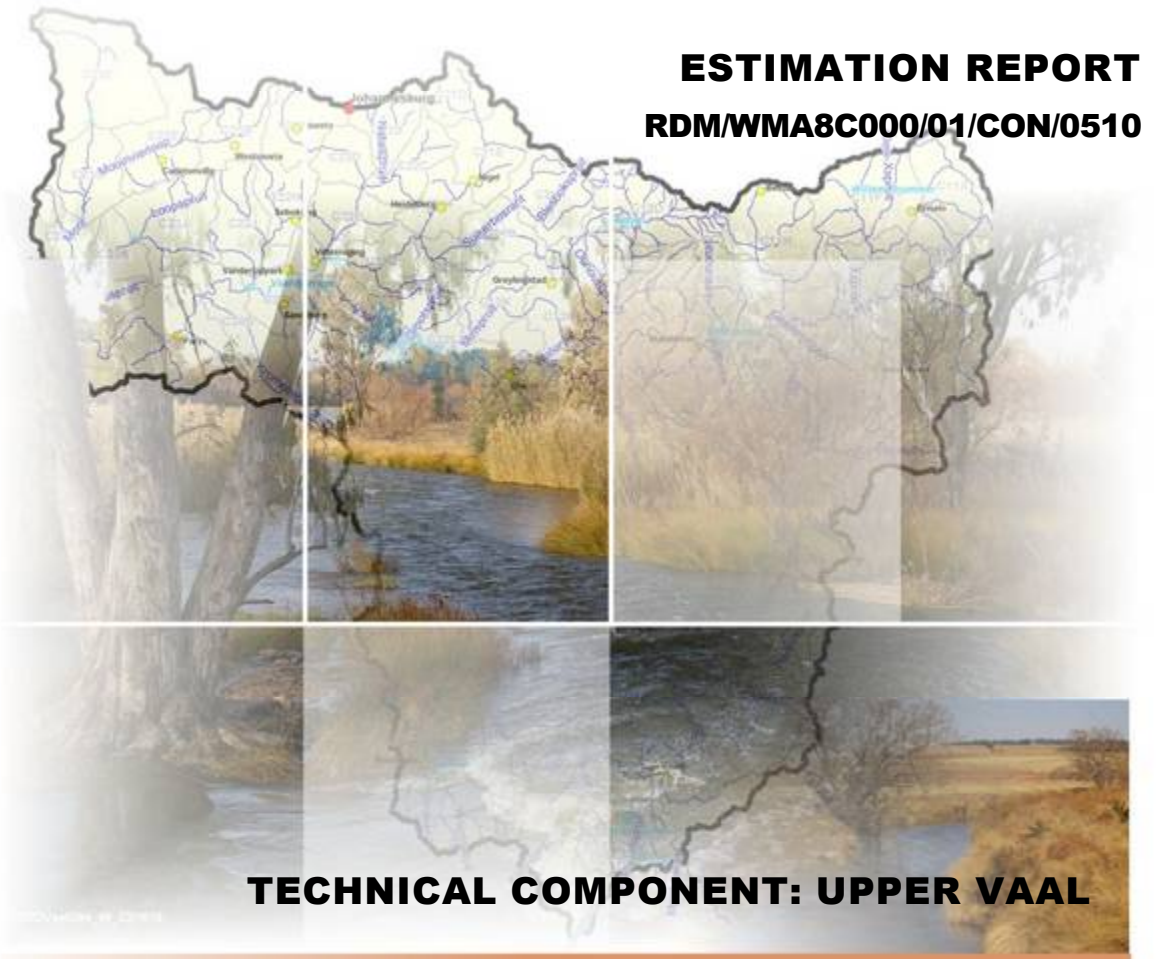
COMPREHENSIVE RESERVE DETERMINATION

INTEGRATED VAAL RIVER SYSTEM

SURFACE WATER



ESTIMATION REPORT

RDM/WMA8C000/01/CON/0510

TECHNICAL COMPONENT: UPPER VAAL

JULY 2010

REPORT NO.: RDM/WMA8C000/01/CON/0510
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water & forestry
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Water Affairs and Forestry
REPUBLIC OF SOUTH AFRICA

COMPREHENSIVE RESERVE DETERMINATION STUDY OF THE INTEGRATED VAAL RIVER SYSTEM

UPPER VAAL WATER MANAGEMENT AREA TECHNICAL COMPONENT: ESTIMATION REPORT

Report number: RDM/WMA8C000/01/CON/0510

JULY 2010

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The Desktop Reserve model adjustments for hydronodes in the Sabie, Crocodile and Mokolo River catchments were performed by AL Birkhead, A Desai, D Louw, J Mackenzie.

Dr CJ Kleynhans developed the approach to determine the biophysical similarity of sites and predict the indicator fish guilds. This was undertaken for this study by Dr Pieter Kotze.

EXECUTIVE SUMMARY

INTRODUCTION

A comprehensive EWR study has been undertaken for the whole Vaal River. The Vaal catchment was divided into three study areas namely the upper, middle and lower Vaal. This study comprises the Upper Vaal Water Management Area (WMA 8) in support of strategic, national and catchment management, development and planning.

A comprehensive Reserve study assesses EWRs at EWR sites that are usually situated on the main rivers and large tributaries. For the purpose of, amongst others, Compulsory Licensing and general licensing, Reserves have to be determined at many points (hydronodes) in the catchment. EWR sites at each of these nodes where EWRs are determined at a comprehensive level will become time consuming and therefore costly.

The objective of this task is to provide an estimate which will be of higher confidence than the Desktop Reserve Model at every hydronode in the Sabie, Crocodile and Mokolo systems (the Komati information has already been supplied through a WRC/DWAF research project). The report therefore deals with the extrapolation/estimation approach, methods and results.

APPROACH

Extrapolation consists of determining which sites are sufficiently similar to the comprehensive EWR sites in terms of biophysical similarity as well indicator guilds used for setting EWRs. The relevant EWR results are then hydrologically extrapolated to those points.

Estimation consists of the following:

- The collection of Rapid III level hydraulic information at selected sites in the catchments of the Sabie-Sand, Crocodile, Mokolo and upper Vaal Rivers.
- The analysis of the field data and provision of hydraulic characterisations for the sites in accordance with the procedures described by Birkhead (2010).
- Examining the EWR results for these (Rapid III) sites in conjunction with (Intermediate and Comprehensive level) flow requirements for the purpose of developing a simple method for estimating EWR at hydronodes in these catchments.
- Predicting the indicator fish guilds at each hydronode.
- Estimating the EWRs at each hydronode for the Recommended Ecological Category (REC) (using the information generated as part of the Desktop EcoClassification (Kleynhans & Louw, 2007).

The decision-making process to determine whether to estimate or extrapolate is summarised in the flow diagram below (Figure 1).

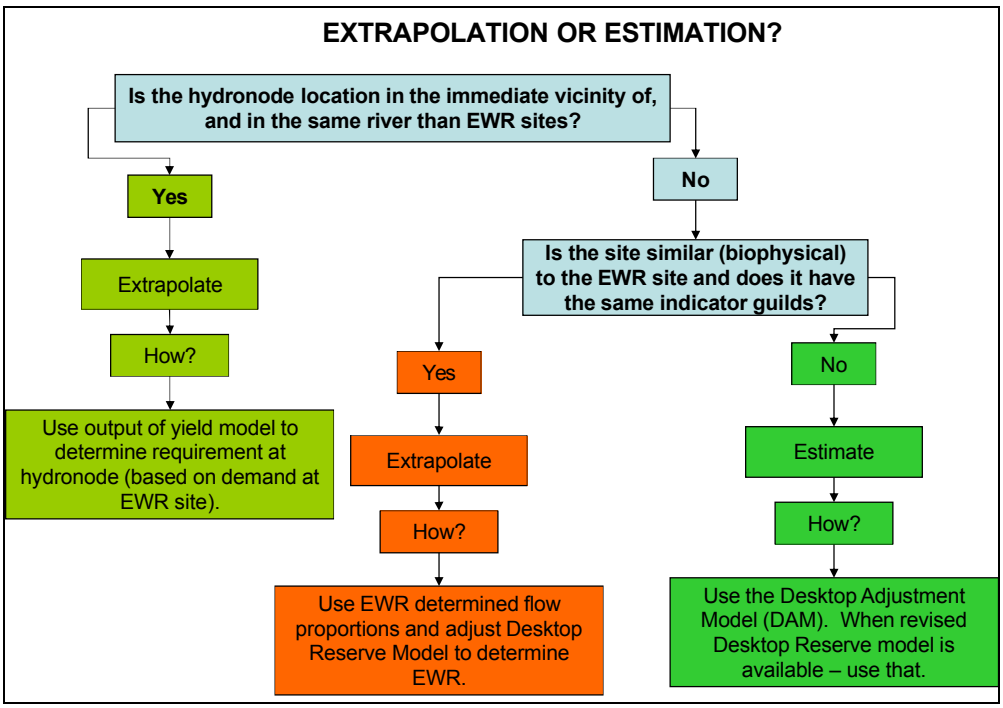

Figure 1 **Flow diagram showing when it is appropriate to extrapolate or when estimation is required**

HYDRONODES AND DATABASE

Hydronodes are points on a map which represents a catchment, usually at the quinary scale. These points were selected by Rivers for Africa situated mostly at the oulet of quaternary catchments and other sites where surveys have been undertaken and were included in an Excel database. Additional points were also provided in the database, the so-called known fish sites. This inclusion was required as the database was used to compare the known fish sites with hydronodes to derive the indicator fish guild for which the EWR must be set. For each point in the database, a range of biophysical information was provided to characterise the nodes and fish sites.

PREDICTION OF INDICATOR FISH GUILDS

Conceptually the prediction approach is based on the physical similarity between sites were fish information is available and hydronodes without fish information. If sites are physically similar to a high degree (many variables the same), then the assumption can be made that the same indicator fish guild would be present at both sites

The results of the above analysis provide the indicator guilds for each hydronode (Table 1). The hydronodes are in the tows shaded grey. The indicator fish guilds are provided in the rows below the hydronodes and refers to LSR (large semi-rheophilics) and SSR (small semi-rheophilic).

Table 1 Indicator fish guilds at the hydronodes

UV Uklip	UV9	UV17	UV25	UV Cor	UV28	UV31	UV WV	UV35	UV36	UV45	UV53	C1VAAL-KVAAL	C1VAAL-BRAKS	C1VAAL-VILLI	8VF3	8VF5	C1BLES-UNSPE	C1KVAA-UNSPE	C1KLIP-UNSPE (8KF2)	C1KLIP-UNSPE (8KF1)
SSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	SSR	SSR	SSR	LSR	LSR	LSR
C1LEEU-NDLEE	C1RIET-AMERS	C1SAND-UNSPE	C1WATE-EWR01	C1WATE-EWR02	C8KLIP-VAALD	8WF1	8WF3	8EF1	8EF2	8EF3	8EF4	8EF6	C8NUWE-CONFL	8NF2	C8MEUL-UNSPE	8MF1	8MF2	8CF1	C23F	C22G
LSR	SSR	LSR	LSR	LSR	LSR	SSR	LSR	SSR	LSR	LSR	LSR	LSR	LSR	LSR	SSR	SSR	LSR	LSR	SSR	LSR
C23A	C21A	C21B	C12K	C82E	C82D	C83E	C83D	C81J	C81G	C81C	C13C	C82A	C13E	C13G	C13H	C12A	C12J	C13A		
SSR	SSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	SSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR		

CALIBRATION SITES USED FOR EWR ESTIMATION

Various EWR sites (Rapid Level III, Intermediate and Comprehensive) were used to develop an EWR estimation method for hydronodes where no hydraulic data existed. These sites focussed on smaller rivers (to add to the database which is based on comprehensive determinations focussing on large rivers) in the Mokolo, Komati, Crocodile, Sabie and Upper Vaal catchments.

EWR ESTIMATION METHOD

EWR sites were determined as part of this study. EWRs available at the EWR sites are for specific Ecological Categories (ECs) (may include the Present Ecological State (PES), Recommended Ecological Category (REC) and/or the Alternative Ecological Category (AEC)), specified separately for fish and macroinvertebrates. For the Rapid Level III sites (Komati, Sabie, Crocodile, Mokolo and upper Vaal River catchments), the Fish Flow Habitat Assessment (FFHA) model (developed by Dr C.J. Kleynhans) was used for estimating the EWRs (the model was modified for application to macro-invertebrates). The FFHA model provides a consistent procedure for estimating EWRs (at the Rapid Level III and higher) and gives requirements for the A to D range of Ecological Categories (ECs).

The EWR data were entered into an Excel data base for processing, together with the tabulated (modelled) hydraulic information (or lookup tables) for the site cross-sections. Code was written in Visual Basic Applications (VBA) to compile EWR and hydraulic data as a function of ecological and hydrological parameters. The ecological information included the indicator fish guild and macroinvertebrate taxa, and the hydrological information included the season and percentage (time) exceedance of maintenance and drought conditions on the flow duration table (FDT).

For each of the four fish guilds (Small Semi-Rheophilic (SSR), Large Semi-Rheophilic (LSR), Small Rheophilic (SR) and Large Rheophilic (LR), and a single macro-invertebrate taxa (flow dependant cobble dwelling (FDCD)), there were three variables to consider. These included hydrological season (wet or dry), percentage point on the FDT (the points denoting maintenance and drought conditions) and EC (B, C or D - the FFHA model considered an A to be natural). Thirty-six data sets for fish and 12 for macroinvertebrates were used.

For each of these 48 data sets, the EWR requirement (from the Comprehensive and Rapid Level III (FFHA model) studies), hydrological (natural flow) and relevant hydraulic information (wetted channel width, maximum depth, average depth and average velocity) were compiled. Following from the findings of a previous EWR estimation study (Birkhead, 2008), the data was analysed to assess whether the EWR could be expressed as a constant unit-width value (i.e. a constant discharge per unit (wetted) width of channel).

A regression procedure was coded (using VBA) to automate the curve-fitting for the 48 data sets, and allowed the regressions to be easily re-determined with changes to the data sets.

APPLICATION OF ESTIMATION TO HYDRONODES

A procedure for applying the EWR estimation method as a Desktop Adjustment Method (DAM - refer to Birkhead, 2008) was developed using MS-Excel and VBA. The procedure consists of the various steps which were used to provide EWR estimates for the 62 hydronodes.

The final results as the .rul and .tab tables are provided as electronic data (RDM Report no RDM/WMA8C000/01/CON/0710; DWA, 2010).

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ABBREVIATIONS, ACRONYMS AND GLOSSARY OF TERMS

AEC	Alternative Ecological Category
Alt	Altitude
DAM	Desktop Adjustment Method
DRM	Desktop Reserve Model
Dry	Driest month
EC	Ecological Category
D: NWRP	Directorate: National Water Resource Planning
DWA	Department Water Affairs
DWAF	Department Water Affairs and Forestry
ECOR	EcoRegion
EWR/EFR	Ecological Water Recommendations/Environmental Flow Recommendations. Also referred to as Instream Flow Requirements (IFR)
FDCD	Flow Dependant Cobble Dwelling
FDT	Flow Duration Table
FFHA	Fish Flow Habitat Assessment
FROC	Fish frequency of occurrence
GEOM	Geomorphic
HabSpecs	Habitat specifications
Ind	Indicator
Invert	Macroinvertebrates
LL	Large Limnophilic
LR	Large Rheophilics
LSR	Large Semi-Rheophilics
Maint	Maintenance
MAR	Mean Annual Runoff
ML	Medium Limnophilic
MS	Microsoft
MSR	Medium Semi-Rheophilics
Mm^3	Million cubic metres
m^3/a	Cubic metres per annum
m^3/s	Cubic metres per second
nMAR	Natural mean annual runoff
nr	number
PES	Present Ecological State
Q	discharge
Qnat	Natural discharge
Quat	Quaternary catchment
REC	Recommended Ecological Category
RDM	Resources Directed Measures
RHP	River health programme
RQS	Resources quality services
rul	Reserve Desktop model EWR results in FDT (or rule) format
SL	Small Limnophilic
SR	Small Rheophilics
SSR	Small Semi-Rheophilics
tab	Reserve Desktop model EWR results in table format
VBA	Visual Basic Applications
W	Wetted channel width (m)
WAAS	Water Availability Assessment Study
WAR	Water Allocation Reform

Wet	Wetted month
WRC	Water Research Commission
% pt	percentage point (time equalled or exceeded)

1 BACKGROUND

Various studies led and contributed to a current Water Research Commission (WRC) study, K5/1856: DEVELOPMENT OF A REVISED DESKTOP RESERVE ESTIMATION MODEL. In essence, the purpose of this WRC study was to revise the Desktop Reserve Model (DRM) (Hughes & Hannart, 2003). This model can then be applied on a catchment wide basis to supply Reserve estimates to various nodes. As the Revised Desktop Ecological Reserve model will only be available in 2011, a process had to be determined in the interim to estimate Reserves to various nodes that were of higher confidence than the existing DRM. The background to all the preceding studies is provided below.

1.1 2007 WRC AND DWA KOMATI STUDY

The following is an extract of Kleynhans *et al.* (2008): Principles of a process to estimate and/or extrapolate environmental flow requirements (Report produced for the Water Research Commission, South Africa by Water for Africa (Pty) Ltd. KV 210/08).

The Department of Water Affairs and Forestry (DWAF) has announced its Water Allocation Reform (WAR) programme as an important component of the roll out of the National Water Act of 1998. The main focus of the WAR programme is to reconcile existing and future water demands with its availability. Water resource planning requires recognition of the Ecological Reserve, and estimates of Ecological Water Requirements (EWRs) are therefore required.

Ecological Reserve (quantity) determinations at the Comprehensive and Intermediate levels have generally been determined for sites located along main-stem rivers and major tributaries, where water resources are often in high demand. Frequently, no EWR information is available for the smaller tributaries. The establishment of sites to provide EWRs at all locations of interest necessary for water resource planning is not pragmatic and beyond available resources. There is therefore a need to develop a cost-effective and efficient method for estimating EWRs for numerous river locations with reasonable levels of accuracy. This requirement is necessary to support the WAR initiative and to better evaluate individual water use licence applications.

The primary objective of this project was to develop a procedure for extrapolating EWR low-flow result from Reserve sites to additional locations (termed hydronodes) that have a degree of ecologically similarity. The extrapolation procedure refers to hydrological extrapolation by adjusting default parameters in the Desktop Reserve model, and is the current approach for estimating EWRs for additional river locations. The Desktop Reserve model is based on the results of previous EWR assessments, and therefore almost entirely on EWR-hydrological relationships derived for rivers with substantial runoff. With the exception of Rapid level III estimates, little cognisance is given as to whether hydrological extrapolation is ecologically justified. The "extrapolation" concept was extended to the "estimation" concept at an early stage of the study. The reason for this is that an "estimation" approach does not limit the method to the use of existing Ecological Reserve results, but rather allows for the development of a method that explicitly incorporates biological information, flow preferences for the biota present, and availability of hydraulic habitat.

A procedure has been developed for establishing the extent to which different river locations have physical similarity. Based on this, the assumption is that physical similarity implies similar fish guilds under natural conditions. The identification of likely indicator species may subsequently be used for informing ecological flow requirements at additional (un-sampled) river locations.

Estimation of EWRs requires the definition of habitat preferences or requirements. These have been provided through habitat specifications (or HabSpecs), which are numerical values for a combination of hydraulic parameters and flow-classes that define required hydraulic habitat and hence flows for "groups" of biota that exploit environmental resources in a similar way (referred to as guilds for fish and communities for invertebrates). Habitat specifications are a function of hydrological variability (e.g. drought, maintenance and season) and Ecological Category (EC) for the river. In this study, HabSpecs were determined for two fish guilds: small rheophilic fish and large semi-rheophilic fish and a single community of invertebrates - cobble-dwelling rheophilics. Habitat specifications were computed using an optimisation method based primarily on the results of previous EWR studies. This effectively provides "calibrated" numerical rules that are based on the collective knowledge and understanding of river ecologists involved in previous ecological flow assessments. Habitat specifications provide a simple and consistent rule-based approach for estimating EWRs where hydraulic characterisation of flow conditions is available - presently at Rapid level III assessments and higher.

The HabSpecs indicate that hydraulic habitat is more sensitive to changes in low flows in smaller rivers (MAR <–30 Mm^3/a) than larger rivers, with the relevant fish guilds and invertebrate communities used, which supported by studies in the international literature.

The Nkomati Water Availability Assessment Study (WAAS) formed the basis for application of the methods (site similarity and EWR estimation) developed within this study. Overall, the HabSpec predicted ecological flows for 10 tributary sites were considered to provide more reasonable estimates, compared with Desktop model generated values, for the smaller streams with lower MARs (below – 30 Mm^3/a) and small rheophilic fish. Desktop model estimates were considered to provide increasing underestimates of EWRs with reducing stream size below approximately 30 Mm^3/a. For sites with mean annual runoff in excess of approximately 30 Mm^3/a, Desktop model estimates were considered reasonable recommendations for ecological low-flows. Since the HabSpec estimation method is independent of hydrology, estimates should be confined to between Desktop and natural (albeit modelled) flows. For the sensitive rheophilic biota considered, the application of HabSpecs for EWR estimation indicates that higher proportions of natural flows are required with reducing stream size and during the drier season.

The HabSpec generated low-flows for the selected (tributary) river sites were expressed as a function of the inundated low-flow channel width, and unit-width discharges were found to be remarkably constant. These flows were used to define the minimum seasonal drought and maintenance discharges required to achieve the recommended EC for the sensitive rheophilic biota. It needs to be emphasized that the unit-width EWR results from this study are applicable to specific fish guilds and invertebrate communities and hydrological characteristics of the Nkomati River catchment. Further study is required for the reasoning behind this (unit width) finding, as well as the development of more generalised and tested procedures for estimating EWRs for different biota and geomorphologies. This is taking place during concurrent research projects funded by the Water Research Commission as well as DWAF Reserve studies.

1.2 K8/795: COLLATION AND SYNTHESIS OF HYDRAULIC INFORMATION FROM ENVIRONMENTAL FLOW REQUIREMENT STUDIES

The above analysis was undertaken by Birkhead and Desai. The following is an extract of the draft WRC report.

Large quantities of river hydraulic information have been collected over the past decade in the course of undertaking Environmental Flow Requirement (EFR) assessments (including Instream Flow Requirements), and more recently, Ecological Reserve studies. The clients involved have been mainly the Department of Water Affairs (South Africa), as well as private organisations and government departments in neighboring countries (e.g. Swaziland, Lesotho and Mocambique). These data are in electronic format and hardcopies in the form of project reports, electronic files (workbook data), and total approximately 46 projects, 218 sites and 821 cross-sections.

Kleynhans et al. (2008) discuss the principles of a process to estimate and/or extrapolate Environmental Flow Requirements. The estimation component requires the prediction, at the desktop level, of the (ecologically relevant) low-flow inundated channel width. The (current) Water Research Commission (WRC) project (K5/1856), requires the development of a hydraulics sub-model for estimating hydraulic habitat. This information will be used for the WRC project but was also extensively used in the determinations of the approaches used in the interim to estimate Ecological Reserves at various nodes.

The objectives of this project have been to:

- Collate available hydraulic and relevant site-related information from previous (mainly) EFR studies, and
- determine whether the data display empirical relationships.

1.3 CURRENT WRC STUDY (K5/1856)

The Desktop Reserve model (Hughes & Hannart, 2003) was developed to enable quick estimates to be made of the Ecological Reserve for rivers at any site within the country. The Reserve estimates are currently based on a three stage process and are strongly associated with the concepts of the Building Block Methodology. The first stage is to determine the annual volumes of the low flow maintenance and drought requirements, as well as the maintenance high flow requirements as percentages of the mean annual runoff.

The second stage is to translate the annual requirements into seasonal distributions. This is based on the seasonal distributions of the reference hydrology time series. The third stage is to combine the monthly maintenance and drought flow Reserve estimates into complete tables (or curves) of assurance rules (equivalent to flow duration curves). The shapes of the assurance rule curves are determined in the model from the values of the maintenance and drought flow estimates as well as the flow duration curve characteristics of the reference flows.

It is clear, therefore, that the existing Desktop Reserve model is very dependent upon the characteristics of the reference hydrology used and that it largely ignores the advances in understanding of habitat-flow-ecology relationships that have emerged in the last 5 years or so. It also ignores regional differences in these relationships that are related to regional differences in the natural biotic assemblages and ecological functioning, as well as differences in the relationships between flow, hydraulics and habitat. The latter are assumed to vary across different geomorphological zones.

The pressures on DWA to generate Reserve estimates are well known and partly related to the Water Allocation Reform (WAR) program and the need to give effect to the National Water Act. The Desktop Reserve model has been demonstrated to be an appropriate analysis tool, whether used with default parameters or after adjustment through a Rapid Reserve assessment. However,

the uncertainty associated with the outputs from the Desktop Reserve model remains a major concern, especially if these outputs are ever likely to be challenged in a court of law.

Improvements to the desktop model require the incorporation of more of our understanding of the ecological processes into the model so that it is not only driven by hydrology.

The ecological component of the WRC study follows directly on from the existing project (K8/657) where the major focus has been to establish the principles and concepts of ecological similarity of sites and using filter models to identify the indicator species at approximately 800 fish sites in the country. The broad principles to specify habitat requirements (linked to the indicator species/groups, geomorphological zones and river width/size) were determined and tested on the cobble bed systems in the Komati River.

2 INTRODUCTION

In order for the Department of Water Affairs (DWA) to make informed decisions regarding the authorization of future water use and the magnitude of the impacts of the present and proposed developments in the Vaal River System, higher levels of confidence is needed for the Reserve Determination within this study area. Therefore a Comprehensive Reserve determination study within Water Management Area (WMA) 8 has been undertaken to provide input to the Reconciliation studies and the integrated water quality management plan recently undertaken by the National Water Resources Planning Directorate (D: NWRP) of the DWA.

For the purpose of, amongst others, Compulsory Licensing and general licensing, Reserves have to be determined at many points (hydronodes) in the catchment. EWR sites at each of these nodes where EWRs are determined at a comprehensive level will become time consuming and therefore costly.

.

The objective of this task is to provide an estimate which will be of higher confidence than the Desktop Reserve Model at every hydronode in the Upper Vaal WMA. The report therefore deals with the approach, methods and results.

The Desktop Reserve Model is being refined as part of the current WRC project K5/1856. This should give higher confidence answers than the current Desktop Reserve Model but will highly likely only be finalised in 2011. A prototype approach, applied for this study and described in the report, is however available that can be used in the interim. This process is further refined from the approach used on the Komati River (Kleynhans *et al*, 2008).

2.1 TERMS OF REFERENCE OF THIS TASK

Determine estimated EWRs at selected hydronodes in the Upper Vaal WMA.

2.2 APPROACH

The approach consisted of two processes, extrapolation and estimation.

Extrapolation consists of determining which sites are sufficiently similar to the comprehensive EWR sites in terms of biophysical similarity as well indicator guilds used for setting EWRs. The relevant EWR results are then hydrologically extrapolated to those points.

Estimation consists of the following:

- The collection of Rapid III level hydraulic information at selected sites in the catchments of the Sabie, Crocodile, Mokolo[1] and upper Vaal Rivers.
- The analysis of the field data and provision of hydraulic characterisations for the sites in accordance with the procedures described by Birkhead (2010).
- Examining the EWR results for these (Rapid III) sites in conjunction with (Intermediate and Comprehensive level) flow requirements for the purpose of developing a simple method for estimating EWR at hydronodes in these catchments.
- Predicting the indicator fish guilds at each hydronodes and

[1]The data collated in all these rivers were used for the hydraulic database to generate the ecological requirements for different guilds.

- Estimating the EWRs at each hydronode for the Recommended Ecological Category (REC) (using the information generated as part of the Desktop EcoClassification (Kleynhans & Louw, 2007).

Bullet 1 and 2 above are well documented in Birkhead (2010) and therefore no further explanations are provided.

The decision-making process to determine whether to estimate or extrapolate is summarised in Figure 2.1.

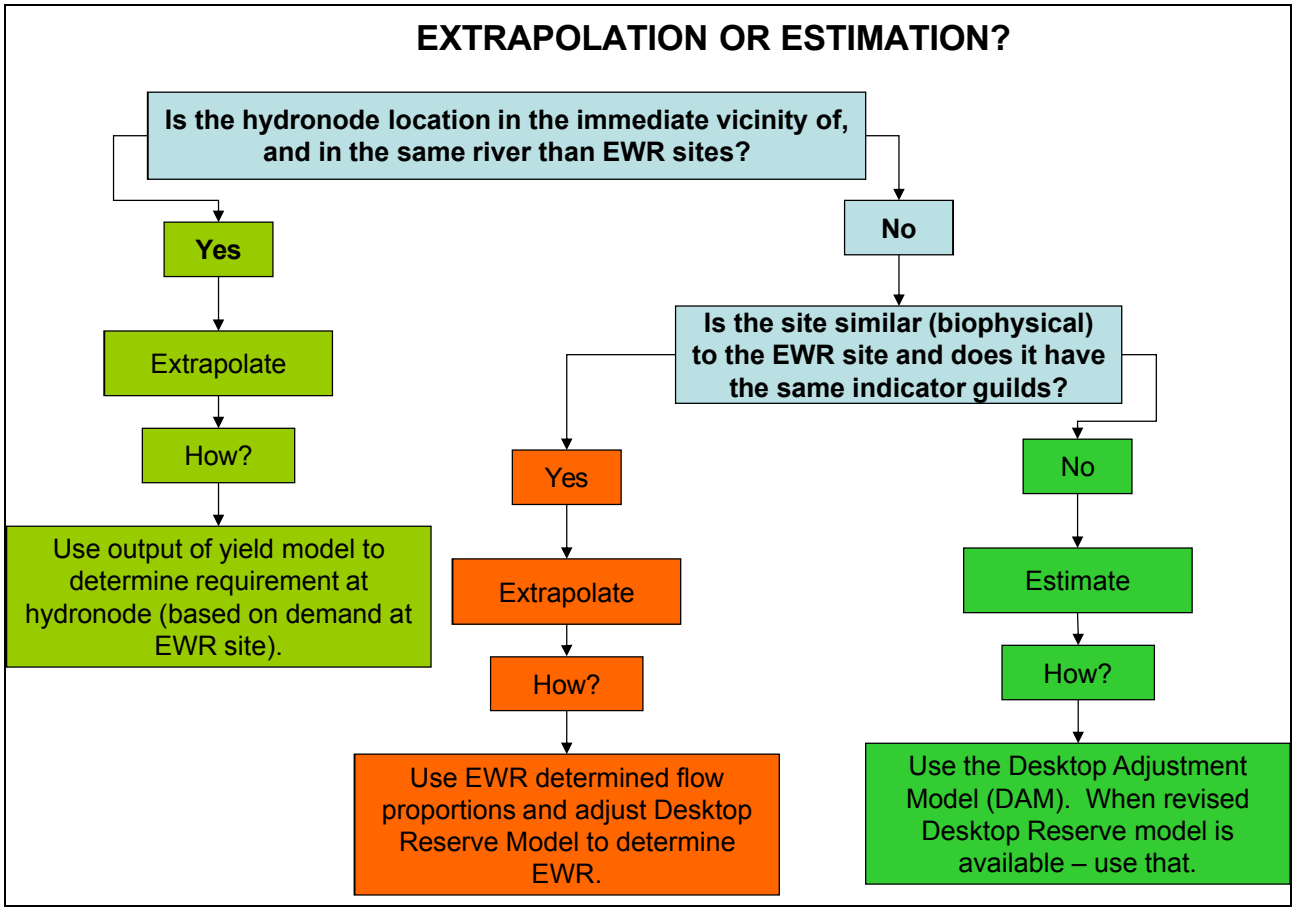

Figure 2.1 Flow diagram showing when it is appropriate to extrapolate or when estimation is required

2.3 PURPOSE OF THIS REPORT

The purpose of this report is to describe the approach and results of the extrapolation and estimation process applied to the Upper Vaal WMA.

The estimation of EWR requirements at hydronodes in the Komati River catchment is described in the Water Research Commission (WRC) Report of Kleynhans *et al.* (2008). This report should be consulted for background information.

3 HYDRONODES AND HYDRONODE DATA BASE

Hydronodes are usually selected as part of a detailed hydrological study and are based at the outlet of quinary catchments. As this information was not available, the following process was followed to select hydronodes or purposes of estimation.

- The estimation process is not applicable to situations where the present day hydrology is higher than natural and or where water quality issues dominate the situation. Therefore quaternary catchments where the aforementioned situations occurred were identified first, since no hydronodes could be selected in these areas.
- Calibration sites (sites where physical measurements were undertaken) were selected next as sites where estimation was required.
- All known fish sites and National River Health Programme sites were selected. The sites that did not fall in the quaternary catchments described in the first bullet above became hydronodes.
- The outlet of any quaternary catchment that did not form part of the areas described in bullet 1 above and did not include any hydronodes (calibration sites and known fish sites (bullet 2 and 3 above) close to the outlets, were then selected as outlets.

A data base was set up in an Excel spreadsheet to characterise all the hydronodes. To aid in the determination of the prediction of indicator guilds, all other sites with 'known' fish information (Figure 3.2) were included in the data base. These 'known' fish sites consist of any sites where fish surveys have been undertaken and were extracted from:

- Reference Frequency of Occurrence of Fish species in South Africa (Kleynhans *et al.,* 2007a).
- Fish surveys undertaken as part of the current Reserve study at EWR sites and at Estimation Calibration (Figure 3.2) sites.

The data base is provided electronically (DWA, 2010). The information that is provided in each column of the data base is described below. Note that reference to a site can mean an actual site or a node which represents a point on a map and which might not have been visited.

- ***Column A:*** SITE NAME: The final site name compiled after considering all the names allocated to the site (column B, C, D, and E).
- ***Column B:*** OTHER NAMES: EWR site names, RHP names and nicknames).
- ***Column C:*** EWR SITE & CALIBRATION SITES: EWR sites listed according to their names within this study. Calibration sites were named mostly UV (for Upper Vaal) and an arbitrary number.
- ***Column D:*** RHP SITE: Sites that are National River Health Programme sites (so-called macro sites) are listed (Dallas, 2005) as well as provincial RHP sites.
- ***Column E:*** FISH INFORMATION SITES: The codes as provided in the FROC data base (Kleynhans *et al*., 2007a) are provided as well as the EWR and Estimation Calibration sites.
- ***Column F:*** Shreve: Shreve system to provide the stream order (Shreve, 1967).
- ***Column G:*** Strahler: Strahler system to provide the stream order (Strahler 1952, 1957).
- ***Column H:*** LATITUDE is provided in the decimal degree format.
- ***Column I***: LONGITUDE is provided in the decimal degree format.
- ***Column J:*** QUAT: Refers to the quaternary catchment in which the site is situated.
- ***Column K:*** MAJOR RIVER: This refers to the major river into which the river flows where the site is located. E.g. a site located in the Wilge River will be represented by the Vaal

River as the major river. Any sites were located in the Vaal, only the major river column will be completed.

- ***Column L:*** TRIBUTARY: This represents the river in which the site is located.
- ***Column M:*** ECOR: EcoRegion (Level 2) (Kleynhans *et al*., 2007b) in which the site is situated.
- ***Column N:*** GEOM ZONE: Geomorphic Zone (Rountree and Wadeson, 1999) in which the site is situated.
- ***Column O:*** ALT (m): Altitude obtained from Google Earth.
- ***Column P:*** AREA: Area is provided for each node as square km (km^2).
- ***Column Q:*** nMAR: Natural Mean Annual Runoff according to the modelled hydrology as supplied by WRP (and modified where required by IWR Water Resources) and IWR Water Resources.
- ***Column R:*** WIDTH: Estimated width of the channel (see Chapter 7).
- ***Column S-T:*** Comments regarding calculation of area and nMAR calculations.
- ***Column U***: PERENIAL: Indication of whether the stream is perennial.
- ***Column V***: INDICATOR GUILDFish indicator guild.
- ***Column W***: COMMENTS: Comments relevant to fish indicator guild.
- ***Column X***: MOST SIMILAR FISH SITE (FOR WHICH DATA IS AVAILABLE).
- ***Column Y***: CLOSEST SIMILARITY TO EWR SITE: Provides the EWR site which is the most similar.
- ***Column Z***: CLOSEST SIMILARITY TO EWR SITE: Indicates similarity to most EWR sites that can be used for extrapolation (i.e., EWR 2, 3, 6, 8, 9 – sites not influenced by more water than natural.
- ***Column AA***: SIMILARITY VALUE: Provides the similarity value
- ***Column AB***: METHOD: Provides the method (estimation, extrapolation or yield) that should be used to estimate the Reserve
- ***Column AC***: PES: Provides the PES for the quat as estimated by Desktop EcoClassification (RDM/WMA8C000/01/CON/0207; DWAF, 2008).
- ***Column AD***: REC: Provides the Recommended Ecological Category as derived from the EIS from the Desktop EcoClassification (DWAF, 2008).

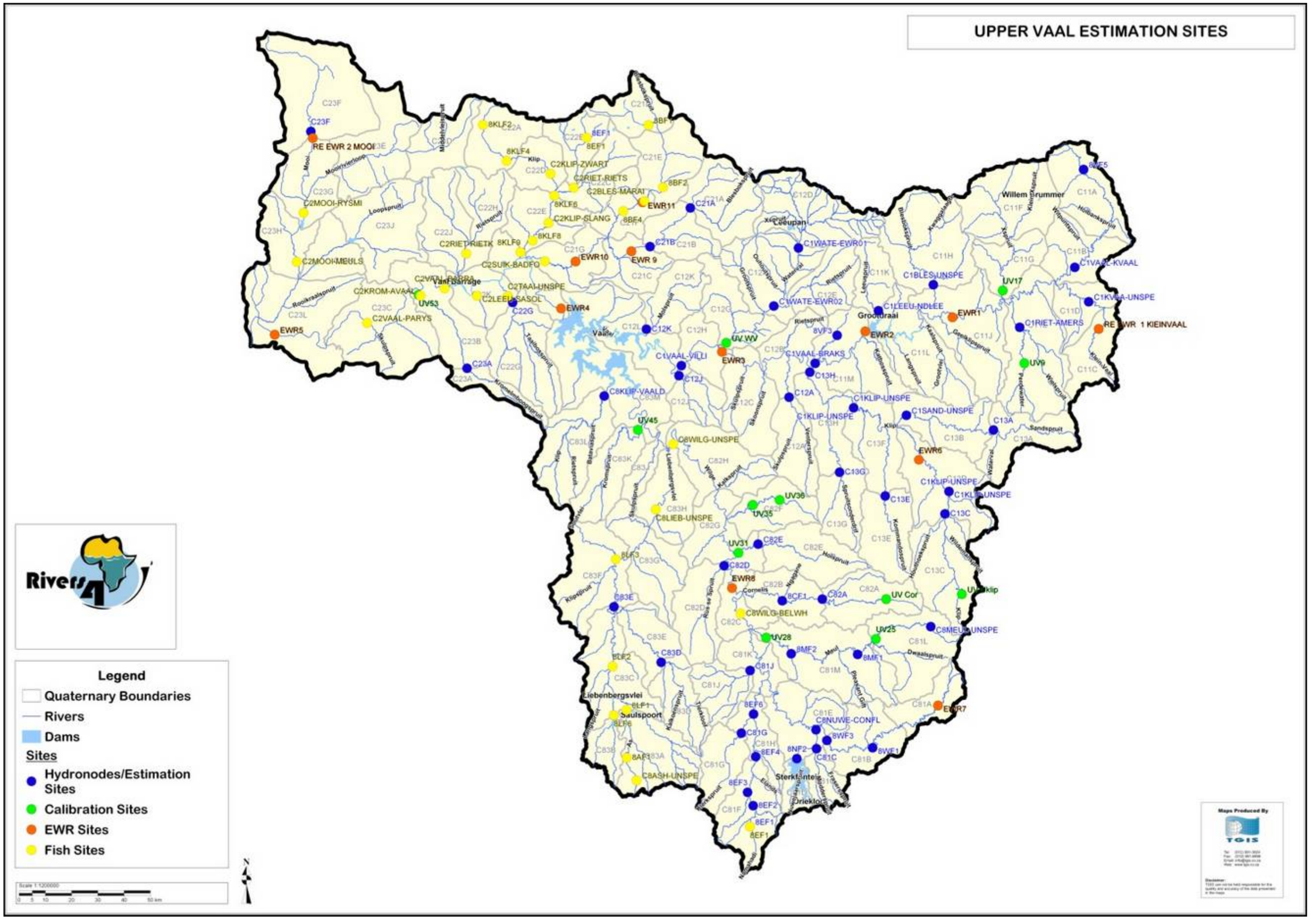

Figure 3.1 Localities of Upper Vaal hydronodes, fish and calibration sites

4 PREDICTION OF INDICATOR FISH GUILDS

This work followed on from the prediction of indicator species as undertaken for the Komati River and documented in Kleynhans *et al.* (2008). Kleynhans further refined the process using different methods for the Mokolo, Crocodile and Sabie River catchments.

Conceptually the prediction approach is based on the physical similarity between sites were fish information is available and hydronodes without fish information. If sites are physically similar to a high degree (many variables or characteristics the same), then the assumption can be made that the same indicator fish guild would be present at both sites.

The results of the Upper Vaal system is provided in excel format as part of the electronic information (DWAF, 2010).

The similarity work for the Upper Vaal was undertaken by Dr Kotze. The following broad approach in estimating the species composition, and thus most appropriate indicator guild, of the Upper Vaal River hydronodes was applied:

Each extrapolation site was plotted in Google earth to determine if any existing fish sites (where fish information was available) could be used to determine the expected fish species composition. The Fish Frequency of Occurrence (FROC) database, as well as other fish distribution information was used during this process. If no sites with fish data were found, a similarity matrix was used to determine the most comparable fish sites (with actual data) with the extrapolation site/node. The similarity matrix was based on comparison of the following criteria:

- Shreve stream order
- Strahler stream order
- Quaternary catchment
- Geomorph Zone
- Altitude (m)
- nMAR (million m^3/a)
- Width

The most similar site with available fish data was then used to determine the expected fish species of the estimation site/node. The above mentioned aspects were however also compared individually between the sites (especially width, nMAR and geomorph zone, as well as visual comparison using Google Earth) before a final conclusion was made regarding the expected fish species composition of the estimation site/node. A dendogram and Euclidian Distance analysis were also undertaken to confirm the conclusions

A summary of the results is provided in the Table 4.1:

Abbreviations used for indicator guilds were:

SR:	Small Rheophilic	SL:	Small Limnophilic	SSR:	Small Semi-rheophilic
LR:	Large Rheophilic	LL:	Large Limnophilic	LSR:	Large Semi-rheophilic

Table 4.1 Fish guilds per hydronode based on comparison with sites with highest similarity

UV Uklip	UV9	UV17	UV25	UV Cor	UV28	UV31	UV WV	UV35	UV36	UV45	UV53	C1VAAL-KVAAL	C1VAAL-BRAKS	C1VAAL-VILLI	8VF3	8VF5	C1BLES-UNSPE	C1KVAA-UNSPE	C1KLIP-UNSPE (8KF2)	C1KLIP-UNSPE (8KF1)
SSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	SSR	SSR	SSR	LSR	LSR	LSR
C1LEEU-NDLEE	C1RIET-AMERS	C1SAND-UNSPE	C1WATE-EWR01	C1WATE-EWR02	C8KLIP-VAALD	8WF1	8WF3	8EF1	8EF2	8EF3	8EF4	8EF6	C8NUWE-CONFL	8NF2	C8MEUL-UNSPE	8MF1	8MF2	8CF1	C23F	C22G
LSR	SSR	LSR	LSR	LSR	LSR	SSR	LSR	SSR	LSR	LSR	LSR	LSR	LSR	LSR	SSR	SSR	LSR	LSR	SSR	LSR
C23A	C21A	C21B	C12K	C82E	C82D	C83E	C83D	C81J	C81G	C81C	C13C	C82A	C13E	C13G	C13H	C12A	C12J	C13A		
SSR	SSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	SSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR	LSR		

This information supplied formed the basis for the estimation process as it was now known which relationship for which guild to apply at each site.

5 CALIBRATION SITES

5.1 CALIBRATION SITES USED FOR EWR ESTIMATION

Photographs of the EWR sites (Rapid Level III, Intermediate and Comprehensive) used to develop an EWR estimation method for hydronodes where no hydraulic data existed (and specifically applicable to these catchments), are illustrated in Table 5.1 for the Sabie River and Crocodile River catchments, Table 5.2 for the Mokolo River catchment, and Table 5.3 for the Upper Vaal River catchment. Their locality and other pertinent information are provided in Table 5.4.

The calibration sites for estimation from the Nkomati River catchment (refer to Birkhead, 2008) were included in this study to extend the EWR and hydraulic data base.

Certain Rapid III, Intermediate and Comprehensive sites were omitted for various reasons, and included sites:

- Where present day flow conditions were substantially modified from natural flow conditions (primarily due to upstream flow regulation by large dams), since EWR estimation (Section 6) is related to natural flows.
- With inappropriate geomorphic characteristics (riffle and rapid units were favoured with gravel, cobble and small boulder substrates).
- With high uncertainty in the (modelled) natural hydrology.

Table 5.1 Calibration sites in the Sabie and Crocodile River systems used for EWR estimation (Photographs: D. Louw)

SABIE AND CROCODILE RIVER SYSTEMS: CALIBRATION SITES FOR ESTIMATION	
	
Sekgamarago	**Buffelskloofspruit (cross-section A)**
	
Buffelskloofspruit (cross-section B)	**Lonely Creek**

	
Sabane	**Blystaanspruit**
	
Sabie	**Nels**
	
NoordKaap	**Houtbosloop**

Table 5.2 Calibration sites in the Mokolo River system used for EWR estimation (Photographs: D. Louw)

MOKOLO SYSTEM RIVER SYSTEM: CALIBRATION SITES FOR ESTIMATION	
	
Renosterbosspruit (cross-section A)	**Renosterbosspruit (cross-section B)**

Sand

Klein Vaalriverspruit

Jim se Loop

Tambotie (cross-section A)

Tambotie (cross-section B)

Frikkie se Loop,

Upper Dwars

Lower Dwars (Cross-section B)

	
Sterk	**Taaibos**

Table 5.3 Calibration sites in the Upper Vaal River system used for EWR estimation (Photographs: D. Louw)

UPPER VAAL RIVER SYSTEM: CALIBRATION SITES FOR EWR ESTIMATION	
	
Klip	**Grootspruit (cross-section B)**
	
Cornelius	**Skulpspruit**
	
Kromelmboogspruit	**Kromspruit**

Meul (cross-section A)

Meul (cross-section B)

Holspruit

Waterval

Table 5.4 Sites used for hydronode EWR estimation

Quat	Site nr	River	Alt (m)	Co-ordinates		MAR (Mm^3)	Discharge (m^3/s)[1]	Ind fish guild[2]		Ind invert taxa[3]		% pt FDT[4]	
				Latitude	Longitude			Dry	Wet	Dry	Wet	Maint[5]	Dry
NKOMATI RIVER CATCHMENT													
Calibration sites													
X12K	X12K1	Phalangampepe	731	-26.0453	31.0503	4.2	0.050	SR	SR	FDCD[6]	FDCD	70	95
X12G	X12G2	Bergstroom	1200	-25.9678	30.8333	4.8	0.026	SR	SR	FDCD	FDCD	70	95
X11F	X11F1	Bankspruit	1545	-25.8469	30.3506	6.7	0.075	SR	SR	FDCD	FDCD	70	95
X12G	X12G1	Mawelawala	1144	-25.9652	30.8216	9.9	0.037	SR	SR	FDCD	FDCD	70	95
X12H	X12H2	Sandspruit	800	-26.0497	30.8972	10.5	0.037	SR	SR	FDCD	FDCD	70	95
X11A	X11A1	Vaalrivierspruit	1531	-26.0069	30.02664	10.6	0.019	SR	SR	FDCD	FDCD	70	95
X11D	X11D1	Klein Komati	1640	-25.8881	30.1203	10.7	0.050	SR	SR	FDCD	FDCD	70	95
X12K	X12K2	Mlondozi	1098	-26.0472	31.0442	14.2	0.17	SR	SR	FDCD	FDCD	70	95
X11E	X11E1	Swartspruit	1444	-25.93695	30.235	15.4	0.045	SR	SR	FDCD	FDCD	70	95
X12B	X12B1	Buffelspruit	1562	-26.0628	30.3939	27.9	0.086	SR	SR	FDCD	FDCD	70	95
X11G	X11G3	Komati	935	-25.9531	30.7249	370	1.5	LSR	LSR	FDCD	FDCD	70	95
SABIE and CROCODILE RIVER CATCHMENTS													
Calibration sites													
X32A	E8Sek	Sekgamarago	886	-24.69327	30.92953	1.0	0.02	SR	SR	FDCD	FDCD	70	95
X21D	E2aBKS	Buffelskloofspruit	1184	-25.43842	30.44713	10.8	0.10	SR	SR	FDCD	FDCD	70	95
X21D	E2bBKS	Buffelskloofspruit				10.8	0.10	SR	SR	FDCD	FDCD	70	95
X31G	E9Lon	Lonely Creek	1146	-25.10324	30.71097	11.2	0.34	SR	SR	FDCD	FDCD	70	95
X31D	E6Saban (a)	Sabane	533	-25.03414	31.01989	16.4	0.031	SSR	SSR	FDCD	FDCD	70	95
X31D	EcSaban (b)	Sabane						SSR	SSR	FDCD	FDCD	70	95
X22A	E3Bly	Blystaanspruit	1032	-25.28752	30.59633	19.3	0.51	SR	SR	FDCD	FDCD	70	95

Quat	Site nr	River	Alt (m)	Co-ordinates		MAR (Mm^3)	Discharge (m^3/s)[1]	Ind fish guild[2]		Ind invert taxa[3]		% pt FDT[4]	
				Latitude	Longitude			Dry	Wet	Dry	Wet	Maint[5]	Dry
X31A	E10Sab	Sabie	1099	-25.12100	30.71700	26.5	0.41	SR	SR	FDCD	FDCD	70	95
X22D	E5Nels	Nels	1065	-25.28945	30.76464	30.4	1.2	SR	SR	FDCD	FDCD	70	95
X32B	E1Kaap	Kaap(North)	678	-25.60761	30.97650	43.5	0.27	SR	SR	FDCD	FDCD	70	95
X22A	E4Hout	Houtbosloop	865	-25.35516	30.66591	56.8	0.78	SR	SR	FDCD	FDCD	70	95
EWR sites													
X31B	EWR 1	Sabie	862	-25 04.424	30 50.924	140.2		SR/LR	SR/LR	FDCD	FDCD	70	95
X31D	EWR 2	Sabie	463	-25 01.675	31 03.099	262.1		SR/ R	SR/LR	FDCD	FDCD	70	95
X31K	EWR 3	Sabie	369	-24 59.256	31 17.572	495.9		SR/SR	SR/SR	FDCD	FDCD	70	95
X31C	EWR 4	Mac Mac	582	-25 00.800	31 00.243	65.8		SR/ R	SR/LR	FDCD	FDCD	70	95
X31G	EWR 5	Marite	457	-25 01.077	31 07.997	157.1		SR/ R	SR/LR	FDCD	FDCD	70	95
X32C	EWR 7	Tlulandziteka	543	-24 40.829	31 05.188	28.9		SR/LSR	SR/LSR	FDCD	FDCD	40	95
X21A	EWR 1	Crocodile	1852	-25 29.647	30 08.656	15.2				FDCD	FDCD	70	95
X21B	EWR 2	Crocodile	1207	-25 24.555	30 18.955	47.1		SR	SR	FDCD	FDCD	70	95
X24H	EWR 6	Crocodile	470	-25 38.968	31 14.572	1063		SR/LSR	SR/LSR		FDCD	70	95
MOKOLO RIVER CATCHMENT													
Calibration sites													
A42F	8	Taaibos	1011	-24 11.128	27 51.673	1.8	0.49	SSR	MSR	FDCD	FDCD	50	95
A42B	2XSA	Renosterbos-spruit	1284	-24.50804	27.86574	1.9	0.081	SSR	MSR	FDCD	FDCD	50	95
A42B	2XSB	Renosterbos-spruit						SR	SR	FDCD	FDCD	50	95
A42A	1	Sand	1356	-24.65283	28.231	2.1	0.14	SR	SR	FDCD	FDCD	50	95
A42E	11	Klein Vaalrivierspruit	1098	-24.21941	28.05363	2.7	0.42	SSR	LSR	FDCD	FDCD	50	95
A42E	6	Jim se Loop	1209	-24.27184	28.20002	2.8	0.19	SSR	MSR	FDCD	FDCD	50	95
A42H	7XSB	Tambotie	983	-23.81291	27.94885	2.8	0.52	MSR	MSR	FDCD	FDCD	50	95
A24D	9	Frikkie se Loop	1221	-24.31397	27.95724	3.9	0.66	SR	SR	FDCD	FDCD	50	95
A42E	4	Upper Dwars	1188	-24.26661	28.21718	10.3	0.46	SSR	LSR	FDCD	FDCD	50	95
A42E	5XSA	Lower Dwars	1212	-24.26736	28.21873	14.1	0.66	SSR	LSR	FDCD	FDCD	50	95
A42E	5XSB	Lower Dwars						SSR	LSR	FDCD	FDCD	50	95
A24D	10	Sterk	1191	-24.30554	27.89699	26.1	2.2	SR	SR	FDCD	FDCD	50	95
UPPER VAAL RIVER CATCHMENT													
C13C	8 (UVKlip)	Klip	1757	-27.82105	29.64983	5.75	0.14	SSR	SSR	FDCD	FDCD	60	95
C82F	3B(UV36)	Grootspruit	1643	-27.49946	28.95117	6.24		LSR	LSR	FDCD	FDCD	60	95
C82A	7(UVCor)	Cornelius	1852	-27.83821	29.35921	7.93	0.006	LSR	LSR	FDCD	FDCD	60	95
C11E	9(UV9)	Skulpspruit	1635	-27.02988	29.88956	12.11	0.004	LSR	LSR	FDCD	FDCD	60	95
C23B	1(UV53)	Kromelmboog-spruit	1416	-26.79594	27.56550	14.36	0.006	LSR	LSR	FDCD	FDCD	60	95
C83K	2(UV45)	Kromspruit	1492	-27.25842	28.40691	25.72	0.006	LSR	LSR	FDCD	FDCD	60	95
C81L	6B(UV25)	Meul	1691	-27.97461	29.31991	26.50	0.35	LSR	LSR	FDCD	FDCD	60	95
C82G	5(UV31)	Holspruit	1558	-27.67999	28.79244	32.93	0.049	SR	LSR	FDCD	FDCD	60	95
C81M	6A(UV28)	Meul	1588	-27.96968	28.89911	103.85	0.94	LSR	LSR	FDCD	FDCD	60	95
C12G	4(UVWV)	Waterval	1499	-26.96028	28.74577	176.80	0.48	LR	LR	FDCD	FDCD	60	95

1 Single measured discharge for Rapid III level assessment
2 Indicator fish guild
3 Indicator invertebrate guild
4 Percentage point (time equalled or exceeded) on the flow duration table
5 Maintenance
6 Flow Dependant Cobble Dwelling invertebrates

6 EWR ESTIMATION METHOD

6.1 EWR DATA AND SYNTHESIS

The EWR data for the sites in Table 5.4 were provided (for the Comprehensive level sites) from the Reserve study. These results are for specific Ecological Categories (ECs) (may include the Present Ecological State (PES), Recommended Ecological Category (REC) and/or the Alternative Ecological Category (AEC)), specified separately for fish and macroinvertebrates. For the Rapid Level III sites (Nkomati, Sabie, Crocodile, Mokolo and upper Vaal River catchments), the Fish Flow Habitat Assessment (FFHA) model (developed by Dr C.J. Kleynhans) was used for estimating the EWRs (the model was modified for application to macroinvertebrates). The FFHA model provides a consistent procedure for estimating EWRs (at the Rapid Level III and higher) and gives requirements for the A to D range of Ecological Categories (ECs).

The EWR data were entered into an Excel data base for processing, together with the tabulated (modelled) hydraulic information (or lookup tables) for the site cross-sections. Code was written in Visual Basic Applications (VBA) to compile EWR and hydraulic data as a function of ecological and hydrological parameters. The ecological information included the indicator fish guild and macroinvertebrate taxa, and the hydrological information included the season and percentage (time) exceedence of maintenance and drought conditions on the flow duration table (FDT).

For each of the four fish guilds (Small Semi-Rheophilic (SSR), Large Semi-Rheophilic (LSR), Small Rheophilic (SR) and Large Rheophilic (LR) – (there was insufficient data to consider Medium Semi-Rheophilic (MSR)), and a single macro-invertebrate taxa (flow dependant cobble dwelling (FDCD)), there were three variables to consider. These included hydrological season (wet or dry), percentage point on the FDT (the points denoting maintenance and drought conditions) and EC (B, C or D - the FFHA model considered an A to be natural). Therefore, there were twelve permutations (or data sets) per guild or taxa. However, for the small and large fish guilds, the semi-rheophilic and rheophilic guilds were taken to have the same flow requirements in the wet season (refer to Table 5.4). This effectively increased the EWR data base for the wet season. There were therefore 36 data sets for fish and 12 for macroinvertebrates.

For each of these 48 data sets, the EWR requirement (from the Comprehensive and Rapid Level III (FFHA model) studies), hydrological (natural flow) and relevant hydraulic information (wetted channel width, maximum depth, average depth and average velocity) were compiled. Following from the findings of a previous EWR estimation study (Birkhead, 2008), the data was analysed to assess whether the EWR could be expressed as a constant unit-width value (i.e. a constant discharge per unit (wetted) width of channel). Unfortunately (since this was previously found to be a simple means of expressing the flows), the flow requirements were noted to vary as a function of the natural flow. The reason for this difference (i.e. compared with the previous study) is uncertain, but could be related to a different method (FFHA) being used to estimate the EWRs - where the natural hydrology was more explicitly taken into account. Building on the findings of this previous study, the data were analysed by plotting the relative EWR (as proportion of the natural flow) against the natural flow per unit width of wetted channel (e.g. Figure 6.1).

According to previous findings, the proportional requirement should generally increase with reducing natural discharge per unit width (the latter parameter being related to stream size). For the data sets used in this study, the EWR data from the Comprehensive sites (generally main stem rivers) form the upper range of the natural unit width discharge (x-axis), and the FFHA-derived

requirements (for generally the tributaries) plot at the lower range. Although there is substantial scatter in the data, they again (refer to Birkhead, 2008) indicate general trends of increasing proportional requirement with reducing stream size (for the data analysed).

A regression procedure was coded (using VBA) to automate the curve-fitting for the 48 data sets, and allowed the regressions to be easily re-determined with changes to the data sets. A power function given by $Q(\text{EWR})/Q\text{nat} = a - b(Q\text{nat}/W)^c$ was used for the curve fitting, and the regression coefficients (a, b and c) are given in Table 6.1 (W is the wetted channel width).

The EWR data and fitted regression curves are plotted in Figure 6.1 to Figure 6.8 for the 48 data sets given in Table 5.4. From these plots it may be noted that the drought requirements were different for the different ECs. This differs from the rationale used in the Desktop Reserve Model (Hughes and Münster, 2000), quoted below with corrected (current) terminology provided in parentheses:

"It does not really make ecological sense to think in terms of varying the drought requirements with class [category], *as drought flows are considered to be the minimum required to prevent the system from collapsing. After some discussion amongst experienced IFR specialists it was decided that the drought low flow requirements for all the management classes* (Ecological Categories) *should be the same and similar to maintenance D requirement"*

The reason for varying the drought requirements in this study, in accordance with the EWR data supplied from the FFHA model is (Kleynhans, *pers. comm.*):

"For 'large' streams the above (Hughes and Münster, 2000) rationale may be valid, but for 'smaller' streams with higher (than D) ECs, a D category maintenance flow does not provide sufficient hydraulic habitat (e.g. depth and velocity) for rheophilic (fish) guilds to survive. Physico-chemical (e.g. temperature and oxygen) conditions also enter strongly into the overall habitat condition. The size and habitat guild of the indicator species need to be considered."

The regression relationships plotted in Figure 6.1 to Figure 6.8 are only applicable for the data ranges to which they were fitted, and maximum values of the natural unit width discharges are provided in Table 6.1. Application of this method for EWR estimation at hydronodes is described in Chapter 8.

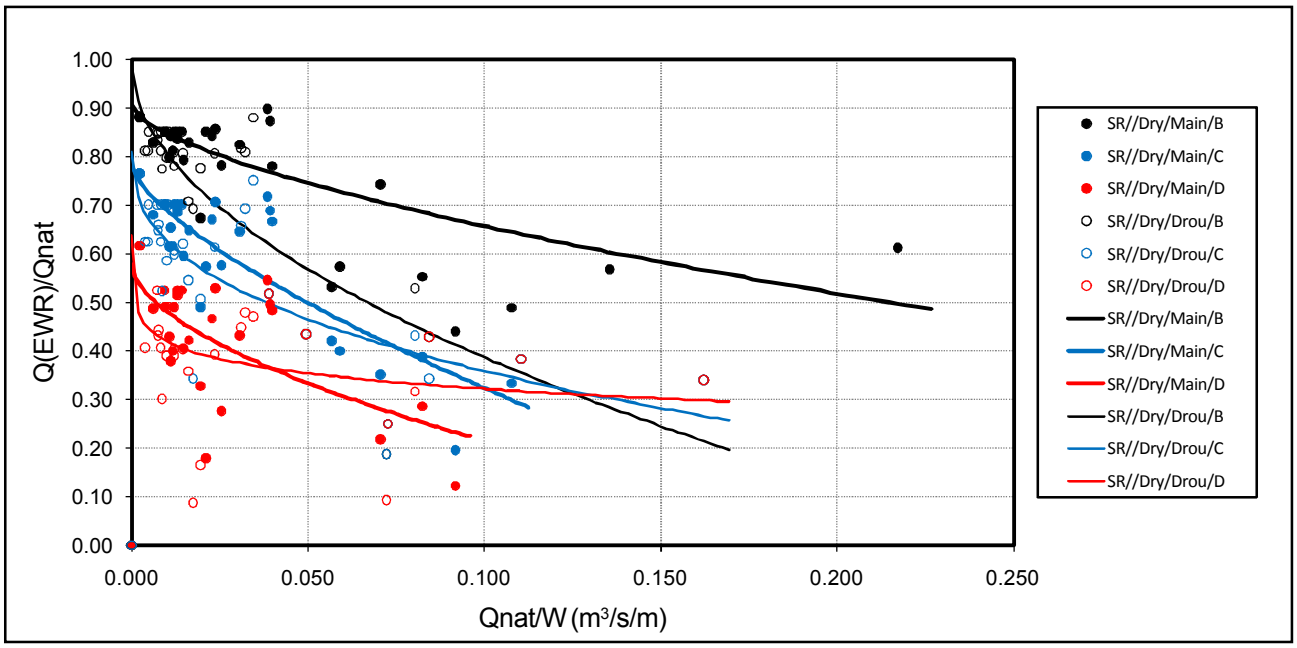

Figure 6.1 **EWR requirement as a proportion of the natural unit discharge as a function of the natural unit width discharge for SR fish for the dry season (drought and maintenance conditions, B to D categories)**

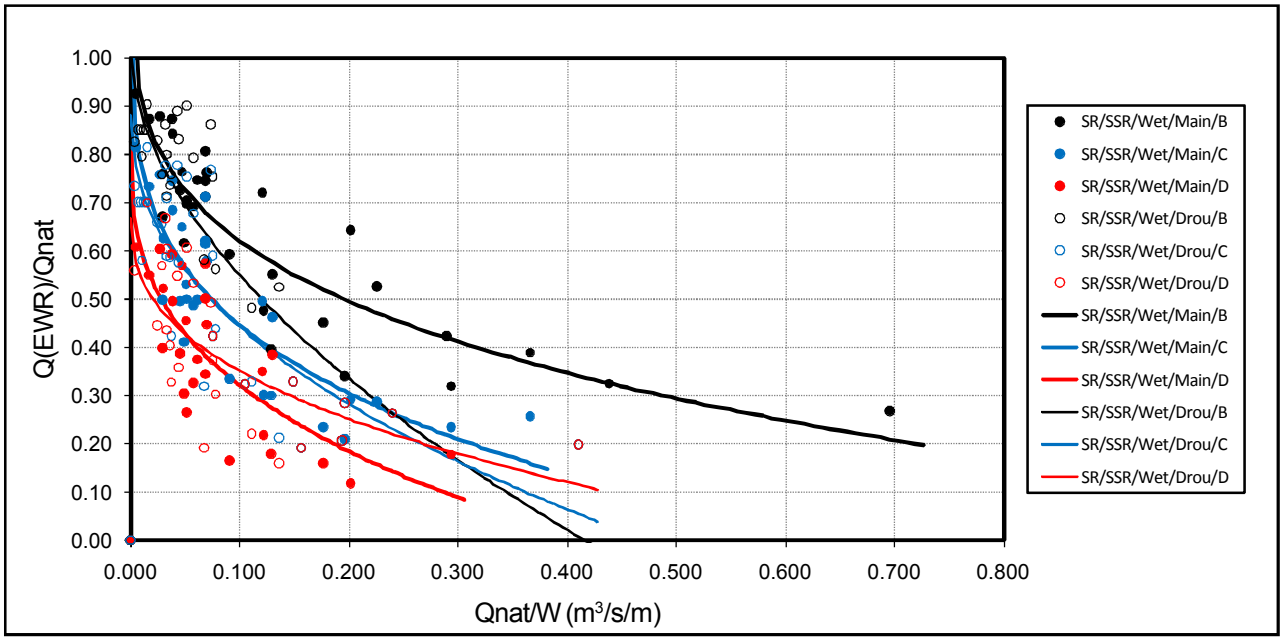

Figure 6.2 **EWR requirement as a proportion of the natural unit discharge as a function of the natural unit width discharge for SR and SSR fish for the wet season (drought and maintenance conditions, B to D categories)**

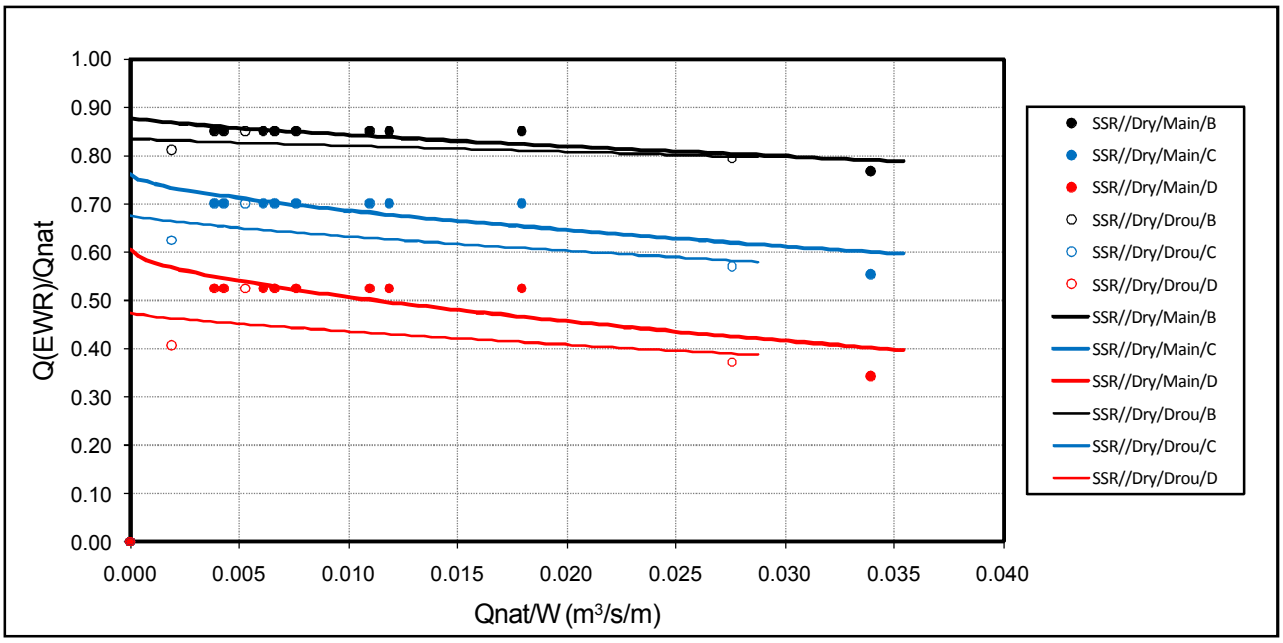

Figure 6.3 EWR requirement as a proportion of the natural unit discharge as a function of the natural unit width discharge for SSR fish for the dry season (drought and maintenance conditions, B to D categories)

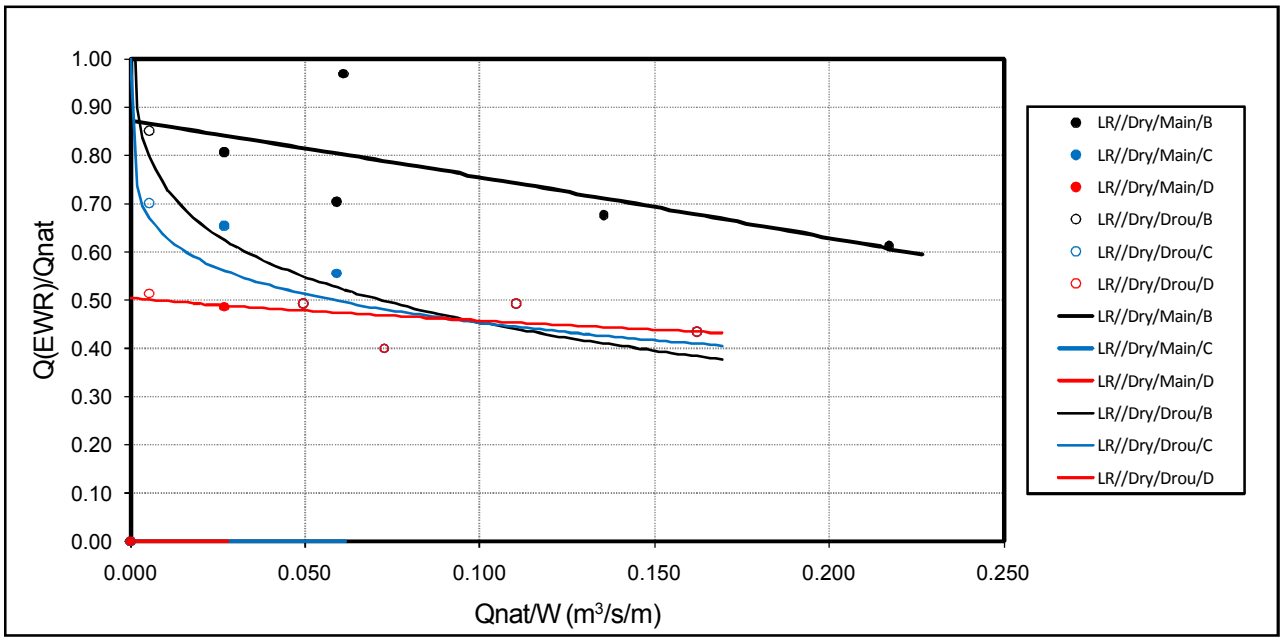

Figure 6.4 EWR requirement as a proportion of the natural unit discharge as a function of the natural unit width discharge for LR fish for the dry season (drought and maintenance conditions, B to D categories). Note: insufficient data for relationships for C and D categories

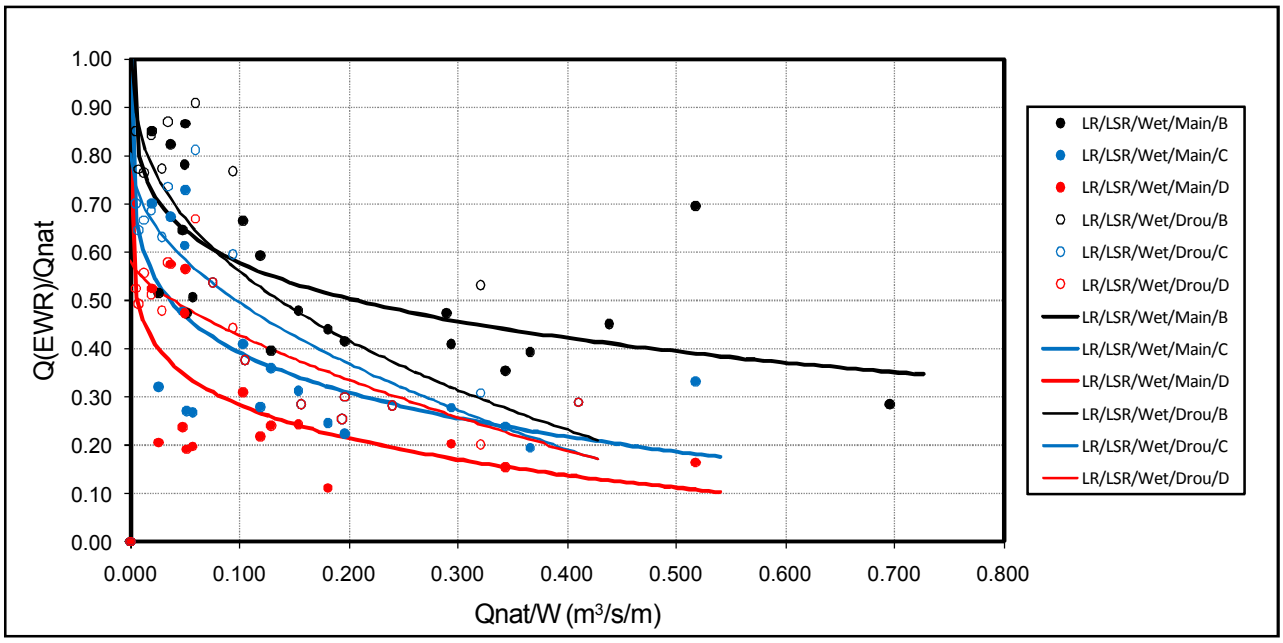

Figure 6.5 EWR requirement as a proportion of the natural unit discharge as a function of the natural unit width discharge for LR and LSR fish for the wet season (drought and maintenance conditions, B to D categories)

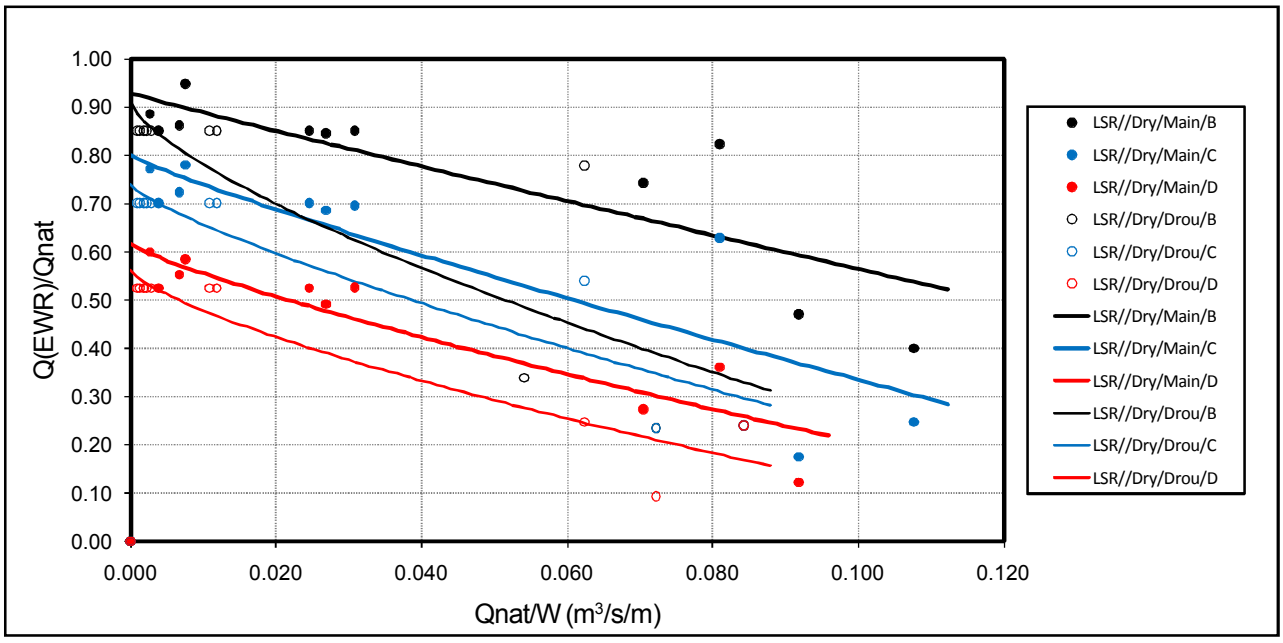

Figure 6.6 EWR requirement as a proportion of the natural unit discharge as a function of the natural unit width discharge for LSR fish for the dry season (drought and maintenance conditions, B to D categories)

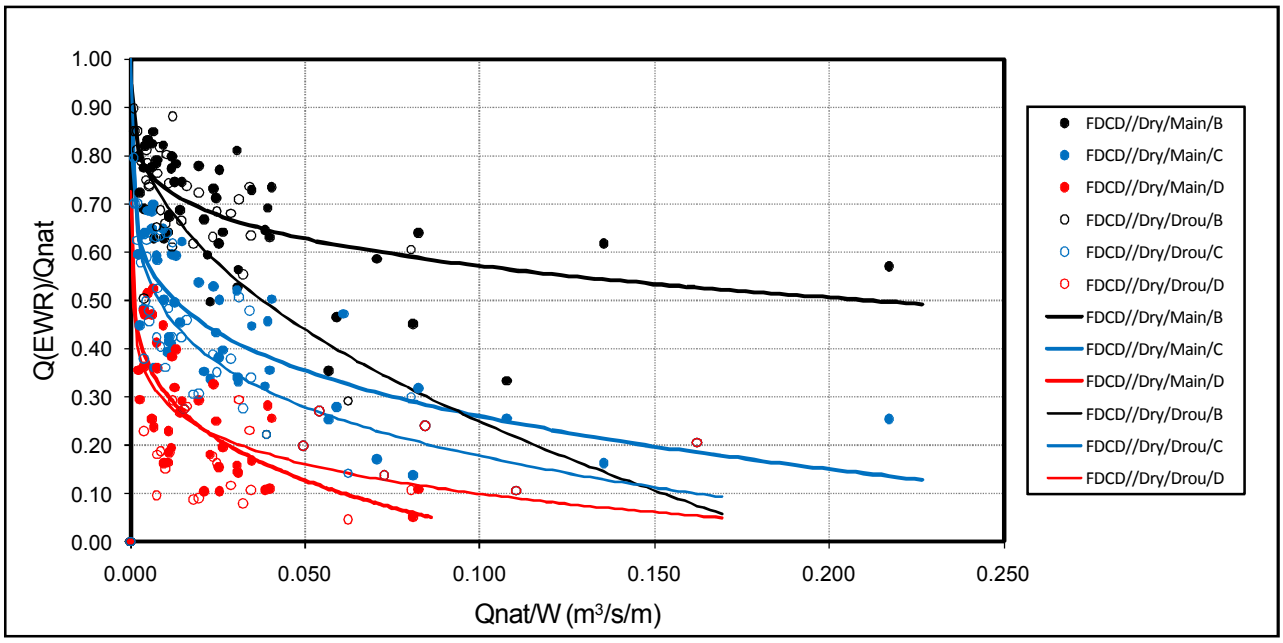

Figure 6.7 EWR requirement as a proportion of the natural unit discharge as a function of the natural unit width discharge for FDCD macroinvertebrates for the dry season (drought and maintenance conditions, B to D categories)

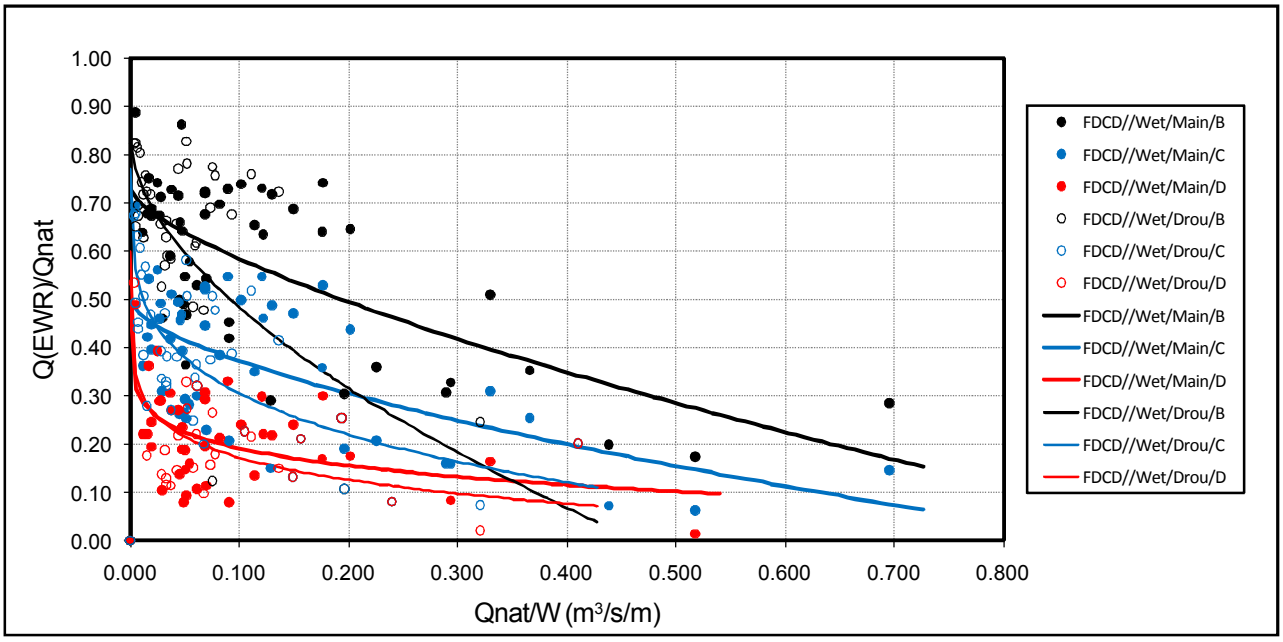

Figure 6.8 EWR requirement as a proportion of the natural unit discharge as a function of the natural unit width discharge for FDC) macroinvertebrates for the wet season (drought and maintenance conditions, B to D categories)

Table 6.1 Regression coefficients in $Q(EWR)/Qnat = a - b(Qnat/W)^c$

Series	Guild/taxa		Season	Position on FDT	Ecological Category	Max.: Qnat/*W*	Regression coefficients		
	Indicator 1	Indicator 2					*a*	*b*	*c*
1	SR		Dry	Maintenance	B	0.217	0.904	1.084	0.642
2	SR		Dry	Maintenance	C	0.108	0.780	2.276	0.697
3	SR		Dry	Maintenance	D	0.092	0.578	1.354	0.573
4	SR		Dry	Drought	B	0.162	0.990	1.987	0.517
5	SR		Dry	Drought	C	0.162	0.816	1.100	0.381
6	SR		Dry	Drought	D	0.162	0.793	0.595	0.101
7	SR	SSR	Wet	Maintenance	B	0.695	1.301	1.192	0.244
8	SR	SSR	Wet	Maintenance	C	0.366	1.201	1.336	0.248
9	SR	SSR	Wet	Maintenance	D	0.294	0.823	1.118	0.348
10	SR	SSR	Wet	Drought	B	0.410	1.015	1.637	0.546
11	SR	SSR	Wet	Drought	C	0.410	0.888	1.236	0.444
12	SR	SSR	Wet	Drought	D	0.410	0.674	0.790	0.389
13	SSR		Dry	Maintenance	B	0.034	0.878	1.066	0.739
14	SSR		Dry	Maintenance	C	0.034	0.760	1.356	0.632
15	SSR		Dry	Maintenance	D	0.034	0.604	1.554	0.602
16	SSR		Dry	Drought	B	0.028	0.835	0.951	0.909
17	SSR		Dry	Drought	C	0.028	0.677	1.310	0.734
18	SSR		Dry	Drought	D	0.028	0.474	1.372	0.776
19	LR		Dry	Maintenance	B	0.217	0.870	1.341	1.065
20	LR		Dry	Maintenance	C	0.059	Insufficient data		
21	LR		Dry	Maintenance	D	0.027	Insufficient data		
22	LR		Dry	Drought	B	0.162	1.551	1.476	0.129
23	LR		Dry	Drought	C	0.162	1.223	1.001	0.114
24	LR		Dry	Drought	D	0.162	0.505	0.309	0.809
25	LR	LSR	Wet	Maintenance	B	0.695	1.368	1.065	0.129
26	LR	LSR	Wet	Maintenance	C	0.518	1.243	1.159	0.134
27	LR	LSR	Wet	Maintenance	D	0.518	0.953	0.928	0.141
28	LR	LSR	Wet	Drought	B	0.410	1.043	1.142	0.374
29	LR	LSR	Wet	Drought	C	0.410	0.805	0.963	0.492
30	LR	LSR	Wet	Drought	D	0.410	0.583	0.728	0.671
31	LSR		Dry	Maintenance	B	0.108	0.928	3.290	0.957
32	LSR		Dry	Maintenance	C	0.108	0.799	3.558	0.885
33	LSR		Dry	Maintenance	D	0.092	0.617	2.748	0.824
34	LSR		Dry	Drought	B	0.084	0.911	3.292	0.701
35	LSR		Dry	Drought	C	0.084	0.738	3.108	0.789
36	LSR		Dry	Drought	D	0.084	0.562	2.359	0.724
37	FDCD		Dry	Maintenance	B	0.217	0.993	0.681	0.208
38	FDCD		Dry	Maintenance	C	0.217	0.894	1.078	0.230
39	FDCD		Dry	Maintenance	D	0.082	0.755	1.183	0.212
40	FDCD		Dry	Drought	B	0.162	0.936	2.012	0.467
41	FDCD		Dry	Drought	C	0.162	1.190	1.440	0.153
42	FDCD		Dry	Drought	D	0.162	1.067	1.205	0.095
43	FDCD		Wet	Maintenance	B	0.695	0.727	0.718	0.700
44	FDCD		Wet	Maintenance	C	0.695	0.495	0.528	0.635
45	FDCD		Wet	Maintenance	D	0.518	0.614	0.556	0.119
46	FDCD		Wet	Drought	B	0.410	0.831	1.281	0.566
47	FDCD		Wet	Drought	C	0.410	0.830	0.866	0.217
48	FDCD		Wet	Drought	D	0.410	0.893	0.886	0.090

6.2 ESTIMATING WETTED CHANNEL WIDTH

To apply the EWR estimation method at hydronodes, the wetted channel width as a function of discharge, is required. This would generally be provided through hydraulic analyses, but no site-specific hydraulic information is available at hydronodes. A general relationship between wetted

channel width and discharge was derived using modelled (width *vs.* discharge) data for sites used in this study (Figure 6.9). Also plotted in Figure 6.9 are the data and relationship derived from measured hydraulic data from previous IFR/EWR studies (Birkhead and Desai, 2009), indicating that the relationships compare reasonably well, with deviations at the lower and upper data ranges. The width-discharge relationship derived from modelled data, and used in this study, is given by $W = 9.561Q^{0.309}$.

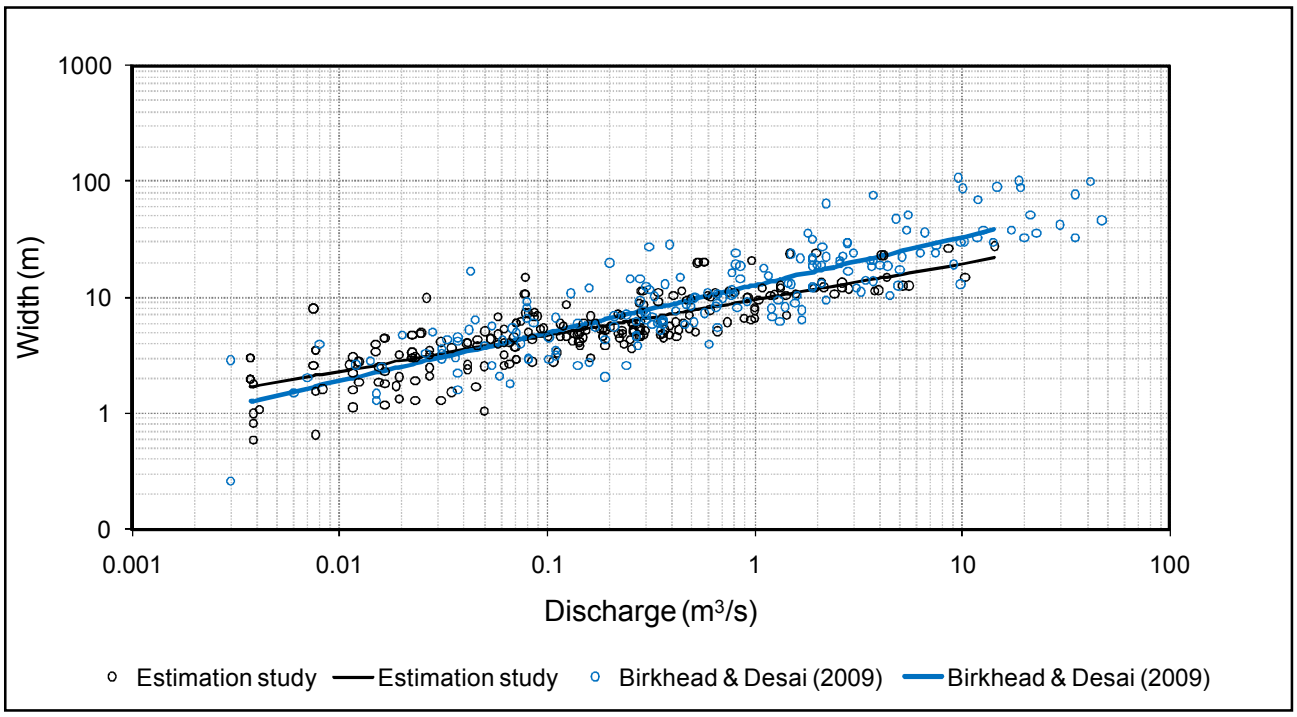

Figure 6.9 Data and relationships between wetted channel width and discharge for sites used in this study (i.e. modelled) and from the hydraulic data base of Birkhead and Desai (2009)

7 APPLICATIONOF ESTIMATION TO HYDRONODES

A procedure for applying the EWR estimation method (described in Chapter 7) as a Desktop Adjustment Method (DAM - refer to Birkhead, 2008) was develop using MS-Excel and VBA. The procedure consists of the following steps:

- Compile a data base of the following information for the hydronodes where EWR estimates are required:
  - Hydronode number.
  - Quaternary number.
  - River name.
  - Locality comment.
  - Mean annual runoff.
  - Hydrology region (a Desktop Reserve parameter).
- Select from a drop-down menu for each hydronode:
  - The EWR estimation method. These include -
    - 'Extrap.', i.e. where the flow requirement will be directly extrapolated from the EWR site results using the Reserve Desktop Model (this method should, however, only be used where the two sites are ecologically similar - refer to Kleynhans *et al*. (2008) and Chapter 5 of this document).
    - 'DAM', i.e. apply the Desktop Adjustment Method described in this report.
    - 'Def. Desk', i.e. apply the default Reserve Desktop Model (no adjustments).
    - 'Fit Desk', i.e. fit the Reserve Desktop Model to the results of a flow assessment method (e.g. FFHA in this context).
    - 'Yield model', i.e. allow the yield model to derive flow requirements based on EWRs at hydronodes in close proximity (uses flow continuity).
- Enter the presence of fish indicator guilds. For the purposes of this study, these are limited to SR, LR, SSR and LSR. From a drop-down menu, model application computes (if selected, as this may also be entered manually) the relevant fish indicator fish guild, i.e. the guild with the highest flow requirements applicable to hydrological season (i.e. wet or dry) and the two exceedence points on the FDT (i.e. maintenance or drought). For medium-sized semi-rheophilics, large semi-rheophilics are assumed (since insufficient data exists for the former guild).
- For indicator macroinvertebrate taxa only FDCD are used, and if appropriate to the local morphology - otherwise macroinvertebrates should be excluded and only fish indicator guilds used.
- Enter the natural (modelled) discharge, as well as the default Desktop Reserve Model flow requirements. The natural flows (maintenance and drought, wet and dry seasons) were derived from appropriate exceedence values on the natural FDTs (EWR rule tables). These exceedences were determined by assessing the positions (of maintenance and drought default Reserve Desktop estimate values) on the corresponding EWR rule tables (i.e. 'Reserve flows without high flows').
- Execute (run) the DAM estimation procedure (VBA Macro), which computes:
  - Wetted channel width;
  - For indicator fish guilds and macroinvertebrate taxa, the relative (to natural) EWR estimate;
  - The maximum (of the fish and macroinvertebrate) DAM estimate;
  - The maximum of the DAM and default Reserve Desktop Model estimates (i.e. the DAM requirement is not permitted to be less than the default Reserve Desktop

Model value, since the upper ranges of the fitted relationships in Figure 6.1 to Figure 6.8 were not determined with sufficient certainty).

- Finally, default Reserve Desktop Model parameters (maintenance and drought distributions and scaling factors) are adjusted (and recorded) to achieve the closest agreement with the DAM EWR estimates, and the standard EWR .rul and EWR .tab tables text files are saved for the ensuing yield modelling.

This procedure was used to provide EWR estimates for 61 hydronodes in the Upper Vaal WMA. The above spreadsheet and data are provided in the electronic data (DWA, 2010) as well as the .rul and .tab tables.

As explained previously and in Chapter 6, the EWR estimates were supplied using basically either an extrapolated or estimated approach. The extrapolation approach is undertaken in two different ways as follows:

- Where the flow requirement will be directly extrapolated from EWR site results using the Reserve Desktop Model (indicated as 'extrapolate' in Table 7.1).
- Allowing the yield model to derive flow requirements based on EWRs at hydronodes which will/can be overridden by the comprehensive EWR requirements. This will typically be a site upstream of an EWR site or between two EWR sites. (indicated as 'yield model' in Table 7.1)

All the EWR rules for the extrapolated and estimated approach are provided electronically.

The hydronodes and method used to determine the EWRs are provided in the tables and figures below.

Table 7.1 Estimation methods followed at the Vaal hydronodes

Hydronode	Quat	River	Method
UV Uklip	C13C	Klip	Estimate
UV9	C11E	Skulpspruit	Estimate
UV17	C11G	Drinkwaterspruit	Estimate
UV25	C81L	Meul	Estimate
UV Cor	C82A	Cornelius	Estimate
UV28	C81M	Meul	Estimate
UV31	C82G	Holspruit	Estimate
UV WV	C12G	Waterval	Estimate
UV35	C82F	Grootspruit	Estimate
UV36	C82F	Grootspruit	Estimate
UV45	C83K	Kromspruit	Estimate
UV53	C23B	Kromelmboogspruit	Estimate
C1VAAL-KVAAL	C11B	Vaal	Yield model
C1VAAL-BRAKS	C11M	Vaal	Yield model
C1VAAL-VILLI	C12L	Vaal	extrapolate from EWR 3
8VF3	C11M	Brakspruit	Estimate
8VF5	C11A		Estimate
C1BLES-UNSPE	C11H	Blesbokspruit	Estimate
C1KLIP-UNSPE (8KF2)	C13F	Klip (Grootdraai)	Estimate
C1KLIP-UNSPE (8KF1)	C13D	Klip (Grootdraai)	Estimate
C1LEEU-NDLEE	C11L	Leeuspruit	Estimate
C1RIET-AMERS	C11E	Rietspruit	Estimate
C1SAND-UNSPE	C13B	Sandspruit	Estimate
C1WATE-EWR01	C12F	Waterval	Existing EWR results
C1WATE-EWR02	C12F	Waterval	Existing EWR results
C8KLIP-VAALD	C83L	Klip (flows into Vaal Dam from FS)	Estimate
8WF1	C81B	Wilge	Estimate

Hydronode	Quat	River	Method
8WF3	C81B	Wilge	Estimate
8EF1	C81F	Elands	Estimate
8EF2	C81F	Elands	Estimate
8EF3	C81F	Elands	Estimate
8EF4	C81H	Elands	Estimate
8EF6	C81H	Elands	Estimate
C8NUWE-CONFL	C81E	Nuwejaarspruit	Estimate
8NF2	C81D	Nuwejaarspruit	Estimate
C8MEUL-UNSPE	C81L	Meul	Estimate
8MF1	C81M	Meul	Estimate
8MF2	C81M	Meul	Estimate
8CF1	C82B	Cornelisspruit	Estimate
C23F	C23F	Mooi River	Estimate
C22G	C22G	Taaibosspruit	Estimate
C23A	C23A	Kromelmboogspruit	Estimate
C21A	C21A	Suikerbosrand	Estimate
C21B	C21B	Suikerbosrand	Extrapolate from EWR 9
C12K	C12K	Molspruit	Estimate
C82E	C82E	Holspruit	Estimate
C82D	C82D	Rus-se-spruit	Estimate
C83E	C83E	Tierkloof	Estimate
C83D	C83D	Tierkloof	Estimate
C81J	C81J	Vaalbankspruit	Estimate
C81G	C81G	Klerkspruit	Estimate
C81C	C81C	Fraser/Modder	Estimate
C13C	C13C	Klip	Estimate
C82A	C82A	Cornelis	Estimate
C13E	C13E	Komandospruit	Estimate
C13G	C13G	Spruitsonderdrif	Estimate
C13H	C13H	Klip	Estimate
C12A	C12A	Skulpspruit	Estimate
C12J	C12J	??	Estimate
C13A	C13A	Sandspruit	Estimate

8 REFERENCES

Birkhead, A.L. 2008. Chapter 3 in: Principles of a process to Estimate and/or extrapolated environmental flow requirements. Water Research Commission report no. KV 210/08, Pretoria, South Africa.

Birkhead, A.L. 2010. The role of Ecohydraulics in the South African Ecological Reserve. In: Ecohydraulics for South African Rivers, James, C.S. and King, J.M. (eds), Water Research Commission report no. TT K5/1767/1, Pretoria, South Africa.

Birkhead A.L. and Desai, A.Y. 2009. Collation and synthesis of hydraulic information collected over the past decade in southern Africa to inform Environmental Flow Requirements. Water Research Project K8/795.

Dallas, H.F. 2005. Inventory of National River Health Programme Monitoring sites volume 1. The Freshwater Consulting Group/Freshwater Research Unit, University of Cape Town Prepared for: Environmentek (CSIR) and Resource Quality Services, Department of Water Affairs and Forestry

Department of Water Affairs and Forestry (DWAF), 2008. Resource Directed Measures: Comprehensive Reserve determination study of the Integrated Vaal River System. Upper Vaal Water Management Area Technical Component: Desktop EcoClassification report. Report produced by Koekemoer Aquatic Services and Water for Africa. Authored by Louw, D. Report no: RDM/WMA8C000/01/CON/0207.

Department of Water Affairs (DWAF), 2010. Resource Directed Measures: Comprehensive Reserve determination study of the Integrated Vaal River System. Upper Vaal Water Management Area Technical Component: Electronic Information. Compiled by Koekemoer Aquatic Services and Water for Africa. Report no: RDM/WMA8C000/01/CON/0710.

Hughes, D.A. and Münster, F. 2000. Hydrological information and techniques to support the determination of the water quantity component of the Ecological Reserve for rivers. Report No. TT 137/00. Water Research Commission, Pretoria.

Hughes, D.A. & Hannart, P. 2003. A desktop model used to provide an initial Estimate of the ecological instream flow requirements of rivers in South Africa. *Journ. Hydrol.* **270**(3-4), 167-181.

Kleynhans, C.J., Louw, M.D. 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. TT328/08.

Kleynhans, C.J., Louw, M.D., Moolman, J. 2007a. Reference frequency of occurrence of fish species in South Africa. Report produced for the Department of Water Affairs and Forestry (Resource Quality Services) and the Water Research Commission. Report TT 331-08.

Kleynhans, C.J., 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, C.J., Birkhead, A.L., and Louw, M.D. 2008. Principles of a process to Estimate and/or extrapolated environmental flow requirements. Water Research Commission report no. KV 210/08, Pretoria, South Africa.

Rountree, K.M. and Wadeson, R.A. 1999. A Hierarchical Geomorphological Model for the Classification of Selected South African Rivers, WRC Report No. 497/1/99, WRC, Pretoria.

Shreve, R.L. 1967. 'Infinite topologically random channel networks', J. of Geology, 75, 178-86.

Strahler, A.N. 1952. Hypsometric (area-altitude) analysis of erosional topography. Bulletin Geological Society of America. 63: 1117-1142

Strahler, A.N. 1957. "Quantitative analysis of watershed geomorphology", Transactions of the American Geophysical Union 8 (6): 913–920.