PRINCIPLES OF A PROCESS TO ESTIMATE AND/OR EXTRAPOLATE ENVIRONMENTAL FLOW REQUIREMENTS

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EXECUTIVE SUMMARY

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 hydro-nodes) 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.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

AL BIRKHEAD
Streamflow Solutions

1.1 BACKGROUND

The Department of Water Affairs and Forestry (DWAF) has announced its Water Allocation Reform (WAR) programme (refer to http://www.dwaf.gov.za/WAR) 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. In water-stressed catchments (those with high demand relative to availability), this process will lead to Compulsory Licensing, which may, in turn, result in re-allocation of water entitlements. Water availability and future planning is addressed using water resource yield modelling that accounts for natural spatial and temporal (time-dependant) water distributions, anthropogenic demands on the resource and projected changes in these over time, as well as future operational approaches. This also requires full recognition of the Ecological Reserve, and estimates of Ecological Water Requirements (EWRs) are therefore required at numerous positions within catchments for water resource planning.

Ecological Reserve (quantity) determinations at the Comprehensive and Intermediate levels have generally been determined using sites located along main-stem rivers and major tributaries within catchments, where water resources are often in high demand. Frequently, no EWR information is available for the smaller tributaries in catchments, and these have generally been addressed through lower confidence assessments, including (in order of reducing confidence), Rapid III; hydrological extrapolation of main-stem or major tributary results; and desktop estimates using the Reserve Desktop model. The establishment of sites to provide EWRs at all locations of interest necessary for water resource planning is, however, not pragmatic and beyond the means of 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 has been identified as urgent by both the National Water Resources Planning (NWRP) and Resources Directed Measures (RDM) Directorates of the DWAF to support their WAR initiative, as well as to better evaluate individual water use licence applications.

1.2 PROJECT OBJECTIVES

The original objective of this project was to develop a procedure for extrapolating EWR results (primarily low-flow) from Comprehensive and Intermediate Reserve sites to additional locations (termed hydro-nodes) that have a degree of ecologically similarity. The extrapolation process refers to hydrological extrapolation through the adjustment of default parameters in the Desktop Reserve model. This, and default Desktop model estimates are the current approach for estimating EWRs for additional river locations required for water resource planning. 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 (in excess of approximately 30 Mm^3/a). The model has become the most cost-effective method for estimating ecological flows in South Africa and other countries, and is increasingly used to predict EWRs for rivers with runoff below approximately 30 Mm^3/a. With the exception of Rapid level III EWR estimates, little cognisance is given as to whether hydrological extrapolation of "larger" river results or direct application of the Desktop model, particularly for rivers with "low" runoff, is ecologically justified. This original project objective is addressed in Chapter 2 of this report, which discusses an approach for assessing physical site similarity and predicting fish EWR indicator species. Using this, the ecological justification for extrapolating EWRs can be assessed, and fish indicator species at additional (un-sampled river sites) may be predicted. A procedure for predicting invertebrate indicator taxa is not as developed (as for the fish), with a brief description of the method provided in the Appendix.

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 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.

The principles for developing, testing and applying such an estimation model are described in Chapter 3 of this report. A step-wise approach is followed, that considers the feasibility of the related components. These include the identification of collective "groups" of biota that exploit the same class of environmental resources in a similar way; for such a group, the definition of habitat-specifications (i.e. a consistent set of numerical "rules" for quantifying hydraulic habitat); and the prediction of available hydraulic habitat at a river site in the absence of field data. The latter component requires substantial development, and is being addressed by concurrent projects funded by the Water Research Commission. In this project, habitat-specifications have been defined using EWR results and an optimisation procedure for small rheophilic and large semi-rheophilic fish guilds and cobble-dwelling rheophilic invertebrate communities. Habitat-specifications have been related directly to EWRs as a function of low-flow channel width. Rapid level III field data and hydraulic modelling for ten sites in the Nkomati River catchment has used, with naturalised runoff varying between 4 and 28 Mm^3/a.

The Nkomati Water Availability Assessment Study (WAAS), initiated in 2006 (and co-funder of this study), requires estimates of the Ecological Reserve for approximately 70 hydro-nodes. This catchment is therefore the basis for application of methods developed within this project. Ecological Water Requirements from a recent Comprehensive Reserve study are available for five sites (in South Africa), with natural runoff for main-stem sites varying from 161 to 567 Mm^3/a, and two major tributary sites in excess of 33 Mm^3/a. Comparatively, 24 of the hydro-nodes are located on substantially smaller rivers, with naturalised runoff below 30 Mm^3/a. A procedure has been developed for predicting the EWRs for the Nkomati catchment hydro-nodes, using a combination of hydrological extrapolation of Reserve results, the estimation method developed within this study, and default Desktop model estimates. The method selected depends on an assessment of ecological similarity, prediction of the biota present, and river size as provided using runoff.

2 DEVELOPING AN APPROACH FOR ASSESSING SITE SIMILARITY AND PREDICTING FISH INDICATOR SPECIES

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2.1 INTRODUCTION

The objective of this component of the study was to determine the physical similarity between different localities within a river system. Based on this, the contention is that localities with similar physical attributes will tend to have similar fish species or guilds under natural reference conditions. This will allow the likely presence of fish species which are useful indicators of flow requirements, to be predicted. Therefore, only indicator species are selected and not all species comprising the fish assemblage.

This purpose of this investigation is to provide:

- Guidelines to derive the physical similarity between sites.
- Guidelines on how to use available fish information from sampled sites to derive fish species potentially present at a site. This concentrated on indicator species, useful for determining ecological flow requirements.
- Guidelines on the velocity-depth preference and no-flow intolerance categorisation of indicator species.

The following assumptions apply:

- Flow requirements at EWR sites (for fish) may be assessed using indicator species.
- If EWR sites have a high degree of physical similarity to other sampled sites, and the fish species between these sites are similar, the flow requirements at the EWR site may be extrapolated to the similar sites requiring EWR determination (this relates to the “extrapolation” component of this study).
- If there is a high physical similarity between sampled sites (based on species present) and unsampled sites, the indicator species at unsampled sites can be predicted (this relates to the “estimation” component of this study).

2.2 TERMINOLOGY

The following terminology is used for the naming of sites:

- If a site has been sampled, the site name refers to the original name of the site as it is indicated in Kleynhans *et al.* (2007) and in the River Health Programme (RHP) Rivers Database (2007: available from DWAF, Resource Quality Services). This includes RHP names (e.g. X1GLAD-UNSPE) and EWR sites. River Health Programme sites are all named according to the first letter of the Water Management Area (WMA), followed by the sub-catchment number (e.g. X1 in above example).
- EWR site names are referred to as EWR, followed by a number or name (e.g. K1 for Nkomati EWR 1).
- Other sites where fish surveys have been undertaken, including historical and present day information, are named according to the names in the Reference Fish Frequency of Occurrence database (Kleynhans *et al.*, 2007). These sites are named according to the WMA number (5 for the Inkomati), the first letter of the WMA name (I for Inkomati), followed by "F" for fish and a number denoting the consecutive site number in the WMA (i.e. 5IF210).
- In Table 2.1 all sites are listed in rows of the first column, as well as where they correspond to rows in columns denoting their primary data-collection purpose (e.g. EWR, RHP, etc.).
- Hydrological nodes (river locations requiring EWRs for the Nkomati WAAS) are named according to their quaternary, followed by consecutive numbering for the number of nodes in the quaternary.

2.3 DETERMINING SITE SIMILARITY USING PHYSICAL PARAMETERS

2.3.1 Data collation

This involves collating data for all available sites, as has been undertaken for the Nkomati catchment in Table 2.1. The sites include 68 hydrological nodes, RHP and six EWR sites. The available sites also incorporate other sampled locations, including within this study, 10 sites sampled in May 2007 (indicated with the prefix "E"). For each of the sites, the following environmental attributes are determined:

- <u>Level 1 EcoRegions</u>, as delineated by Kleynhans *et al*. (2005). EcoRegions are identified based on similarity of determinants such as climate, geomorphology, geology and natural vegetation. The individual attributes that determine the characteristics of a riverine EcoRegion were not considered separately in this study (Level 1 Ecoregion numbers and their descriptive names are: 3 - Lowveld; 4 - North Eastern Highlands; 10 - Northern Escarpment Mountains; 11 - Highveld; 12 - Lebombo Uplands).
- <u>Altitude</u> is largely considered as a surrogate for water temperature (<u>www.newton.dep.anl.gov/askasci/env99/env029.htm</u>; accessed Feb 2007). Temperature is also an important variable in determining the oxygen concentration of water (DWAF, 1996). Altitude at the hydrological nodes and sites vary from 115 to 1608 m.

Table 2.1 Site information for the surveyed sites and hydro-nodes in the Nkomati River catchment

Site Name	Hydrological node	EWR Site	RHP Site	Sampled Site	Quaternary	Streamorder	Latitude	Longitude	Tributary name	EcoRegion	Geomorphological zone	Altitude (m ASML)
5IF210				5IF210	X13L	1	-25.5000	31.8000	Nkomati	3	E	234
5IF222	X14F-1				X14F	1	-25.6213	31.4982	Mhlambanyat	3	D	493
5IF24				5IF24	X11D	1	-25.8432	30.0533	Klein Nkomati	11	D	1716
5IF245				5IF245	X13K	1	-25.6984	31.8337	Mambane	3	E	259
5IF248				5IF248	X11F	1	-25.7295	30.3443	Bankspruit	10	D	1850
5IF263				5IF263	X14A	1	-25.8363	31.1521	Lomati	4	C	1174
5IF270				5IF270	X11E	3	-25.8927	30.2350	Nkomati	10	E	1584
5IF277				5IF277	X12J	1	-25.9167	30.9500	Mtsoli	10	D	1212
5IF279	X11E-1			5IF279	X11E	1	-25.9369	30.2350	Swartspruit	10	D	1446
5IF28				5IF28	X11E	1	-25.9620	30.2149	Swartspruit	11	D	1564
5IF310				5IF310	X12K	1	-26.1166	30.9833	Mlondozi	10	D	974
5IF52	X11E-2			5IF52	X12E	1	-26.1511	30.5263	Theespruit	11	D	1385
5IF8				5IF8	X12A	1	-26.1225	30.2309	Buffelsspruit	11	D	1794
E-BANKSP	E-BANKSPRUIT			E-BANKSPR	X12F	1	-25.8469	30.3506	Bankspruit	10	C	1545
E-MLOND	E-MLONDOZI			E-MLONDOZI	X12K	1	-26.0472	31.0442	Mlondozi	10	D	1098
E-X11A1	X11A-1			E-X11A1	X11A	2	-26.0069	30.0266	Vaalrivierspruit	10	E	1531
E-X11K4	E-X11K4			E-X11K4	X12G	3	-25.9531	30.7249	Nkomati	10	E	1144
E-X12B1	E-X12B1			E-X12B1	X12A	1	-26.0628	30.3939	Buffelspruit	11	D	1562
E-X12D1	E-X12D1			E-X12D1	X11D	1	-25.8881	30.1203	Klein Nkomati	10	D	1640
E-X12G1	E-X12G1			E-X12G1	X12G	1	-25.9652	30.8216	Mawelawala	10	D	1144
E-X12G2	E-X12G2			E-X12G2	X12G	1	-25.9678	30.8333	Bergstroom	10	C	1200
E-X12H2	E-X12H2			E-X12H2	X12H	2	-26.0497	30.8972	Sandspruit	10	D	800
E-X12K1	E-X12K1			E-X12K1	X12K	1	-26.0453	31.0503	Phalangampe	10	C	1098
JE7	X13D-1			JE7	X13D	1	-26.0980	31.3986	Nkomati	3	E	393
X11B-2	X11B-2				X11B	3	-25.9470	30.0847	Nkomati	10	D	1504
X11C-1	X11C-1				X11C	1	-25.9501	30.0351	Witkloofspruit	10	E	1528
X11D-1	X11D-1				X11D	1	-25.9017	30.1692	Klein Nkomati	10	E	1471
X11D-2	X11D-2				X11D	3	-25.9017	30.1722	Nkomati	10	E	1470
X11D-3	X11D-3				X11D	3	-25.8842	30.2097	Nkomati	10	E	1460
X11G-1	X11G-1				X11G	3	-25.8394	30.4867	Nkomati	10	E	1159
X11G-2	X11G-2				X11G	1	-25.9456	30.3952	Bergstroom	10	C	1548
X11H-1	X11H-1				X11H	3	-25.8821	30.6200	Nkomati	10	E	1037
X11J-1	X11J-1				X11J	1	-25.8383	30.6742	Gladdespruit	10	D	1075
X11K-1	X11K-1				X11K	2	-25.8373	30.6877	Gladdespruit	10	D	1053
X11K-2	X11K-2				X11K	2	-25.9133	30.6542	Gladdespruit	10	E	978
X11K-3	X11K-3				X11K	3	-25.9147	30.6472	Nkomati	10	D	979
X11K-4	X11K-4				X11K	3	-25.9480	30.6853	Nkomati	10	E	934
X12A-1	X12A-1				X12A	2	-26.0164	30.4142	Buffelspruit	10	D	1306
X12C-1	X12C-1				X12C	1	-25.9742	30.4856	Phaphenyane	10	D	1213
X12D-2	X12D-2				X12D	2	-25.9525	30.6828	Seekoeispruit	10	E	936
X12F-1	X12F-1				X12F	1	-26.0589	30.6617	Mlingase	10	D	1140
X12F-2	X12F-2				X12F	1	-26.0185	30.8104	Nthazathshe	10	D	900
X12F-3	X12F-3				X12F	3	-26.0111	30.8614	Theespruit	10	E	874
X12G-1	X12G-1				X12G	3	-25.9722	30.8192	Mawelawala	10	E	852
X12G-2	X12G-2				X12G	3	-25.9753	30.8356	No Name	10	E	855
X12G-3	X12G-3				X12G	3	-26.0067	30.8567	Nkomati	10	E	831
X12H-1	X12H-1				X12H	3	-26.01	30.9414	Nkomati	10	E	782
X12H-2	X12H-2				X12H	2	-26.0322	30.9256	Sandspruit	10	D	791
X12J-1	X12J-1				X12J	1	-25.9792	31.0447	Mtsoli	10	D	806
X12J-2	X12J-2				X12J	1	-25.9786	31.0461	Manzimpaya	10	D	797
X12J-3	X12J-3				X12J	1	-26.0108	31.0792	Mtsoli	10	D	723
X12K-1	X12K-1				X12K	1	-26.0439	31.0494	Phalangampe	10	C	729

Site Name	Hydrological node	EWR Site	RHP Site	Sampled Site	Quaternary	Streamorder	Latitude	Longitude	Tributary name	EcoRegion	Geomorphological zone	Altitude (m ASML)
X12K-2	X12K-2				X12K	3	-26.0347	31.0892	Nkomati	4	E	733
X13A-1	X13A-1				X13A	3	-26.0614	31.1800	Nkomati	4	D	629
X13B-1	X13B-1				X13B	3	-26.0864	31.2681	Nkomati	4	D	599
X13B-2	X13B-2				X13B	3	-26.0846	31.3034	Nkomati	3	D	524
X13C-1	X13C-1				X13C	1	-26.0869	31.2985	Mkomazane	3	B	495
X13E-1	X13E-1				X13E	3	-26.0750	31.5350	Nkomati	3	E	311
X13F-1	X13F-1				X13F	1	-26.0519	31.5567	Mzimnene	3	E	318
X13F-2	X13F-2				X13F	3	-26.0533	31.5633	Nkomati	3	E	307
X13G-1	X13G-1				X13G	3	-26.0097	31.5944	Nkomati	3	E	310
X13G-2	X13G-2				X13G	2	-25.9303	31.6133	Mphofu	3	F	297
X13G-3	X13G-3				X13G	3	-25.9328	31.6153	Nkomati	3	F	277
X13H-1	X13H-1				X13H	1	-25.9639	31.7386	Sand	3	E	271
X13H-2	X13H-2				X13H	3	-25.9294	31.7600	Nkomati	3	F	262
X13J-2	X13J-2				X13J	1	-25.6839	31.7769	Mzinti	3	E	215
X13J-3	X13J-3				X13J	3	-25.6850	31.7789	Nkomati	3	E	213
X13J-4	X13J-4				X13J	3	-25.6378	31.7889	Nkomati	3	E	197
X13K-1	X13K-1				X13K	1	-25.5283	31.9553	Ngwenyeni	12	E	149
X13K-2	X13K-2				X13K	4	-25.5278	31.9550	Nkomati	12	E	146
X13L-1	X13L-1				X13L	1	-25.4469	31.9083	Ngweti	3	E	155
X13L-2	X13L-2				X13L	4	-25.4383	31.9744	Nkomati	12	E	115
X14A-1	X14A-1				X14A	1	-25.8539	31.1811	Mlumati	10	D	779
X14B1	X14B1				X14B	~1	-25.7568	31.2549	Igitigili	4	D	1006
X14B-2	X14B-2				X14B	2	-25.8236	31.2983	Mlumati	3	D	516
X14C-1	X14C-1				X14C	1	-25.8317	31.3686	Phophonyane	3	E	442
X14D-1	X14D-1				X14D	2	-25.8308	31.3747	Mlumati	3	E	435
X14D-2	X14D-2				X14D	3	-25.7811	31.3942	Mlumati	3	E	403
X14E-1	X14E-1				X14E	3	-25.7619	31.4892	Mlumati	3	E	328
X14G-1	X14G-1				X14G	3	-25.6683	31.5533	Mlumati	3	E	286
X14G-2	X14G-2				X14G	3	-25.7114	31.5328	Mlumati	3	E	327
X14H-1	X14H-1				X14H	3	-25.6375	31.7881	Mlumati	3	D	197
X1BOES-BOESM	X11B-1		X1BOES-BOESM	X1BOES-BOESM	X11B	2	-26.0233	30.0618	Boesmanspruit	11	E	1608
X1GLAD-UNSPE		G1	X1GLAD-UNSPE	X1GLAD-UNSPE	X11J	1	-25.7708	30.6263	Gladdespruit	10	D	1230
X1KOMA-CROCC			X1KOMA-CROCC	X1KOMA-CROCC	X13L	4	-25.4412	31.9786	Nkomati	12	D	115
X1KOMA-DVYGE	X11F-1	K1	X1KOMA-DVYGE	X1KOMA-DVYGE	X11H	3	-25.8543	30.3766	Nkomati	10	D	1296
X1KOMA-SONGI	X12H-3	K2	X1KOMA-SONGI	X1KOMA-SONGI	X12K	3	-26.0388	31.0031	Nkomati	10	E	745
X1KOMA-TONGA		K3	X1KOMA-TONGA	X1KOMA-TONGA	X13J	3	-25.6669	31.8013	Nkomati	3	D	201
X1KOMA-VAALW			X1KOMA-VAALW	X1KOMA-VAALW	X11A	2	-26.0341	29.9293	Nkomati	11	E	1598
X1LOMA-DDRIE		L1	X1LOMA-DDRIE	X1LOMA-DDRIE	X14H	3	-25.6494	31.6231	Mlumati	3	E	254
X1SEEK-SEEKO			X1SEEK-SEEKO	X1SEEK-SEEKO	X12C	2	-25.9482	30.5610	Seekoeispruit	10	D	1090
X1TEES-CONFL		T1	X1TEES-CONFL	X1TEES-CONFL	X12F	1	-26.0193	30.8520	Theespruit	10	D	847
X2KOMA-UVYGE			X2KOMA-UVYGE	X2KOMA-UVYGE	X11H	3	-25.8486	30.5647	Nkomati	10	D	1114

- Strahler stream order (Strahler, 1952) was obtained from the 1:500,000 scale digital dataset of South African River (Silberbauer, 2006). On this scale, stream orders 1 to 4 can be distinguished. Where a stream does not appear on the 1:500,000 scale map, its stream order was considered to be approximately 1 (indicated as ~1). Stream order was used as the only indicator of stream size. Alternative approaches are discussed in Section 2.4. Stream order was the only indicator of stream size readily available at the time of this analysis.
- Mean annual runoff (MAR) at the hydrological nodes were initially used but due to inaccuracies was removed at the analysis stage. This would have been a useful indicator of stream size (refer to Section 2.4).
- Longitudinal geomorphic zone (Rowntree and Wadeson, 1999). The identification of the geomorphic zone (slope) by Moolman *et al.* (2002) was used, and zones in the Nkomati river are provided in Table 2.2.
- Hydrological seasonality. All sites were considered perennial and this attribute was therefore not used as a criterion.

Table 2.2 Longitudinal zones in the Nkomati River (adapted from Rowntree and Wadeson, 1999).

Longitudinal zone	Characteristic channel features	
	Zone class	Description
Mountain stream	B	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	Moderately steep stream dominated by bedrock or boulder. Reach types include plain-bed, pool-rapid or pool riffle. Confined or semi-confined valley floor with limited flood plain development.
Upper Foothills	D	Moderately steep, cobble-bed or mixed bedrock-cobble bed channel, with plain-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	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	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.

2.3.2 Data analysis and interpretation

Similarity was interpreted on the basis of the number of environmental attributes that nodes and other localities have in common. The Bray Curtis analysis of similarity was used to determine the similarity between sites using the freeware statistical software, PAST (Hammer *et al.*, 2001). For the purpose of this study, Bray-Curtis similarity was categorized according to the following scale: 0.9 to 1.0 = very high similarity; 0.8 to 0.9 = high similarity; 0.6 to 0.8 = moderate similarity; 0.4 to 0.6 = low similarity; 0.2 to 0.4=very low similarity, and 0.0 to 0.2 = no similarity.

The premise is that the higher the similarity between localities, the higher the confidence that such localities are likely to have similar fish assemblages. Since broad environmental attributes have been used, only sites with “very high” similarity were selected for further consideration. The results of the analysis are given in Table 2.3.

With reference to the main objective of this study, i.e. extrapolation and estimation of EWRs for hydro-nodes, the following applies:

- If stream size is similar and if the flow indicator species are the same or similar in terms of size and flow preferences, the EWRs for these sites will be comparable and may be scaled hydrologically (i.e. hydrological extrapolation);
- For sites with different river size (i.e. runoff) but flow indicator species that are the same or similar in terms of size and flow preferences, the flow requirements need to be interpreted in terms of fundamental hydraulic parameters (velocity, depth and width) - i.e. estimation based on biotic presence, flow preferences and habitat availability. This also applies for sites with indicator species with different flow preferences and/or size.

Table 2.3 Results of Bray Curtis similarity between hydrological nodes and sampled river sites.

Hydrological nodes	5IF210	5IF222 (HN X14F-1)	5IF24	5IF245	5IF248	5IF263	5IF270	5IF277	5IF279	5IF28 (HN X11E-1)	5IF310	5IF52 (HN X11E-2)	5IF8	E-BANKSPRUIT (HN)	E-MLONDOZI (HN)	E-X11A1	E-X11K4	E-X12B1	E-X12D1	E-X12G1	E-X12G2	E-X12H2	E-X12K1	JE7 (HN X13D-1)	X1BOES-BOESM (HN X11B-1)	X1GLAD-UNSPE (EWR G1)	X1KOMA-CROCC	X1KOMA-DVYGE(HN X11F-1, EWR K1)	X1KOMA-SONGI (HN HN X12H-3, EWR K2)	X1KOMA-TONGA (EWR K3)	X1KOMA-VAALW	X1LOMA-DDRIE (EWR L1)	X1SEEK-SEEKO	X1TEES-CONFL (EWR T1)	X2KOMA-UVYGE
X11B-2			+				+		+	+		+	+	+		+		+	+						+	+		+			+				
X11C-1			+		+		+		+	+		+	+	+		+		+	+						+			+			+				
X11D-1			+				+	+	+	+		+	+	+		+		+	+						+	+		+			+				
X11D-2			+				+	+	+	+		+	+	+		+		+	+						+	+		+			+				
X11D-3			+				+	+	+	+		+		+		+		+	+		+				+	+		+			+				
X11G-1						+		+			+	+			+		+			+	+		+			+		+					+		+
X11G-2			+		+		+		+	+		+	+	+		+		+	+						+			+			+				
X11H-1						+		+			+				+		+			+	+		+			+							+		+
X11J-1						+		+			+				+		+			+	+		+			+		+					+		+
X11K-1						+		+			+				+		+			+	+		+			+							+		+
X11K-2						+					+				+		+			+		+	+										+	+	+
X11K-3						+					+				+		+			+		+	+										+	+	+
X11K-4											+				+		+					+	+										+	+	+
X12A-1						+	+	+	+	+		+		+	+	+	+	+		+	+		+			+		+			+		+		+
X12C-1						+		+	+			+			+		+			+	+		+			+		+					+		+

Hydrological nodes	5IF210	5IF222 (HN X14F-1)	5IF24	5IF245	5IF248	5IF263	5IF270	5IF277	5IF279	5IF28 (HN X11E-1)	5IF310	5IF52 (HN X11E-2)	5IF8	E-BANKSPRUIT (HN)	E-MLONDOZI (HN)	E-X11A1	E-X11K4	E-X12B1	E-X12D1	E-X12G1	E-X12G2	E-X12H2	E-X12K1	JE7 (HN X13D-1)	X1BOES-BOESM (HN X11B-1)	X1GLAD-UNSPE (EWR G1)	X1KOMA-CROCC	X1KOMA-DVYGE(HN X11F-1, EWR K1)	X1KOMA-SONGI (HN HN X12H-3, EWR K2)	X1KOMA-TONGA (EWR K3)	X1KOMA-VAALW	X1LOMA-DDRIE (EWR L1)	X1SEEK-SEEKO	X1TEES-CONFL (EWR T1)	X2KOMA-UVYGE
X12D-2											+				+		+			+		+	+										+	+	+
X12F-1						+		+			+	+			+		+			+	+		+			+		+					+		+
X12F-2											+				+							+	+						+				+	+	
X12F-3											+											+							+					+	
X12G-1											+											+							+					+	
X12G-2											+											+							+					+	
X12G-3											+											+							+					+	
X12H-1																						+							+					+	
X12H-2																						+							+					+	
X12J-1											+											+							+					+	
X12J-2											+											+							+					+	
X12J-3																						+							+					+	
X12K-1																						+							+					+	
X12K-2																						+							+					+	
X13A-1																													+						
X13B-1		+																																	
X13B-2		+																																	
X13C-1		+																																	
X13E-1				+																												+			
X13F-1				+																															
X13F-2				+																												+			
X13G-1				+																												+			
X13G-2				+																												+			
X13G-3	+			+																												+			
X13H-1	+			+																												+			
X13H-2	+			+																												+			
X13J-2	+			+																										+		+			
X13J-3	+			+																										+		+			
X13J-4	+																													+					
X13K-1																																			
X13K-2																																			
X13L-1																																			
X13L-2																											+								
X14A-1																						+							+					+	
X14B1						+		+			+				+		+			+	+		+										+	+	+
X14B-2		+																																	
X14C-1		+																						+											
X14D-1		+																						+											
X14D-2																								+											
X14E-1																								+											
X14G-1	+			+																												+			
X14G-2																								+											
X14H-1	+																													+					

+ indicates Bray Curtis similarity > 0.8999* ("very high")

Hydrological nodes not displaying "very high" similarity to sampled river sites are shaded

2.4 PREDICTING INDICATOR SPECIES BASED ON PHYSICAL SIMILARITY

2.4.1 Selecting indicator species at sampled river sites

Information on fish species present at sampled sites was obtained from Kleynhans *et al.*, 2007. The fish assemblage at a site or hydro-node needs to be assessed in terms of the presence of species that can be used as indicators of EWRs. The following characteristics were considered in the selection of such indicator species:

- Rheophilics: requiring flowing water during all phases of the life-cycle. These include fast-rheophilics (requiring fast flow (>0.3 m/s) during most phases of the life cycle and slow-rheophilics (requiring slow (<0.3 m/s) during most phases of the life-cycle.
- Semi-rheophilics: requiring flowing water during certain phases of the life-cycle.

These include fast-semi-rheophilics (requiring fast flowing water (>0.3 m/s) during certain phases of the life-cycle) and slow-semi-rheophilics (requiring slow flowing water (<0.3 m/s) during certain phases of the life-cycle).

- Limnophilics: no particular flow requirements during any phase of the life. Water level (associate with discharge), may, however, be required to provide particular cover features during certain life-cycle stages.

Only rheophilic and semi-rheophilic species were considered in the current study.

Size (both length and body depth) provides an indication of the dimensions of the habitat necessary when considering velocity and depth hydraulic parameters. It is expected that "larger" species would require "more habitat" and consequently more flow to complete their life-cycle.

For this purpose, length may be considered as follows:

- Small size < 15 cm total body length;
- Intermediate size 15 to 25 cm total body length; and
- Large size > 25 cm total body length.

Body depth should also be taken into account when considering habitat "size":

- Whether it is rheophilic, i.e. requires flowing water during all phases of the life-cycle. Such conditions generally relate to velocity depth classes of fast-shallow and fast-deep. Fast flow refers to velocities > 0.30 m/s and deep to depths > 0.30 m. It was recognised during this study, however, that depths < 0.1 m should be excluded from fast-shallow flow-classes, as these do not provide viable depth habitat.
- Whether it is semi-rheophilic, i.e. requires flowing water during the breeding season. Passage through shallow areas could also be a consideration during the dry season.
- Intolerance of the species is in terms of its dependence on fast flowing water.

The information required to select indicator species were obtained from the Fish Response Assessment Index (Kleynhans, 2007). Table 2.4 indicates the fish species occurring in the Nkomati River that are considered to be sufficiently widely distributed to be used as indicators of flow requirements. The table represents tolerances and preferences which have been rated for each fish species, ranging from 5 (very intolerant) to 0 (very tolerant). The ratings were obtained through the collective knowledge of all fish habitat specialists in South Africa. The information is used to select the most appropriate indicator species. For example, a large species that is very flow intolerant will be an appropriate indicator as it requires flow all year round and deeper flows than a smaller species with similar flow intolerance.

Table 2.4 Fish species present at sampled sites and considered to be sensitive indicators of flow conditions (Kleynhans, 2003).

				Velocity-depth class preference				Flow tolerance				Cover					Physical-chemical intolerance (PC)			
Species	Abbreviation	Max. size (cm)	Est. average size (cm)	Fast-deep (FD)	Fast-shallow (FS)	Slow-deep (SD)	Slow-shallow (SS)	No flow intolerant	Moderately no flow intolerant	Moderately intolerant no flow	Tolerant no flow	Overhanging vegetation	Undercut bank & root wads	Substrate	Instream vegetation	Water column	PC change intolerant	PC change moderately intolerant	PC change moderately tolerant	PC change tolerant
Amphilius uranoscopus (Pfeffer, 1889)	AURA	19.5	<15	4.6	4.6			4.8						5			4.8			
Barbus argenteus Günther, 1868	BARG	19.7	<15	3.7	4.3			4.6						5			4.1			
Barbus brevipinnis Jubb, 1966	BBRI	4.5	4			3.3	4.3	4.1				4.7	4.1				4.1			
Labeobarbus polylepis Boulenger, 19 17	BPOL	58.5	40	3.7	4.3	4.2			3.3					5		3.6			2.9	
Labeobarbus marequensis Smith, 1841	BMAR	47	35	4.1	4.4	4.4	3.4		3.2					4.5		4.1			2.1	
Chiloglanis pretoriae van der Horst, 1931	CPRE	6.5	6	4.3	4.9			4.8						4.9			4.5			
Opsaridium peringueyi (Gilchrist & Thompson, 1913)	OPER	15	10	3.2		3.3		4.9								4.4	4.4			

Preference ratings: 1-2=low; >2-3=moderate; >3-4=high; >4-5=very high

Intolerance ratings: 1-2=tolerant; >2-3=moderately tolerant; >3-4=moderately intolerant; >4-5=intolerant

Velocity-depth classes: FD (>0.3m/s & >0.3m); FS (>0.3m/s & < 0.3m); SD (<0.3m/s & >0.5m); SS (<0.3m/s & <0.5m)

Table 2.5 gives the fish species considered to be sensitive indicators of flow conditions at the sampled sites in the Nkomati River catchment. The indicator species at EWR sites were previously used to assess the ecological flow requirements. The principle is that if the same indicator species is derived to be present at any of the hydro-nodes, and the node is sufficiently similar to the EWR site to allow the EWR results to be hydrologically extrapolated.

Table 2.5 Flow indicator species at sampled sites.

Sampled sites	Indicator species
EWR Sites	
X1GLAD-UNSPE (EWR G1)	AURA
X1KOMA-DVYGE(HN X11F-1, EWR K1)	AURA, BPOL
X1KOMA-SONGI (HN HN X12H-3, EWR K2)	AURA, BPOL
X1KOMA-TONGA (EWR K3)	BMAR, CPRE, OPER
X1LOMA-DDRIE (EWR L1)	BMAR, OPER
X1TEES-CONFL (EWR T1)	AURA, BPOL
Other sites	
5IF210	OPER
5IF222 (HN X14F-1)	BMAR
5IF24	AURA
5IF245	AURA
5IF248	BPOL
5IF263	BBRI
5IF270	AURA, BPOL
5IF277	AURA, BPOL
5IF279	AURA, BPOL
5IF28 (HN X11E-1)	BARG
5IF310	BPOL, CPRE
5IF52 (HN X11E-2)	AURA, BMAR
5IF8	BPOL, CPRE
E-BANKSPRUIT (HN)	AURA
E-MLONDOZI (HN)	BMAR, CPRE
E-X11A1	AURA, BPOL
E-X11K4	BPOL, CPRE
E-X12B1	AURA
E-X12D1	AURA, BPOL
E-X12G1	BMAR, CPRE
E-X12G2	AURA, BMAR
E-X12H2	BPOL, CPRE
E-X12K1	BMAR, CPRE
JE7 (HN X13D-1)	BMAR, CPRE, OPER
X1KOMA-CROCC	BMAR, OPER
X1BOES-BOESM (HN X11B-1)	AURA, BPOL
X2KOMA-UVYGE	AURA, BPOL
X1SEEK-SEEKO	AURA, BPOL
X1KOMA-VAALW	AURA, BPOL

2.4.2 Deriving indicator species at hydro-nodes.

The species derived to be sensitive indicators of flow at hydrological nodes are indicated in Table 2.6. Shaded cells in the table denote nodes that did not have a “very high’ similarity when compared to sampled river sites (i.e. Table 2.5), and indicator species were derived based on expert knowledge.

Table 2.6 Flow indicator species at hydro-nodes.

Hydro-node	Derived indicator species
X11B-2	AURA, BPOL
X11C-1	AURA, BPOL
X11D-1	AURA, BPOL
X11D-2	AURA, BPOL
X11D-3	AURA, BPOL
X11G-1	AURA, BPOL
X11G-2	AURA, BPOL
X11H-1	AURA, BPOL
X11J-1	AURA, BPOL
X11K-1	AURA, BPOL
X11K-2	AURA, BPOL
X11K-3	AURA, BPOL
X11K-4	AURA, BPOL
X12A-1	AURA, BPOL
X12C-1	AURA, BPOL
X12D-2	AURA, BPOL
X12F-1	AURA, BPOL
X12F-2	AURA, BPOL
X12F-3	AURA, BPOL
X12G-1	AURA, BPOL
X12G-2	AURA, BPOL
X12G-3	AURA, BPOL
X12H-1	AURA, BPOL
X12H-2	AURA, BPOL
X12J-1	AURA, BPOL
X12J-2	AURA, BPOL
X12J-3	AURA, BPOL
X12K-1	AURA, BPOL
X12K-2	AURA, BPOL
X13A-1	AURA, BPOL
X13B-1	AURA, BPOL
X13B-2	AURA, BPOL
X13C-1	BMAR
X13E-1	BMAR, OPER
X13F-1	BMAR
X13F-2	BMAR, OPER
X13G-1	BMAR, OPER
X13G-2	BMAR, OPER
X13G-3	BMAR, OPER
X13H-1	BMAR, OPER
X13H-2	BMAR, OPER
X13J-2	BMAR, OPER
X13J-3	BMAR, OPER
X13J-4	BMAR, CPRE, OPER
X13K-1	BMAR
X13K-2	BMAR, AURA
X13L-1	BMAR
X13L-2	BMAR, OPER
X14A-1	AURA, BPOL
X14B1	AURA, BPOL
X14B-2	BMAR
X14C-1	BMAR, CPRE, OPER
X14D-1	BMAR, CPRE, OPER
X14D-2	BMAR, CPRE, OPER
X14E-1	BMAR, CPRE, OPER
X14G-1	BMAR, CPRE, OPER
X14G-2	BMAR, CPRE, OPER
X14H-1	BMAR, CPRE, OPER

2.5 SUMMARY

This component of the study developed a procedure for establishing the extent to which different river locations are similar based on broad environmental attributes. Based on this, it is assumed that physical similarity implies similar fish assemblages under natural conditions. The identification of likely indicator species may subsequently be used for informing ecological flow requirements.

Fish assemblages are assessed in terms of the presence of species that are indicators of ecological flows, and included flow (velocity) dependence (i.e. rheophilic, semi-rheophilic or limnophilic guilds) and fish size (length and body depth) characteristics. Preference and tolerance ratings to fundamental determinants of fish habitat (viz. velocity-depth classes, no-flow intolerance, cover and physical-chemical intolerance) were used to identify fish species that are sensitive indicators of flow conditions at sampled river sites. Based on this information and a condition of very high similarity between sampled sites and (un-sampled) hydro-nodes, fish indicator species at the latter sites were predicted.

Recommendations regarding the use of the procedures and necessary further development of the biological estimation and extrapolation of ecological flows, include:

- Natural MAR for the nodes and other sites will improve the ability to distinguish between stream size and make an improved prediction of indicator species.
- Stream ordering should consider the use the approach of Shreve (Gordon *et al.*, 1994), as this will allow better distinction between stream sizes than the Strahler approach (used here) due to its accumulative stream ordering.
- Different models and approaches to predict species distribution under reference (and present) conditions should be considered, i.e. fish filter models (Chessman, 2006; Quist *et al.*, 2005) and artificial neural networks (Olden *et al.*, 2006).
- It will be essential to distinguish different degrees of perenniality under natural and present conditions.
- The procedure developed for assessing site similarity and predicting fish indicator species requires testing through field data.

The information on the species present at un-sampled nodes can be used to define fish guilds that have similar flow preferences. These preferences or requirements need to be determined in terms of ecologically relevant hydraulic parameters, such as velocity, depth and channel width, as well as flow types (e.g. fast-shallow and fast deep). The determination and application of such “habitat-specifications” to hydro-nodes in the Nkomati catchment is discussed in Chapter 3.

3 DEVELOPING AN APPROACH FOR EWR ESTIMATION USING BIOTIC PRESENCE, FLOW PREFERENCES AND AVAILABILITY OF HYDRAULIC HABITAT

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3.1 OBJECTIVES

The main objectives of this work have been to:

- initiate the development of a "desktop estimation method" for predicting Ecological Water Requirements (EWRs), taking explicit account of biotic requirements and available hydraulic habitat; and
- if the method allows, to apply it (and extrapolated Reserve results) to the Nkomati River catchment to estimate EWRs for approximately 70 river sites or "hydro-nodes" required for hydrological water balance modelling.

To achieve this, a step-wise process has been followed that develops and tests the feasibility of the related components upon which such an estimation method is based.

Reserve determinations at the Comprehensive and Intermediate levels have generally concentrated on main-stem rivers within a catchment, and the smaller tributaries (runoff < –50 Mm^3/a) have been addressed through lower confidence assessments, such as Rapid level III determinations, extrapolation of main-stem results, and Desktop estimates. The Desktop Reserve Model (DWAF, 1999) (referred to as the Desktop model), developed by Prof. D. Hughes[1], is based on the results of previous EWR assessments, and therefore almost entirely on EWR-hydrological relationships derived for rivers with substantial runoff (MAR > –30 Mm^3/a). During the course of Rapid level III assessments over the past few years by the group of river scientists responsible for this study, it has become increasingly apparent that Desktop model estimates appear to often under-estimate the EWRs for rivers with runoff less than approximately 30 Mm^3/a. River ecologists in South Africa have recognised for some time that rivers with lower runoff are often ecologically more sensitive to changes in flow than rivers with higher runoff (with similar biota) - but little further explanation and quantification has been provided as to why this may be the case. For river catchments with given hydrological characteristics, the scaling parameter for physical river size in the Desktop model is effectively MAR. Consequently, scaling or extrapolating EWR results to different river sites in a catchment with the same hydrological characteristics applies runoff to "scale" (i) potentially different biota with (ii) potentially different habitat requirements and (iii) absolute availability of hydraulic habitat (Note: although hydraulic habitat is a fundamental determinant of flow requirements, other important determinants of habitat availability should also be considered (e.g. cover for fish, inundated vegetation (and type), and substrate characteristics for invertebrates).

Application of the Desktop model has indicated realistic estimates of EWRs for rivers with substantial runoff (> –50 Mm^3/a) compared with higher confidence Reserve assessments. This, together with its ease of use has resulted in the model having become the most cost-effective method for estimating ecological flows in South Africa and other countries, and is becoming increasingly used for water resources planning. Unfortunately, the Desktop model is frequently being used to estimate EWRs for rivers with low runoff (< –30 Mm^3/s), rather than the "larger" systems from which its ecological empiricism emanates. This ecological empiricism is established through different relationships between the proportion of runoff and hydrological characteristics, as a function of Ecological Category (EC).

3.2 METHODOLOGY

3.2.1 General approach

The main focus of this work has been to develop an improved method for estimating EWRs at the desktop level for lower runoff tributary sites that are often at the sub-quaternary catchment scale (the original terms of reference was for extrapolating results from Reserve sites generally located on the main stem of a river system or tributaries with substantial runoff). As a point of departure, this study concentrates on low-flows, with the recognition that high-flows will also need to be addressed (pending the success achieved with this initial low-flow study). Since Desktop model estimates are based on natural hydrology, which is frequently provided through modelled monthly data (e.g. WR90), it is recognised that this may be a significant source of error in existing Desktop model estimates, particularly for small streams with low runoff. For this reason, the estimation method pursued in this study initially approaches the problem from a "biotic presence - habitat preference - habitat availability" perspective. However, since ecological flows are best considered within the context of hydrological constraints (e.g. natural and historical flow regimes), the final output requires hydrological context. This is provided for in this study by proposing a simple method involving an adjustment of Desktop generated low-flow EWRs (refer to Section 3.3.5) (Note: the Desktop model was designed to facilitate such adjustments to certain default parameters, which may routinely be made in Rapid III (and higher level) EWR assessments to take advantage of the output format of the Desktop model, i.e. - assurance tables for EWRs).

3.2.2 Assessing ecological water requirements for two tributaries in the Elands River catchment, Mpumalanga

At the outset of this study, tasked with developing an improved method for assessing EWRs for "small" streams, ecological water requirements were assessed for two tributaries of the Elands River (Mpumalanga province), namely the Joubertspruit and Lepelule Rivers (WR90 MARs of 4.9 Mm^3/a and 33 Mm^3/a, respectively, with the MAR for the Joubertspruit being of lower confidence). Rapid level III-type hydraulic information was used in the analysis, i.e. incorporating a single low-flow discharge-depth (rating) measurement. The Elands River system was selected, since this catchment was involved in the development of the original "ecological similarly concept", and furthermore, extensive biological information is available for this system. There are also ecological similarities between the Elands and Nkomati River catchments, the latter requiring EWR estimates for an approximately 70 hydro-nodes (refer to Section 3.3). The recommended low-flow Rapid III EWRs compared well with Desktop generated values for the Lepelule River, but were significantly higher for the Joubertspruit (approximately four times for drought conditions). This again confirmed previous findings of Desktop model under-estimates for small streams.

Using these two rivers, the feasibility was assessed of specifying numerical values for important *hydraulic variables* (e.g. maximum and average depth and velocity) and/or *flow-classes* (e.g. fast-shallow [a velocity-depth flow-class] for fish and fast flow over coarse substrate for invertebrates) to define low-flow EWRs for drought and maintenance conditions (Note: flow-classes refer to "hydraulic habitat" as defined by a combination of hydraulic parameters and other useful determinants of habitat availability, such as inundated vegetation and substrate type). Whereas the hydraulic variables used are dimensional and indicate absolute availability (e.g. depth and width), flow-classes are quantified using relative availability. For example, fast-shallow flow refers to the proportion of the inundated channel width where the flow velocity is greater than 0.3 m/s and the depth is less than 0.3 m. Since aquatic biota have absolute size, it is necessary to include absolute scales of river size in defining hydraulic habitat, since the use of dimensionless (flow-class) parameters provide insufficient criteria. Explicit mention of the absolute scale of biota, although seemingly obvious, is necessary. This is because the size of biota is not explicit in hydrological extrapolation of EWRs using runoff. Hydrological extrapolation applies differences in runoff to account for differences in physical river size (essentially width), absolute size of biota, and habitat requirements (e.g. width, depth and velocity).

The numerical values assigned to the hydraulic variables and flow-classes have been termed *habitat specifications* (or HabSpecs). It was recognised that HabSpecs are a function of hydrological variability (e.g. as drought and maintenance conditions as included in the original Building Block Method (King and Louw, 1998) and Desktop model) as well as seasonality and Ecological Category (EC) (accepted A-F scales). Furthermore, they apply to a collective "group" of biota that exploit the same class of environmental resources in a similar way - referred to as a "guild" for fish (www.cnr.colostate.edu/~brett/fw300/ flashcrd/defn.html). The guild applicable to the Elands River tributaries is "small rheophilics" (up to approximately 10 to 15 cm in length) - the important consideration is that although these species are relatively small, they do require perennial flow and very often fast flow. For the invertebrates, the group is defined by "cobble dwelling rheophilics".

Essentially, the use of HabSpecs is an attempt to provide a consistent set of "rules" for quantifying hydraulic habitat and hence flow requirements for groups of biota with similar requirements.

After the initial assessment using the Joubertspruit and Lepelule Rivers as study cases, two issues related to the use of flow-classes for defining flow requirements required further consideration:

- The first of these was the definition for the velocity-depth class for the small rheophilic fish guild, i.e. fast-shallow flow. It became evident that a preferred velocity-depth definition for this guild should include depths of greater in the range 0.1 to 0.3 m, rather than the original fast-shallow definition of 0 to 0.3 m (Kleynhans, 1999). This is because depths of less than 0.1 m are considered insufficient as a suitable depth class for small rheophilic fish guilds.
- The second issue is the use of the velocity-substrate flow-class for defining invertebrate requirements, e.g. fast flow over coarse substrate. To allow this flow-class to be applied to river sites with different proportions of fine and coarse sediment requires standardised values to be determined (i.e. irrespective of the relative proportions of fine and coarse sediment). The numerical value (percentage) for this flow-class is therefore defined assuming equal proportions of fine and coarse sediment (i.e. 50%), and the value for the flow-class is re-proportioned based on measured (or estimated) site-specific data. Conversely, if standardised sediment proportions are not used to define the HabSpec, discharge (through velocity) will effectively compensate for the suitability of substrate at the site (i.e. higher discharges will compensate for lower proportions of coarse sediment). This is not desirable, since reduced suitability of physical habitat should rather be reflected through the relative abundance and composition of the invertebrate community present, and should not be compensated for by the provision of increased flows and concomitant hydraulic habitat. Essentially, the use of standardised sediment proportions to define the velocity-substrate flow-class implies that sediment composition does not influence the EWR requirement (as calculated from this flow-class alone), but only the

numerical values corresponding to different flows. Applying this reasoning, similar cobble riffles along a stream reach comprising different proportions of fine and coarse sediment, but invertebrate communities with similar habitat requirements, will require the same ecological flows. This provides a meaningful and consistent application of the velocity-substrate flow-class for recommending ecological flows for invertebrates.

The HabSpecs used to define hydraulic habitat have ultimately been determined in this study through an optimisation procedure (discussed in Section 3.2.4) using previous Ecological Reserve results – i.e. they are essentially calibrated values. Nevertheless, the hydraulic variables and flow-classes used must provide ecologically meaningful and quantifiable determinants of hydraulic habitat applicable to the relevant fish guilds and invertebrate communities.

3.2.3 Extending the approach to different river sizes and fish guilds

The use of HabSpecs was subsequently extended to include a range of river sizes, with MARs ranging from 10 Mm^3/a (Leeuspruit – also a tributary of the Elands River) to 834 Mm^3/a (Olifants River, Mpumalanga province). Results from previous Ecological Reserves determinations were used, with the confidence in the results depending on the level of Reserve assessment (i.e. Comprehensive, Intermediate or Rapid III – refer to Table 3.1).

For the larger rivers, HabSpecs for a different set of fish guilds are relevant: large semi-rheophilics of greater than approximately 25 to 30 cm in length. The requirement for fast flowing water is limited to periods during the wet season when reproduction occurs. It is important to consider that this requirement need not be continuous, i.e. it can occur during periods of the wet season when suitable conditions are created following an increase in base flow. Depending on the type of river and its characteristics, flow may drop very low or even cease, during the wet season. Some of the semi-rheophilics may also not permanently inhabit a stream but only make use of it as breeding area during the wet season.

Where small rheophilics and large semi-rheophilics occur together, it follows that the general consideration should be that during the dry season, flow specifications will be based on the requirements of the small rheophilics. During the wet season the breeding requirements of semi-rheophilics will for periods be the major consideration.

An attempt was made to define the HabSpecs for the different ECs (i.e. A to D scale) using a combination of important hydraulic parameters and flow-classes for fish and invertebrates - these important parameters/flow-classes having been identified over the course of Instream Flow Requirement (IFR) and EWR assessments over the past decade. This was done separately for fish and invertebrates, wherever results from previous assessments allowed this differentiation.

In the smaller rivers, "riffles" have been used as the most common geomorphic unit defining critical habitat for rheophilic and semi-rheophilic guilds. For larger rivers, rapids with larger substrate (i.e. boulders) and bedrock and have often characterised EWR sites, and the use of previously determined ecological flows has necessitated their inclusion in this study.

Development of the approach shows promise for a range of river sizes with different biota and associated habitat requirements.

3.2.4 Optimising habitat specifications using EWR results

Initially, HabSpecs were defined by (subjectively) comparing previous low-flow EWRs with modelled (tabulated) relationships between discharge and selected hydraulic parameters (e.g. depth and velocity) and flow-classes (e.g. fast flow over coarse substrate). It became evident, however, that a computational means of defining HabSpecs would be preferable, particularly when additional sites are added to the EWR data-base upon which the HabSpecs are based, thus requiring a tedious and subjective re-evaluation. *Furthermore, an objective procedure for determining HabSpecs using previous Ecological Reserve results effectively provides "calibrated" numerical values that are based on the collective knowledge and understanding of the river ecologists involved in ecological flow assessments over the past few years.* For this reason, a simple computational procedure was developed for calculating the optimal values of the HabSpecs that provides the minimum error between the results of previous Reserves and these estimation results (i.e. using the HabSpecs). This error is defined by the sum of the squares of the relative errors per site, and the minimum error defines the optimised HabSpec values. Relative errors allow flow requirements for rivers with different EWRs to have equal weighting, and errors may be defined in different ways which influences the optimised values.

If errors are defined relative to previous Reserve results (bearing in mind that these emanate from different levels of Reserve with varying confidence, from Rapid III (generally for small rivers) to Comprehensive assessments), then underestimates and overestimates produce equivalent relative errors. For a desktop-type method of analysis this is inappropriate, since in the context of EWRs, overestimates are preferable to underestimates. If the error is defined relative to estimated results, the procedure produces HabSpecs that overestimate flows, since higher estimated discharges give smaller relative errors. Consequently, the relative error has been defined using the mean of previous EWR results and estimated values, since this produces results that slightly favour overestimates.

Table 3.1 lists the rivers and sites from which previous EWR results (excluding the Joubertspruit and Lepelule - refer to Section 3.2.2) were used to optimise the HabSpec requirements for fish and invertebrates. River sites with a range of runoffs have been used (MAR ranging from 5 to 834 Mm^3/a, Table 3.1). Higher confidence

(Intermediate and Comprehensive) assessments exist for the larger river systems, whereas the requirements of smaller systems (MAR < –50 Mm^3/a) have greater uncertainty (generally Rapid level III assessments). The HabSpecs for small rivers are therefore based on limited EWR results with lower confidence than for larger river systems.

Although attention was focused in this study, at least initially, on the use of sites with riffle-type morphologies characterised by cobble-sized substrates, the need to use previous EWR results necessitated the use of sites with more complex hydraulic characteristics associated with boulder and bedrock rapids. Results from certain river sites were also excluded where different guilds or communities of biota are present and where complex morphologies may have resulted in unrepresentative hydraulic characterisation of available habitat at the site.

Table 3.1 River sites used in the optimisation of HabSpecs for fish and invertebrates.

River	Site	Geomorphic unit	Characteristic substrate	Level of EWR assessment	MAR (Mm^3/a)	Optimisation	
						Fish	Invert
Joubertspruit[2]	1	Riffle	Cobble/boulder	Rapid	5	x	x
Leeuspruit	1	Riffle	Cobble	Intermediate	10	x	x
Ncandu	1	Riffle	Cobble	Rapid	19	x	x
Lusushawana	1	Riffle	Cobble	Rapid	31	x	x
Lepelule[2]	1	Riffle	Cobble	Rapid	33	x	x
Gladdespruit	1	Riffle/Run	Cobble	Comprehensive	36	x	x
Mutshindudi	1	Riffle	Cobble	Rapid	47		x
Crocodile 2A	2A	Riffle	Cobble	Intermediate	50		x
Elands	1	Step	Bedrock/boulder	Comprehensive	50		x
Teespruit	1	Run	Sand/gravel	Comprehensive	60	x	
Nkomati	1	Riffle	Cobble/boulder	Comprehensive	181	x	x
Elands	2	Rapid	Boulder	Comprehensive	202	x	x
Lomati[1]	1	Rapid	Boulder	Comprehensive	322	x	
Assegaai	1	Riffle	Cobble/boulder	Intermediate	334	x	x
Blyde[1]	1	Rapid	Boulder	Comprehensive	384	x	
Nkomati	2	Rapid	Boulder	Comprehensive	527	x	x
Olifants	8B	Rapid	Boulder	Comprehensive	834	x	

[1] hydraulic characterisations unrepresentative
[1] EWR sites from this study

Tables 3.2 and 3.3 give the results of the HabSpec optimisation for two fish guilds and a single invertebrate community, for rivers with lower (MAR < –30 Mm^3/a) and higher (MAR > –50 Mm^3/a) runoff. The combination of hydraulic parameters and flow-classes include important determinants of hydraulic habitat, and incorporate variations of the two fundamental determinants of discharge: depth and velocity. For a desktop-type assessment, it is necessary that the selection of parameters defining hydraulic-habitat is quantifiable with reasonable accuracy. For a given fish guild or invertebrate community, the results of the optimisation procedure were most meaningful and consistent (as distinguished by changes in the HabSpecs with EC) when EWR results for the same sites were used to optimise HabSpecs for a range of

ECs.

As discussed previously, the HabSpecs are based on the results of IFR and EWR assessments, particularly for larger river systems with MARs greater than –50 Mm^3/a. The trends that characterise previous EWR assessments are therefore expected to be reflected in the HabSpecs. Such relationships include the similarity in low-flows between the drought wet season and maintenance dry season (EC=C), and maintenance wet season (EC=C) and maintenance dry season (EC=B) flows, as evident in Tables 3.2 and 3.3. The optimised HabSpecs also indicate that habitat availability is sensitive to changes in hydrological season (dry or wet) for drought and the lower EC (C), particularly for smaller rivers (MAR < –30 Mm^3/a). In other words, relative habitat availability is sensitive to changes in low-flows for smaller (runoff) rivers with small rheophilic fish guilds and invertebrate communities - confirming the understanding of river ecologists (refer to Section 3.1).

Initially, the broad category used to define the velocity-depth class for large semi-rheophilic fish guilds was fast-deep flows, i.e. defined by velocity in excess of 0.3 m/s and depth in excess of 0.3 m (Kleynhans, 1999). This definition for depth provided insufficient resolution for drought flows, since the optimised depths (using previous EWR results) were found to be less than 0.3 m, giving a zero HabSpec! For this reason, the depth definition was adjusted to greater than 0.2 m depth (refer to Table 3.2).

The optimised depth (y) and average depth (y_{av}) HabSpecs in Table 3.3 (invertebrate requirements) may be higher than necessary for bed-dwelling communities. Noting that these are optimised values, it is expected that these “depth-based parameters” are surrogate variables for another aspect of the flow requirements not explicitly included: those associated with the marginal and/or fringing vegetation community. Insufficient EWR results exist to explicitly distinguish between the requirements of the cobble-dwelling and vegetation communities, and these surrogate hydraulic parameters may prove useful in further investigations.

Table 3.2 Optimised HabSpecs for small rheophilic and large semi-rheophilic fish guilds for small and large rivers (as measured using MAR).

Hydrological variability	Ecological Category	Season	Fish guilds					
			Small rheophilic (Length < 10 to 15 cm)			Large semi -rheophilic (Length > 25 to 30 cm)		
			Mean annual runoff (Mm^3/a)					
			5 to 30			60 to 520		
			Hydraulic parameter or flow-class					
			y (cm)	*F (%)*	*F.1 (%)*	*y (cm)*	*F (%)*	*F.2 (%)*
Drought		Wet	19	13	4	34	21	18
		Dry	16	2	1	30	11	8
Maintenance	C	Wet	22	23	10	38	31	28
		Dry	18	12	2	33	20	17
	B	Wet	28	43	26	47	53	45
		Dry	21	25	11	35	28	23

Abbreviations:
y=maximum depth
F=fast flow (velocity greater than 0.3 m/s)
F.1=fast flow with a depth greater than 0.1 m
F.2=fast flow with a depth greater than 0.2 m

Table 3.3 Optimised HabSpecs for cobble dwelling rheophilic invertebrate communities determined separately for small and large rivers (as measured using MAR).

Hydrological variability	Ecological Category	Season	Mean annual runoff (Mm^3/a)							
			5 to 30				50 to 530			
			Hydraulic parameter or flow-class							
			y (cm)	*y_{av} (cm)*	*v_{av} (cm/s)*	FCS *(%)*	*y (cm)*	*y_{av} (cm)*	*v_{av} (cm/s)*	FCS *(%)*
Drought		Wet	19	8	15	5	28	15	16	7
		Dry	16	5	8	1	23	12	12	4
Maintenance	C	Wet	22	10	23	14	32	20	29	24(18)
		Dry	18	7	13	4	29	17	16	8
	B	Wet	27	11	27	20	36	24	38	29
		Dry	21	9	22	12	28(30)	16(19)	27	21

Abbreviations:
y=maximum depth
y_{av}=average depth
v_{av}=average velocity
FCS=fast flow (velocity greater than 0.3 m/s) over coarse substrate (greater than 16 mm dia.)
FCS values apply to a standardised proportion of coarse sediment (50%)
(x) - adjusted value based on adjacent categories

3.3 APPLICATION OF HABSPECS FOR ESTIMATING ECOLOGICAL FLOWS AT HYDRO-NODES IN THE NKOMATI CATCHMENT

3.3.1 Background

The Nkomati Water Availability Assessment Study (WAAS), initiated in 2006, requires an assessment of the EWRs for numerous locations (approximately 70 hydro-nodes) on rivers within the Nkomati River catchment for yield modelling purposes. The Nkomati River Comprehensive Reserve assessment (Afridev, 2006), completed in 2005, provided ecological flow recommendations for three sites along the main stem Nkomati River, and three of it's major tributaries, including, the Lomati River, Gladdespruit and Teespruit.

Extrapolation of Ecological Reserve results to the hydro-nodes applies a hydrological scaling, taking no account of biological information (e.g. actual biota present in the river), habitat preferences (e.g. rheophilic guilds) and habitat availability (e.g. physical size of the river). Whereas the ecological similarity concept provides guidance on the biological appropriateness of hydrological extrapolation, this study considers the development of an improved means for estimating ecological water requirements taking explicit consideration of these factors. The first step has been to develop sets of "habitat preference rules" (or HabSpecs) as a function of river and hydrological condition (through the use of wet and dry seasons, and drought and maintenance conditions, and EC).

The use of optimised HabSpecs (Tables 3.2 and 3.3) was subsequently tested for a limited number of sites within the upper Nkomati River catchment.

3.3.2 Data collection

To test the HabSpecs, Rapid level III-type hydraulic data were collected at 11 river sites in the upper Nkomati River catchment (upstream of Swaziland) during the period 14 to 17 May 2007. The site locations were selected using the "ecological similarity concept" (Chapter 2), with sites having been chosen that are ecologically similar to as many of the hydro-nodes as possible, but also being useful in terms of Rapid level III hydraulic assessments (i.e. a single rating point at a low-flow). Table 3.4 provides selected site information, with ten sites located on various tributaries of the upper Nkomati River, and one site on the main stem below Vygeboom Dam in quaternary X12G. The MAR for the upper Nkomati River tributaries vary from 4.2 to 27.9 Mm^3/a – i.e. all within the "small" river range where there is limited information from previous EWRs (refer to Section 3.1 and Table 3.1). Photographs of the 11 sites are given in Figs 3.2 to 3.12, and indicate that the substrates range in size from gravels to cobbles and boulders.

Table 3.4 Location of river sites in the upper Nkomati River catchment and measured discharges during the period of 14 to 17 May 2007.

River name	Quaternary	Site name	MAR* (Mm^3/a)	Discharge (m^3/s)	Latitude	Longitude
Phalangampepe	X12K	X12K1	4.2	0.050	25 02 42.7	31 03 00.7
Bergstroom	X12G	X12G2	4.8	0.026	25 58 04.4	30 50 33.0
Bankspruit	X11F	X11F1	6.7	0.075	25 50 48.9	30 21 02.0
Sandspruit	X12H	X12H2	7.5	0.037	26 02 59.2	30 53 49.7
Mawelawala	X12G	X12G1	10.2	0.037	25 57 49.8	30 49 12.8
Swartspruit	X11E	X11E1	15.4	0.045	25 55 57.5	30 14 05.5
Mlondozi	X12K	X12K2	16.8	0.17	26 02 49.6	31 02 39.1
Klein Nkomati	X11D	X11D1	20.6	0.050	25 53 16.7	30 07 13.0
Vaalrivierspruit	X11A	X11A1	25.5	0.019	26 00 20.0	30 01 50.0
Buffelspruit	X12B	X12B1	27.9	0.086	26 03 45.7	30 23 37.6
Nkomati	X12G	X12G3	370	1.5	25 57 10.5	30 43 29.0

*MAR sourced from the Nkomati Water Availability Assessment Study initiated in 2006.

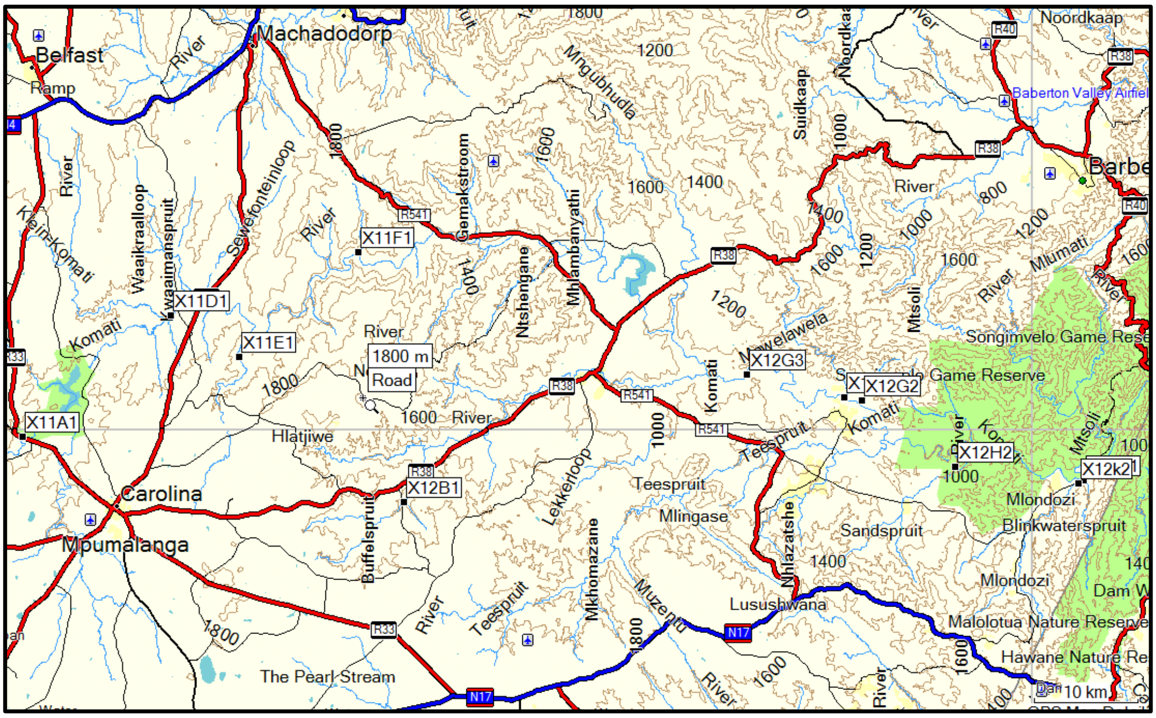

Figure 3.1 Location of sites (Table 3.4) in the upper Nkomati catchment.

Figure 3.2 Phalangampepe River at site X12K1.

Figure 3.3 Bergstroom at site X12G2.

Figure 3.4 Bankspruit at site X12F1.

Figure 3.5 Sandspruit at site X12H2.

Figure 3.6 Mawelawala at site X12G1.

Figure 3.7 Swartspruit at site X12E1.

Figure 3.8 Mnlondozi River River at site X12K2.

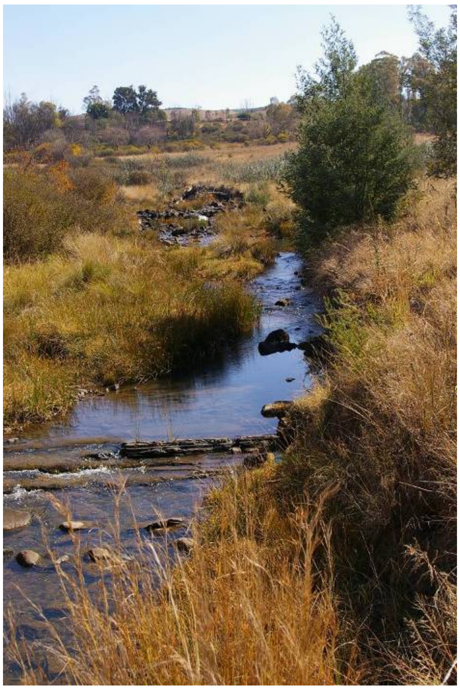

Figure 3.9 Klein Nkomati River at site X12D1.

Figure 3.10 Vaalrivierspruit at site X11A1.

Figure 3.11 Buffelspruit at site X12B1.

Figure 3.12 Nkomati River at site X12G3.

3.3.3 Application of HabSpecs to selected sites

Results from the application of HabSpecs for the 10 upper Nkomati River tributary sites, and one main stem site, are provided in Table 3.5. The modelled natural flows (from the Water Availability Assessment Study) and Desktop generated EWRs are also given for wet and dry seasons, and drought and maintenance conditions. For natural flows, discharges are listed at the 99th and 70th percentile for comparison with drought and maintenance conditions, respectively. It may be noted from Table 3.5 that the HabSpec EWR estimates are higher than modelled natural flows (i.e. also estimated), the occurrence of which increases with higher EC and reducing stream size (i.e. lower MAR). Clearly, the EWR must be bounded by natural flows, but it again needs to be stressed that the natural flows are estimated, and confidence in these predictions reduces with reducing runoff and concomitant stream size. The data in Table 3.5 also indicates that the HabSpec generated EWRs approach the existing Desktop generated values with increasing runoff (i.e. for certain ECs on Vaalrivierspruit, Buffelspruit and the Nkomati River site).

The suitability of the HabSpec generated EWR in providing adequate habitat were assessed by fish and invertebrate ecologists for the 11 upper Nkomati River catchment sites.

Overall, the HabSpec generated ecological flows were considered to provide more reasonable estimates compared with Desktop generated values for the smaller streams with lower MARs, where the latter predictions are regarded as underestimates.

Furthermore, the flow-habitat assessment indicated that the HabSpec estimates be bounded by the Desktop values as lower limit and predicted natural flows as upper limit. This is reasonable even though natural flows are generally modelled. This is because the HabSpec estimated flows are determined independently of hydrology, but it is necessary to provide hydrological context since the modelled hydrology underlies the management of the water resource. Changes in the modelled hydrology, therefore, require that the EWRs be reassessed.

Table 3.5 Results of application of optimised HabSpecs for 11 sites in the upper Nkomati River catchment.

River	Natural (m^3/s)				Desktop (m^3/s)						HabSpec (m^3/s)					
	99%		70%		Drought		Maint C		Maint B		Drought		Maint C		Maint B	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Phalangampepe	0.015	0.042	0.023	0.107	0.006	0.016	0.012	0.031	0.019	0.055	0.015	0.045	0.041	0.091	0.080	0.150
Bergstroom	0.012	0.054	0.019	0.180	0.006	0.020	0.011	0.038	0.017	0.066	0.025	0.075	0.070	0.180	0.150	0.300
Bankspruit	0.023	0.110	0.035	0.230	0.010	0.026	0.018	0.051	0.030	0.090	0.023	0.069	0.065	0.160	0.140	0.280
Sandspruit	0.062	0.110	0.090	0.240	0.018	0.027	0.032	0.051	0.055	0.090	0.028	0.100	0.094	0.220	0.200	0.370
Mawelawala	0.027	0.132	0.046	0.318	0.014	0.041	0.026	0.078	0.043	0.137	0.029	0.100	0.080	0.230	0.180	0.340
Swartspruit	0.054	0.250	0.081	0.510	0.023	0.055	0.043	0.109	0.070	0.195	0.050	0.190	0.180	0.440	0.370	0.750
Mlondozi	0.062	0.170	0.093	0.430	0.025	0.064	0.046	0.124	0.076	0.218	0.038	0.077	0.077	0.170	0.150	0.290
Klein Nkomati	0.077	0.340	0.110	0.700	0.033	0.078	0.059	0.148	0.098	0.261	0.100	0.150	0.130	0.220	0.200	0.390
Vaalrivierspruit	0.042	0.198	0.089	0.459	0.022	0.076	0.044	0.161	0.070	0.283	0.038	0.061	0.053	0.140	0.110	0.190
Buffelspruit	0.150	0.620	0.220	1.100	0.062	0.117	0.121	0.215	0.187	0.378	0.021	0.110	0.110	0.280	0.250	0.550
Nkomati	1.4	7.6	2.0	14.5	0.62	1.4	1.1	2.8	1.8	4.9	0.85	1.3	1.3	1.7	1.4	3.0

Table 3.6 Desktop Adjustment Method using fixed flow requirements/unit width of inundated channel and estimated channel width.

River	Width (m) @ 0.2m	HabSpec ($m^3/s/m$)						DAM (m^3/s)					
		Drought		Maint C		Maint B		Drought		Maint C		Maint B	
		Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Phalangampepe	2.0	0.008	0.023	0.021	0.046	0.040	0.075	0.015	0.042	0.023	0.103	0.023	0.107
Bergstroom	3.9	0.006	0.019	0.018	0.046	0.038	0.077	0.012	0.052	0.019	0.113	0.019	0.180
Bankspruit	3.7	0.006	0.019	0.018	0.043	0.038	0.076	0.021	0.062	0.035	0.137	0.035	0.223
Sandspruit	5.2	0.005	0.019	0.018	0.042	0.038	0.071	0.022	0.066	0.063	0.145	0.090	0.236
Mawelawala	4.3	0.007	0.023	0.019	0.053	0.042	0.079	0.025	0.076	0.046	0.167	0.046	0.272
Swartspruit	5.6	0.009	*0.034*	*0.032*	*0.079*	*0.066*	*0.134*	0.030	0.090	0.081	0.197	0.081	0.321
Mlondozi	5.1	0.007	0.015	0.015	0.033	0.029	0.057	0.031	0.093	0.088	0.203	0.093	0.331
Klein Nkomati	4.2	*0.024*	*0.036*	*0.031*	0.052	0.048	0.093	0.033	0.099	0.095	0.218	0.110	0.355
Vaalrivierspruit	2.6	*0.015*	0.023	0.020	0.054	0.042	0.073	0.035	0.106	0.089	0.233	0.089	0.380
Buffelspruit	3.8	0.006	0.029	0.029	*0.074*	*0.066*	*0.145*	**0.062**	**0.117**	**0.121**	0.239	0.203	0.390
Mean requirement		0.007	0.021	0.020	0.046	0.039	0.075						

underline - natural flows (modelled), **bold -** Desktop values, *italic* - outliers

3.3.4 Application of HabSpecs to hydro-nodes

Habitat specifications provide a simple and consistent rule-based approach for estimating EWRs where hydraulic characterisation of flow conditions is available, i.e. at Rapid III level assessments and higher. The hydraulic characterisation requires a cross-sectional survey through the critical geomorphological unit (usually riffle or rapid), rating measurement at a low-flow, and assessment of the bed substrate - as undertaken for 11 sites in the upper Nkomati River catchment (refer to Section 3.3.2). Use of HabSpecs at the desktop level, however, requires hydraulic characterisation in the absence of field data. This is not yet possible, and an alternative means of estimating EWRs using HabSpecs, or the results of the analyses described so far, is necessary.

Figure 3.13 is a plot of the mean monthly natural low-flow per unit inundated width against mean monthly EWR (expressed as a percentage of the mean monthly natural low-flow). These relationships were developed to allow the HabSpec seasonal low-flow drought and maintenance EWR estimates to be considered within the context of the existing Desktop Reserve model and natural low-flow regime. The width in the independent variable (x-axis), refers to the inundated cross-channel width at a maximum depth of 0.2 m. This channel width is therefore relevant to low-flows, and an appropriate mid-range maximum depth has been selected from Tables 3.2 and 3.3 for the range of ECs considered. The relevant month is the driest or wettest in the natural (modelled) record, and refers to each of the ECs.

The existing Desktop Reserve model gives an approximately fixed proportion of natural flow (horizontal lines) as a function of hydrological characteristics, position on the flow duration curve (as denoted by drought or maintenance) and EC. Estimation of ecological flows using HabSpecs indicates that for small streams (natural runoff < –30 Mm^3/a), the estimated flow requirements are higher than Desktop generated values, increasing to naturally occurring values (albeit modelled natural) as runoff (and stream size) reduces. This provides a means for adjusting the Desktop model values (dry and wet season), based on stream size (using runoff), as derived from the application of HabSpecs.

Although the proposed adjustment in Figure 3.13 is expressed in terms of natural low-flows, it is not derived from natural flow hydrology. Habitat specifications are derived from ecological and habitat considerations and the use of natural flows allows comparison with the existing Desktop Reserve model. Furthermore, it is important to reiterate that the Desktop adjustment indicated in Figure 3.13 refers to rivers with specific hydrological characteristics, fish guilds and invertebrate communities (i.e. small rheophilic fish and cobble-dwelling rheophilic invertebrates).

A Desktop adjustment for small (lower runoff) rivers, as illustrated in Figure 3.13 for the upper Nkomati River catchment, may ultimately be coded into the existing Desktop Reserve Model for ease of application. Prof. D. Hughes felt, however, that there is insufficient data to justify its inclusion in the Desktop model at this stage, particularly given its potential implications to the Ecological Reserve process and Water Resource Management resulting from the significant finding that appreciably larger quantities of the natural low-flows (even up to 100% of modelled values) are required with reducing stream size for rivers with sensitive (rheophilic) biota. It must be stressed, once again, that this is with reference to modelled natural low-flows, which are low-confidence predictions for small river systems. The finding that larger proportions of the natural flow regime are required with reducing stream size in systems with sensitive biota is supported by studies reported in the international literature (e.g. Maret *et al.*, 2006; Conservation Ontario (2005); Jowett (1997) and Beecher (1990)). The Desktop model allows for manual adjustment of certain default Desktop parameters, however, and this is utilised for adjusting Desktop generated EWRs for hydro-nodes in the Nkomati River catchment using a simple fixed unit width requirements, upon which the Desktop adjustments in Figure 3.12 are based.

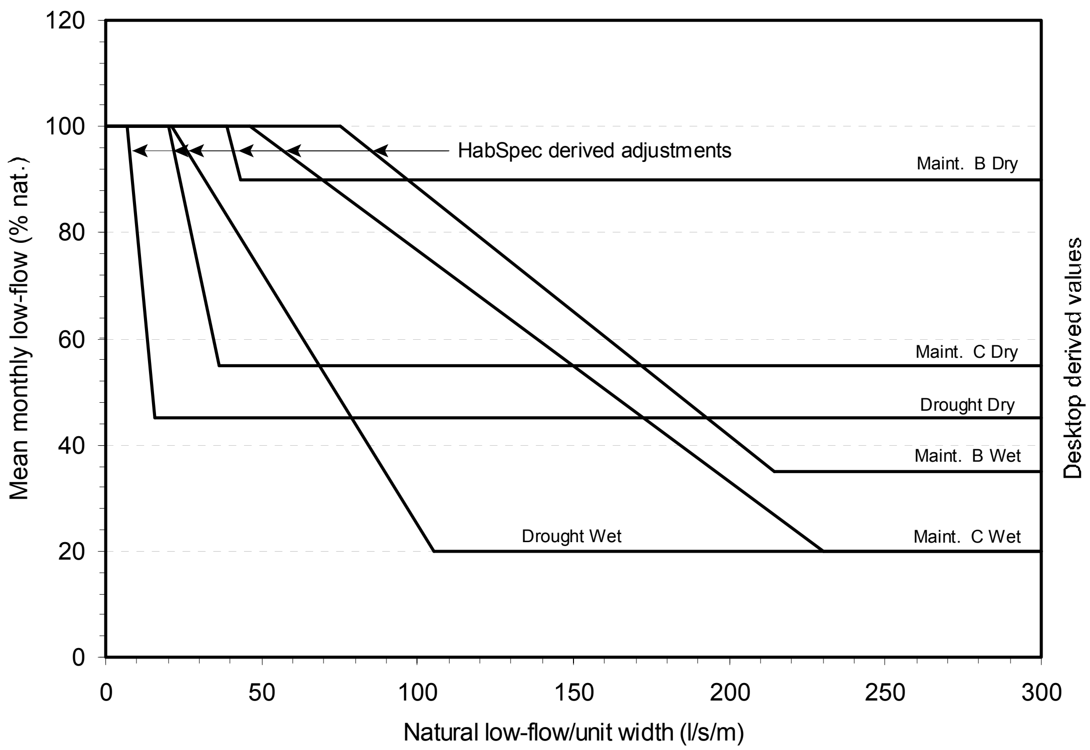

Figure 3.13 Plot of flow requirement per unit inundated width expressed as a % of natural mean monthly runoff derived from the application of HabSpecs for 11 sites in the upper Nkomati River catchment.

The HabSpec generated flows in Table 3.5 are expressed as a function of the inundated width (at a maximum depth of 0.2 m) in Table 3.6. With the exception of two outliers per season (dry or wet), the unit-width low-flows are remarkably constant. Scatter in the data is expected given the low-confidence hydraulic analyses associated with the Rapid level III assessments undertaken. Interestingly, the outliers are associated with three sites, two of which (the Swartspruit and Buffelspruit) are characterised by large bed substrates (large cobbles and small boulders) and mild water surface gradients. Cross-sections were positioned to facilitate Rapid level III hydraulic analyses with reasonable confidence, but may not have characterised critical hydraulic habitat. Neglecting the outliers, the average flow requirement per unit width for the various ECs (of which some are interpolated), is provided in Table 3.7. The average absolute error using Table 3.7 values and all 10 sites is 47% and 25% for drought dry and drought wet, respectively, and between 20% and 25% for the maintenance ECs. Neglecting the outliers, the average absolute error reduces to between 11% and 19%. The values in Table 3.7 define the x-ordinates (natural low-flow per unit width values) in Figure 3.13 where the Desktop adjusted percentages (of mean monthly low-flow) equate to the natural low-flows (i.e. 100%). The flows in Table 3.7 are therefore critical, defining the *minimum seasonal drought and maintenance discharges required to achieve the recommended EC for the sensitive biota considered*. For small rivers, this may equate to a substantial proportion of the natural low-flow but this reduces with increasing natural low-flow runoff, as illustrated in Figure 3.13. It is a significant finding that the low-flow EWR per unit width of inundated channel (at an appropriate low-flow depth) gives an approximately constant value. This finding is likely related to the use of multi-parameter HabSpecs that incorporate the two fundamental determinants of discharge (viz. depth and velocity), and satisfying minimum values for these parameters (i.e. Tables 3.2 and 3.3) for critical habitat for rheophilic species (provided within a riffle) gives a constant unit width discharge.

Table 3.7 Flow requirements per unit width of channel for small rheophilic fish guilds and cobble-dwelling rheophilic invertebrates.

Hydrological Variability	Ecological Category	EWR (litres/s/m)	
		Season	
		Dry	Wet
Drought		7	21
Maintenance	D	11[1]	29[1]
	C/D	16[1]	38[1]
	C	20	46
	B/C	30[1]	61[1]
	B	39	75

[1]interpolated linearly

The Desktop Adjustment Method (DAM) (Figure 3.13 or Table 3.7) is dependant on a fundamental parameter - channel width at an appropriate low-flow depth (0.2 m maximum depth has been used). Although channel width is easily measured in the field, it needs to be derived from available information within the context of a desktop estimation approach. As a starting point, an obvious parameter to correlate channel width against is MAR. Figure 3.14 is a plot of the low-flow channel width against

MAR (natural) for the EWR sites listed in Tables 3.1 and 3.4. The low-flow channel widths correspond to low-flow maximum depths as provided by the HabSpecs (Tables 3.2 and 3.3): –0.2 m and –0.35 m for small (MAR < –50 Mm^3/a) and large (MAR > –50 Mm^3/a) rivers, respectively (approximate mid-range maximum depths for the range of ECs considered). These are the approximate dry season depth requirements for small rheophilic and large semi-rheophilic fish guilds, respectively. Ultimately, it may be necessary to use the dry and wet season depths to estimate the corresponding channel widths for the dry and wet seasons, respectively.

The plot indicates a general trend of increasing width with MAR over the runoff range (5 to 500 Mm^3/a), although there is substantial scatter. The data indicates upper and lower limits, bounding a wide range of channel widths that increase with MAR. The data points for small rivers have reduced range of channel widths than implied by the upper boundary (ranging from 2.0 m to 9.0 m), and a gentle slope indicating increasing width with MAR. Given that the DAM is relevant to small rivers (refer to Figure 3.12), an approximate relationship over the MAR range 4 to 50 Mm^3/a is proposed, as indicated in Figure 3.13. This relationship should be used with caution given the scatter displayed in the data. Given the importance of low-flow channel width in the DAM and ease with which it can be measured in the field, it is recommended that width is measured where possible (for critical riffle and/or rapid geomorphic units) for the purpose of estimating EWRs using the DAM.

Further investigation is required concerning the relationship between low-flow channel width and hydrological characteristics and of the influence of channel shape. Initial indications are that the relationship is also a function of channel shape ("flat-bottomed" versus "v-shaped") and substrate size, and the influence of these determinants requires further study using measured data. Nevertheless, the DAM is considered by the authors to provide higher confidence low-flow EWRs than the existing Desktop model for small rivers (MAR < –50 Mm^3/a) with sensitive rheophilic biota (small rheophilic fish guilds less than 10 to 15 cm in length and rheophilic invertebrate communities) and with similar hydrological and ecological characteristics. For larger river systems (MAR > –50 Mm^3/a), the proposed estimation method using HabSpecs indicates use of the Desktop model (Figure 3.13) to extrapolate Reserve EWRs where ecological similarity permits.

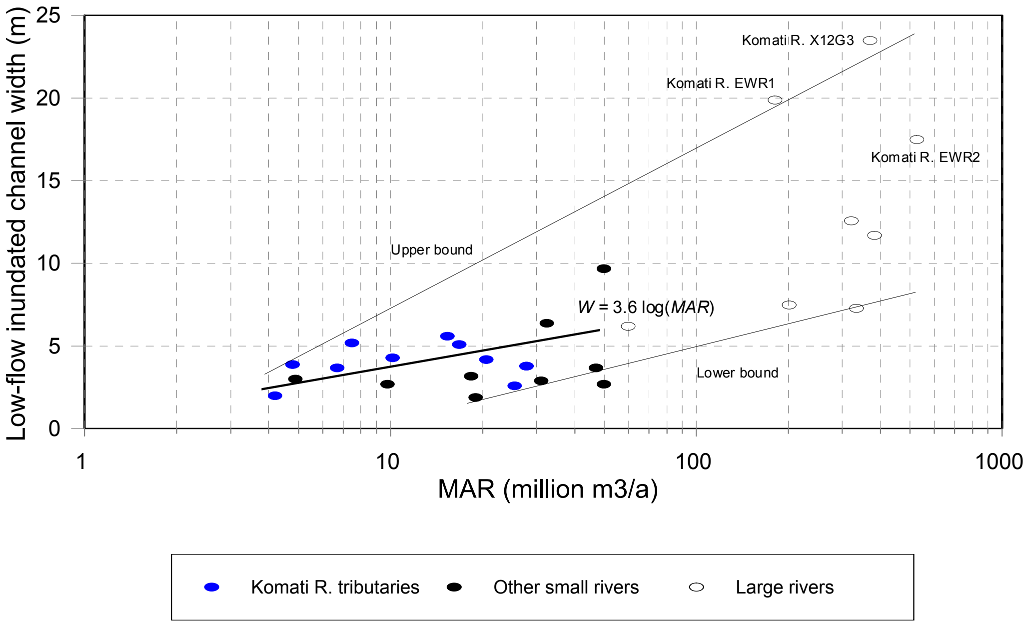

Figure 3.14 Low-flow inundated channel width as a function of natural MAR.

The DAM EWR low-flow estimates for drought and maintenance (C and B) for dry and wet seasons are given in Table 3.6 for the ten tributary sites in the upper Nkomati River catchment, using estimated channel widths (i.e. Fig 3.14 relationship). The DAM estimates are required to be higher than Desktop generated values and lower than natural (modelled) low-flows. These are plotted in Fig. 3.15, together with the HabSpec generated values. For the ten tributary sites using surveyed channel widths, the average absolute error between the HabSpec and DAM estimates of the EWR (drought and maintenance C and B) is 19%. This reduces to 15% when flows are confined to between natural and Desktop generated values. Excluding upper (natural) and lower (Desktop) limits increases the average absolute error of 24%. Given that this estimation method for small streams is at the desktop level, such errors are reasonable.

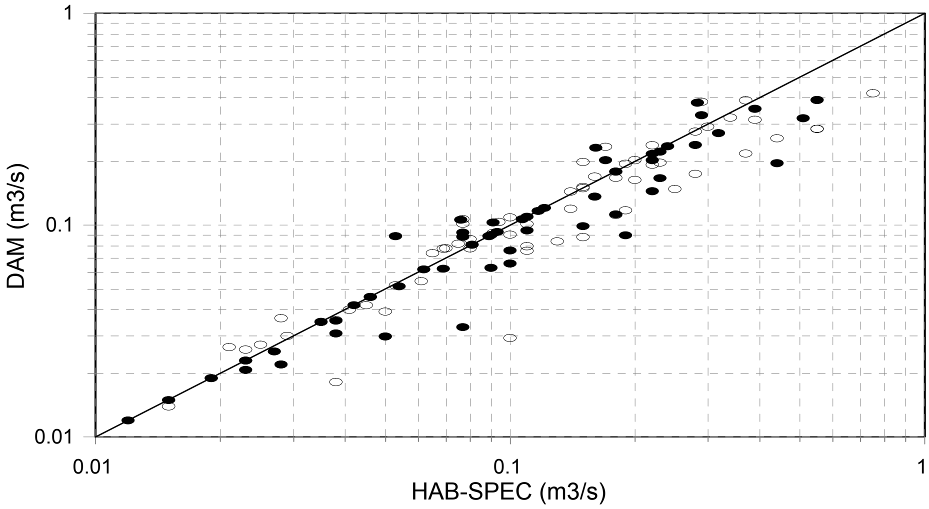

Figure 3.15 Plot of HabSpec versus DAM EWR requirements for the ten tributaries in the upper Nkomati River catchment for drought and maintenance conditions (Table 3.4) (The unfilled markers are estimates taking no account of the (modelled) natural hydrology and using surveyed channel width. The filled markers are estimates confined by lower and upper limits by Desktop estimates and modelled natural flows, respectively, with the DAM based on estimated channel widths).

3.3.5 Procedure for application of the DAM to hydro-nodes

For hydro-nodes with large-semi rheophilic fish guilds (generally MAR > –50 Mm^3/a), the EWRs can be determined by extrapolating Reserve results where ecological similarity permits, or alternatively by using the Desktop model.

For nodes with small rheophilic fish guilds and MAR < –50 Mm^3/a:

- Apply the Desktop model using default parameters;
- Determine the natural drought (95% exceedance) and maintenance (70% exceedance) flows for the driest and wettest months from the natural flow duration table (provided in the .RUL file);
- Estimate the channel width (*W*) at 0.2 m depth, using $W = 3.6 log(\text{MAR})$ where the MAR is expressed in Mm^3/a.
- Estimate the EWR using the flow requirements per unit channel width (Table 3.7), together with the estimate of channel width;
- If these estimates are greater than the Desktop generated values, adjust the Desktop values for drought and/or maintenance. Do not reduce Desktop generated values nor exceed natural low-flows.

3.4 SUMMARY

A step-wise process has been followed to develop and test an EWR “estimation” method, at the desktop level, that takes explicit account of biotic requirements and hydraulic habitat. The method is an extension of the “extrapolation” approach, whereby EWRs are determined by extrapolating EWR results (fundamentally hydrological scaling) from Reserve studies for sites located elsewhere in the catchment, usually with substantial runoff (generally > –50 Mm^3/a). The main focus has been to consider lower runoff rivers (MAR < –30 Mm^3/a), where Desktop model estimates appear to often under-estimate the EWR (since the model is based on results of previous EWR assessments, and almost entirely on ecological-hydrological relationships for rivers with greater runoff). Two tributaries of the Elands River (Mpumalanga province) were initially considered and data from sites on these rivers was used to develop the concept of habitat-specifications, or HabSpecs. HabSpecs are numerical values for a combination of hydraulic parameters (e.g. depth) and flow-classes (e.g. fast-deep flow) that define hydraulic habitat, and are a function of hydrological variability (drought, maintenance and seasonality), EC, and biota. An objective procedure for determining HabSpecs using previous Ecological Reserve results was used that provides “calibrated” numerical values that are based on the collective knowledge and understanding of the river ecologists involved in ecological flow assessments over the past few years.

HabSpecs were determined for two fish guilds, small rheophilics (less than 10 to 15 cm in length) and large semi-rheophilics (greater than 25 to 30 cm in length), as well as for cobble-dwelling rheophilic invertebrate communities. The two fish guilds are associated with rivers with MARs of less than and greater than –30 to 50 Mm^3/a, respectively. For the rheophilic invertebrate communities, different sets of HabSpecs apply to the lower and higher runoffs. The HabSpecs were tested using eleven sites in the upper Nkomati River catchment (biota is similar to that found in the Elands River system), ten of which are on tributaries with MARs below 30 Mm^3/a. The adequacy of the HabSpec EWR estimates in providing sufficient hydraulic habitat was assessed.

Overall the HabSpec generated flows were considered to provide more reasonable estimates of the EWR than the Desktop model, particularly for the sites with lower runoff (lowest MAR –4 Mm^3/a). 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.

Furthermore, the analysis shows that the EWR requirement per unit width of inundated channel is remarkably constant, and can be used to define minimum seasonal drought and maintenance requirements. This resulted in a simple method

(DAM) for adjusting the Desktop generated flows using an approximate estimate of inundated channel width at a relevant low-flow depth. This estimation procedure was applied to certain hydro-nodes in the Nkomati River catchment (MARs < –50 Mm^3/a) to estimate EWR for the purposes of water resources planning. For hydro-nodes with higher runoff, EWR were estimated by extrapolating Reserve results where ecological similarity permitted, or alternatively by applying the Desktop model.

4 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

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The main focus of this study has been to develop an improved method for estimating EWRs at the desktop level for lower runoff (MAR < – 30 Mm^3/a) tributary sites that are often at the sub-quaternary catchment scale. The study has concentrated on low-flows, with the recognition that high-flows also need to be addressed with future developments of the method. Since Desktop model estimates are based on natural hydrology, which is frequently provided through modelled monthly data, it is recognised that this may be a significant source of error in existing Desktop model predictions of ecological flows, particularly for small streams with low runoff. For this reason, the estimation method pursued in this study initially approaches the problem from a “biotic presence - habitat preference - habitat availability” perspective. However, since ecological flows are best considered within the context of hydrological constraints (e.g. natural, historical and present day flow regimes), the final output requires hydrological context. This is provided for in this study by using a simple method for adjusting default Desktop model generated low-flow EWRs. The method is applicable to two fish guilds and invertebrate communities considered within this study, and hydrological characteristics of the Nkomati River catchment.

4.1 ASSESSING SITE SIMILARITY AND PREDICTING FISH INDICATOR SPECIES

This component of the study developed a procedure 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.

The attributes used to establish physical site similarity included, Level 1 Ecoregions; altitude; stream order, and longitudinal geomorphic zone. The Bray Curtis analysis was used to determine the degree of physical similarity, and sites were considered similar if the index was greater than 0.9 (a “very high” condition was used to ensure sufficient confidence in the assessment).

Fish assemblages are assessed in terms of the presence of species that are indicators of ecological flows, and included flow (velocity) dependence (i.e. rheophilic, semi-rheophilic or limnophilic guilds) and fish size (length and body depth) characteristics. Relative ratings to fundamental determinants of fish habitat (viz. velocity-depth classes, flow intolerance, cover and physical-chemical intolerance) were used to identify fish species that are sensitive indicators of flow conditions at sampled river sites. Based on this information and a condition of very high physical similarity between sites with fish information and un-sampled river sites, fish indicator species at the latter sites were predicted.

4.2 DEVELOPING HABITAT SPECIFICATIONS FOR OTHER BIOTIC "GROUPS"

Habitat specifications, or HabSpecs are numerical values for a combination of hydraulic parameters (e.g. depth) and flow-classes (e.g. fast-deep) that define hydraulic habitat and hence flow requirements for "groups" of biota that exploit environmental resources in a similar way (generally referred to as guilds for fish and communities for invertebrates). HabSpecs are also a function of hydrological variability (e.g. drought, maintenance and season) and Ecological Category (EC).

In this study, HabSpecs were determined for two fish guilds: small rheophilic fish (length less than 10 to 15 cm) and large semi-rheophilic fish (length greater than 25 to 30 cm) - refer to Table 4.1. Small and large fish length was found to corresponded with river size, as determined using naturalised runoff in the ranges 5 to 30, and 60 to 520 Mm^3/a, respectively. A single group of invertebrates were used, viz. a cobble-dwelling rheophilic community, and two sets of HabSpecs were developed for this community - each corresponding to similar ranges of runoff as defined for the fish guilds (refer to Table 4.2).

HabSpecs were calculated using an optimisation method based on the results of previous EWR studies for 15 sites (at various levels of Reserve), augmented with data collected in this study from two tributary sites on Elands River (Mpumalanga). This effectively provides "calibrated" numerical rules that are based on the collective knowledge and understanding of river ecologists involved in ecological flow assessments over the past few years.

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 (refer to Tables 4.1 and 4.2). This is supported by studies in the international literature (e.g. Maret *et al.*, 2006; Conservation Ontario (2005); Jowett (1997) and Beecher (1990)).

Table 4.1 Optimised HabSpecs for small rheophilic and large semi-rheophilic fish guilds for small and large rivers (as measured using MAR).

Hydrological variability	Ecological Category	Season	Fish guilds					
			Small rheophilic (Length < 10 to 15 cm)			Large semi -rheophilic (Length > 25 to 30 cm)		
			Mean annual runoff (Mm^3/a)					
			5 to 30			60 to 520		
			Hydraulic parameter or flow-class					
			y (cm)	*F (%)*	*F.1 (%)*	*y (cm)*	*F (%)*	*F.2 (%)*
Drought		Wet	19	13	4	34	21	18
		Dry	16	2	1	30	11	8
Maintenance	C	Wet	22	23	10	38	31	28
		Dry	18	12	2	33	20	17
	B	Wet	28	43	26	47	53	45
		Dry	21	25	11	35	28	23

Abbreviations:
y=maximum depth
F=fast flow (velocity greater than 0.3 m/s)
F.1=fast flow with a depth greater than 0.1 m
F.2=fast flow with a depth greater than 0.2 m

Table 4.2 Optimised HabSpecs for cobble dwelling rheophilic invertebrate communities determined separately for small and large rivers (as measured using MAR).

Hydrological variability	Ecological Category	Season	Mean annual runoff (Mm^3/a)							
			5 to 30				50 to 530			
			Hydraulic parameter or flow-class							
			y (cm)	y_{av} *(cm)*	v_{av} *(cm/s)*	FCS *(%)*	*y (cm)*	y_{av} *(cm)*	v_{av} *(cm/s)*	FCS *(%)*
Drought		Wet	19	8	15	5	28	15	16	7
		Dry	16	5	8	1	23	12	12	4
Maintenance	C	Wet	22	10	23	14	32	20	29	24(18)
		Dry	18	7	13	4	29	17	16	8
	B	Wet	27	11	27	20	36	24	38	29
		Dry	21	9	22	12	28(30)	16(19)	27	21

Abbreviations:
y=maximum depth
y_{av}=average depth
v_{av}=average velocity
FCS=fast flow (velocity greater than 0.3 m/s) over coarse substrate (greater than 16 mm dia.)
FCS values apply to a standardised proportion of coarse sediment (50%)
(x) - adjusted value based on adjacent categories

4.3 ESTIMATING ECOLOGICAL WATER REQUIREMENTS FOR THE NKOMATI RIVER CATCHMENT

The Nkomati Water Availability Assessment Study (WAAS), initiated in 2006, requires estimates of the Ecological Reserve for approximately 70 hydro-nodes. This catchment is therefore the basis for application of methods developed within this project.

4.3.1 Application of HabSpecs to selected river sites

Habitat specifications provide a simple and consistent rule-based approach for estimating EWRs where hydraulic characterisation of flow conditions is available, i.e. presently at Rapid level III assessments and higher. Rapid level III-type hydraulic data collection and modelling was carried out for 11 sites in the upper Nkomati River catchment for the purpose of testing HabSpec generated EWRs.

Overall, the HabSpec predicted ecological flows 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). 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.

4.3.2 Application of HabSpecs to hydro-nodes

Use of HabSpecs requires hydraulic characterisation, and at the desktop level this implies no field data are available. The ability to predict hydraulic characteristics in the absence of field data requires substantial further research and development, and this is being undertaken through concurrent research projects funded by the WRC. For the current study, the need to estimate EWRs for hydro-nodes within the Nkomati River catchment therefore required an alternative approach:

The HabSpec generated low-flows for the selected river sites within the Nkomati River catchment (Section 4.3.1) were expressed as a function of the inundated width (at a maximum depth of 0.2 m). The unit-width low-flows were found to be remarkably constant, with the exception of two outliers - but given the lower-confidence Rapid level III hydraulic data and modelling, scatter is not unexpected. Neglecting the outliers, the average flow requirement per unit width for the various

ECs is provided in Table 4.3. These flows define the *minimum seasonal drought and maintenance discharges required to achieve the recommended EC for the sensitive rheophilic biota considered.*

It is a significant finding that the low-flow EWR per unit width of inundated channel (at an appropriate low-flow depth) gives an approximately constant value. This finding may be related to the use of multi-parameter criteria (HabSpecs) that incorporate the two fundamental determinants of discharge (viz. depth and velocity). Satisfying minimum values for these parameters for critical hydraulic habitat for rheophilic species (provided within a riffle) results in constant unit width discharge. It needs to be re-emphasized, however, that the unit-width EWR results from this study (i.e. Table 4.3) are applicable to specific fish guilds and invertebrate communities (i.e. Tables 4.1 and 4.2), and hydrological characteristics of the Nkomati River catchment. Further testing and development is required for a more general application. This is taking place during concurrent research projects and Reserve studies.

Table 4.3 Flow requirements per unit width of channel for small rheophilic fish guilds and cobble-dwelling rheophilic invertebrates.

Hydrological Variability	Ecological Category	EWR (litres/s/m) Season Dry	Wet
Drought		7	21
Maintenance	D	11[1]	29[1]
	C/D	16[1]	38[1]
	C	20	46
	B/C	30[1]	61[1]
	B	39	75

[1]interpolated linearly

Application of the ecological flows in Table 4.3 requires channel width at an appropriate low-flow depth. An approximate relationship (substantial scatter was noted) was derived for this purpose by correlating low-flow channel widths with MAR using a limited data set. Although this width-runoff relationship needs to be used with caution, this estimation method is considered to provide higher confidence low-flow EWRs than the existing Desktop model for small rivers (MAR < –30 Mm^3/a) with sensitive rheophilic biota (small rheophilic fish guilds less than 10 to 15 cm in length and rheophilic invertebrate communities) and with similar hydrological characteristics.

The following procedure was used for estimating EWRs for each of the 70 hydro-nodes required for water resources modelling in the Nkomati catchment:

For hydro-nodes with large-semi rheophilic fish guilds (generally MAR > –50 Mm^3/a), the EWRs can be determined by:

- Extrapolating (hydrologically) Reserve results where ecological similarity permits, or
- if ecological similarity does not allow, apply the Desktop model with default parameters and naturalised modelled hydrology from the Nkomati WAAS.

For nodes with small rheophilic fish guilds and MAR < –50 Mm^3/a:

- Apply the Desktop model using default parameters (Nkomati WAAS hydrology);
- Determine the natural drought (95% exceedance) and maintenance (70% exceedance) flows for the driest and wettest months from the natural flow duration table (provided in the .RUL file);
- Estimate the channel width (*W*) at 0.2 m depth, using *W* = 3.6*log*(MAR) where the MAR is expressed in Mm^3/a.
- Estimate the EWR using the flow requirements per unit channel width (Table 4.3), together with the estimate of channel width;
- If these estimates are greater than the Desktop generated values, adjust the Desktop values for drought and/or maintenance. Do not reduce Desktop generated values nor exceed natural low-flows.

4.4 RECOMMENDATIONS

The original objective of this project was to develop a procedure for determining the ecological justification for *extrapolating* (hydrologically) EWR results from Reserve sites to additional locations required for water resource planning. This objective was extended in this study to *estimating* EWRs by explicitly incorporating biological information, flow preferences for the biota present, and availability of hydraulic habitat. In developing the principles for extrapolating AND estimating EWRs, the need for further studies, which are well beyond the scope of the project, have become apparent. Some of this work is being addressed in concurrent WRC funded research as well as during the course of Reserve studies.

Recommendations regarding the use of the procedures developed, and studies necessary for further development of this estimation process include:

4.4.1 Assessing site similarity and predicting fish indicator species

- The use of mean annual runoff (where sufficiently accurate) and stream ordering according to the approach of Shreve (Gordon *et al.*, 1994) should be considered for improving predictions of stream size and hence indicator species at a site;
- Different models and approaches need to be considered for predicting species distribution and degrees of perenniality under reference and present conditions;

- The procedure for assessing site similarity and fish assemblages requires testing through field data.

4.4.2 Developing habitat specifications for other groups

- Habitat specifications have been defined for common groups of biota relevant to the Nkomati River catchment (viz. small rheophilic and large semi-rheophilic fish guilds and cobble-dwelling rheophilic invertebrate communities). These need to be extended to other indicator groups, including, for example large rheophilic and small semi-rheophilic fish guilds, and invertebrate communities that utilise fine sediment and inundated vegetation.

4.4.3 Characterising hydraulic habitat at the desktop level

- The use of HabSpecs requires hydraulic characterisation, and at the desktop level this implies no field data are available. The ability to predict hydraulic characteristics in the absence of field data requires substantial further research and development. This is being addressed by two concurrent research projects funded by the WRC. The first of these (K8-795) involves the analysis of available hydraulic information from previous Ecological Reserves. This will allow the assessment of empirical relationships for estimating physical (channel shape) and hydraulic parameters with. The second of these projects (Proposal no. 1001293) will be using this information within a revised desktop approach that explicitly accounts for "biotic presence - habitat preference - habitat availability". This is a refinement of the existing Desktop model where ecological empirisicm is through the use of different ECs.
- The current study indicates that the EWR requirement per unit width of inundated channel is remarkably constant. This, the use of hydrological determinants to estimate low-flow channel widths (MAR was used in this study), and the influence of channel shape, deserves further investigation. This is because such simplifying relationships will alleviate the need for detailed hydraulic characterisation, as revealed in this study for the hydro-nodes in the Nkomati River catchment.

4.4.4 Integrating biological, hydraulic and hydrological components in an updated Desktop Reserve model

- Application of HabSpecs to the Nkomati River catchment concentrated on "smaller" (runoff) streams that have received the least attention during Ecological Reserve studies. Although it was found that the Desktop model provides reasonable estimates for "larger" rivers, further development of the Desktop Reserve model needs to expand the scope of application (from this study) to rivers with different ecological (HabSpecs), geomorphological (hydraulic habitat) and hydrological characteristics.

- Although the application to the Nkomati catchment applied manual adjustment of default Desktop model parameters, this requires automation in an updated model.

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APPENDIX: MACROINVERTEBRATE SITE SIMILARITY

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PROCESS, ATTRIBUTES AND CONFIDENCE

The process followed for assessing the site similarity from a macroinvertebrate perspective is as follows:

Establish a database of macroinvertebrate taxa at family level (SASS data), occurring at different sites (i.e. sampled) in the study area (similar to Table 2.1 for fish) Environmental attributes to be included in the database includes: geographic co-ordinates, Ecoregion level I and II information, the geomorphic zone, altitude, perenniality and stream size characteristics (stream width, stream order or MAR depending on the available information). Filtering is then conducted according to: Ecoregion Level I; Ecoregion Level II; geomorphic zone; altitude and stream size.

Additional reference taxa should be added to the list in order to establish reference conditions for the particular site. Presently, no reference database exists for macroinvertebrate taxa at a national level, and a project has been initiated to generate this information.

The filtered data is then used to make predictions regarding the expected macroinvertebrate taxa at un-sampled (i.e. no SASS data) hydrological nodes. Sites and nodes with that are most similar (in terms of the environmental attributes given above) are used for prediction purposes, with lower similarity implying lower confidence.

SELECTION OF INDICATOR TAXA

Following the filtering process, taxa that are sensitive to both flow and water quality need to be selected. The reference taxa list is used for this purpose and sensitive riffle-dwelling taxa are used. Only riffle-dwellers are presently considered due to the critical habitat that this geomorphological feature provides.

APPLICATION IN THE NKOMATI RIVER CATCHMENT

A database of all available SASS data from sites in the Inkomati catchment was used to define a broad community (i.e. cobble-dwelling rheophilics) for which habitat-specifications were developed within this project (refer to Table 3.3 or Table 4.2). Although the indicator taxa differed slightly between nodes, they have the same general hydraulic habitat requirements pertinent to development of an EWR estimation method at the desktop level.