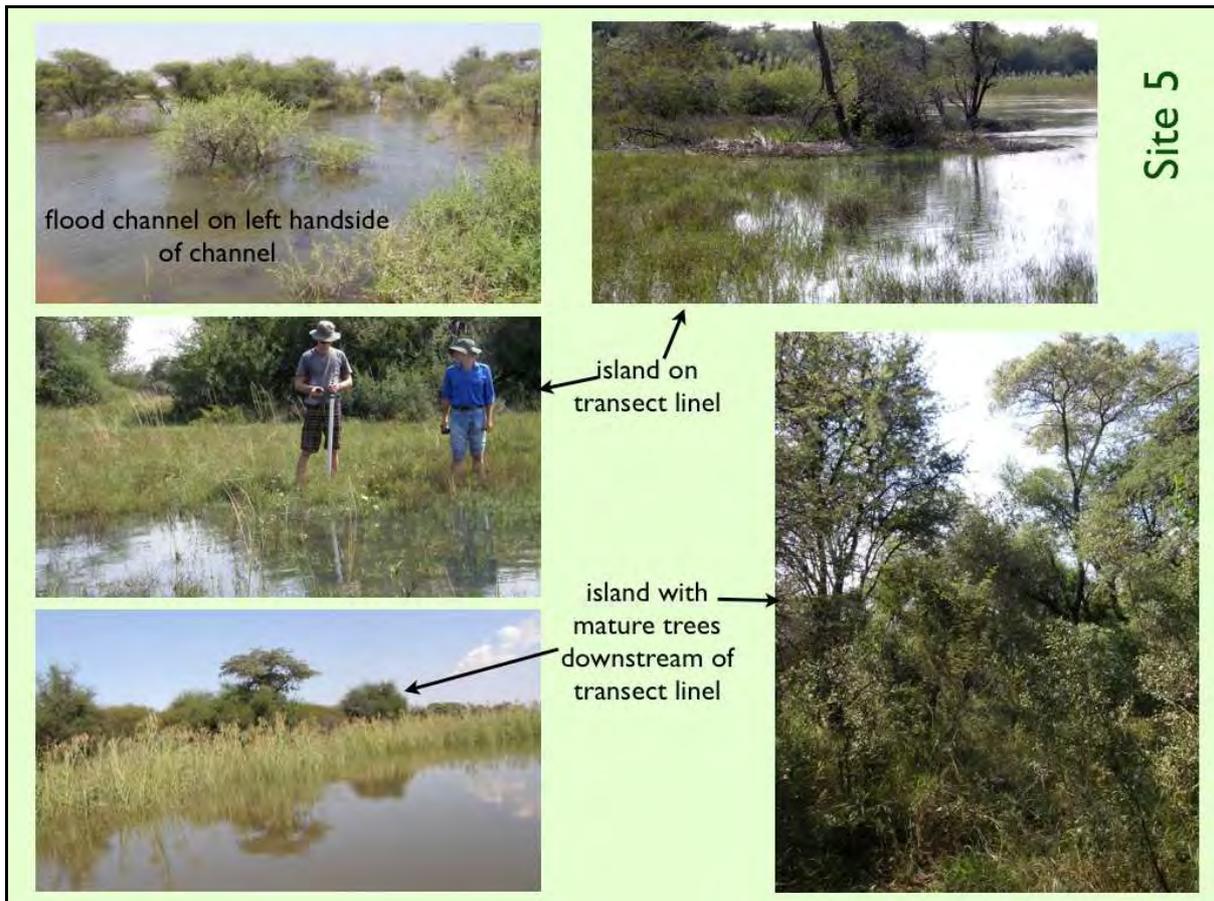


Plate 5: Images from Site 5. Top left to bottom right: floodwaters cover flood zone 2; flood debris on flood zone 2; island with grass and trees (flood zone 3); reeds on channel bed next to island (flood zone 3); tree cover on island (flood zone 3) (Source: Rowntree and van der Waal, 2012).