Orange-Senqu River Basin

Orange-Senqu River Commission Secretariat
Governments of Botswana, Lesotho, Namibia and South Africa

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Hydrology and River Hydraulics

Research project on environmental flow requirements of the Fish River and the Orange-Senqu River Mouth

Technical Report 31
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UNDP-GEF
Orange-Senqu Strategic Action Programme

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Research Project on Environmental Flow Requirements of the Fish River and the Orange-Senqu River Mouth

This report was compiled by Rivers for Africa, e-Flows Consulting (PTY) LTD (iwre@icon.co.za), Pretoria, South Africa with assistance from the Ministry of Environment and Tourism, Directorate of Parks and Wildlife Management, Namibia during surveys and hydrological observed/real time data obtained from Ministry of Agriculture, Water and Forestry, Department of Water Affairs and Forestry, Namibia.

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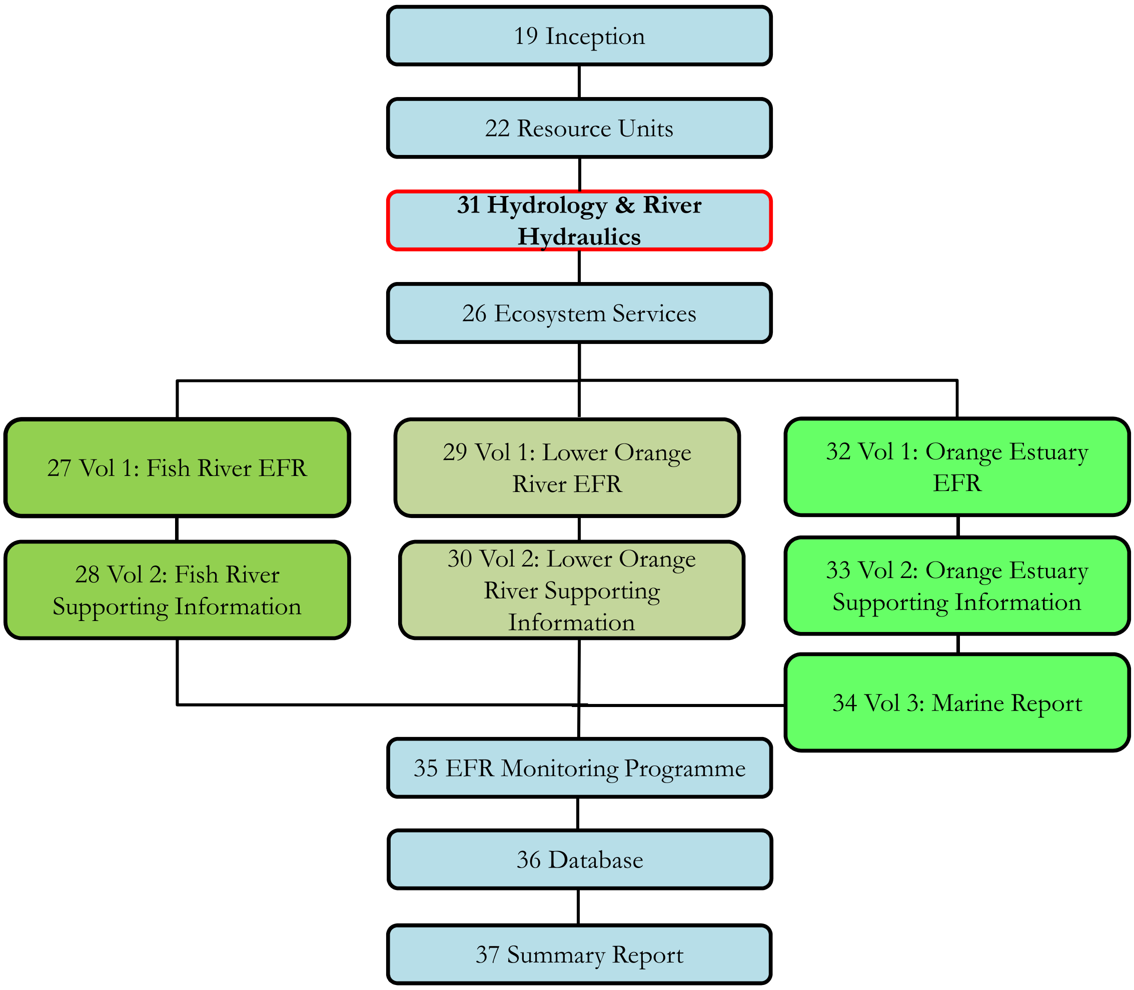
Report list

A list of the Technical Reports that form of this study is provided below. A diagram illustrating the linkages between the reports is also provided.

Technical Report No	Report
19	Inception Report, Research project on environmental flow requirements of the Fish River and the Orange-Senqu River Mouth
22	Delineation of the Study Area – Resource Unit Report, Research project on environmental flow requirements of the Fish River and the Orange-Senqu River Mouth
26	Consequences of Scenarios on Ecosystem Services, Research project on environmental flow requirements of the Fish River and the Orange-Senqu River Mouth
27	River EFR assessment, Volume 1: Determination of Fish River EFR Research project on environmental flow requirements of the Fish River and the Orange-Senqu River Mouth
28	River EFR assessment, Volume 2: Fish River EFR, supporting information Research project on environmental flow requirements of the Fish River and the Orange-Senqu River Mouth
29	River EFR assessment, Volume 1: Determination of the lower Orange River EFR Research project on environmental flow requirements of the Fish River and the Orange-Senqu River Mouth
30	River EFR assessment, Volume 2: Lower Orange River EFR, supporting information Research project on environmental flow requirements of the Fish River and the Orange-Senqu River Mouth
31	**River and Estuary EFR assessment, Hydrology and River Hydraulics** **Research project on environmental flow requirements of the Fish River and the Orange-Senqu River Mouth**
32	Estuary and Marine EFR assessment, Volume 1: Determination of Orange Estuary EFR Research project on environmental flow requirements of the Fish River and the Orange-Senqu River Mouth
33	Estuary and Marine EFR assessment, Volume 2: Orange Estuary EFR: Supporting Information Research project on environmental flow requirements of the Fish River and the Orange-Senqu River Mouth
34	Estuary and Marine EFR assessment, Volume 3: Assessment of the Role of Freshwater Inflows in the Coastal Marine Ecosystem Research project on environmental flow requirements of the Fish River and the Orange-Senqu River Mouth
35	EFR monitoring programme, Research project on environmental flow requirements of the Fish River and the Orange-Senqu River Mouth
36	Database, Research project on environmental flow requirements of the Fish River and the Orange-Senqu River Mouth

Technical Report No	Report
37	Summary Report, Research project on environmental flow requirements of the Fish River and the Orange-Senqu River Mouth

Bold indicates current report.



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Hydrology
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Abbreviations

AMD	Acid mine drainage
DEM	Digital Elevation Model
DRFN	Desert Research Foundation of Namibia
EFR	Environmental flow requirement
FDC	Flow duration curve
GROWAS	Groundwater information system
HEC-RAS	Hydrologic Engineering Centers River Analysis System
LORMS	Lower Orange River Management System
MAR	Mean annual runoff
MAWF	Namibia Ministry of Water Affairs and Forestry
mgbl	Below ground level
MRU	Management resource unit
ORASECOM	Orange-Senqu River Commission
PD	Present day
RO	Release option
RO Opt	Optimised release option
Sc	Scenario
SRTM	Shuttle Radar Topography Mission
WReMP	Water Resources Modelling Platform
WRPM	Water Resources Planning Model

Velocity Depth Classes: Fish

FD	Fast deep
FI	Fast intermediate
FS	Fast shallow
SCS	Shallow over coarse substrate
SD	Slow deep
SS	Slow shallow

Velocity Depth Classes: Macro-invertebrates

FCS	Fast over coarse substrate
FFS	Fast over fine substrate
FVS	Fast very shallow
SCS	Shallow over coarse substrate
SFS	Shallow over fine substrate
SVS	Slow very shallow
VFCS	Very fast over coarse substrate
VFFS	Very fast over fine substrate
VSCS	Very shallow over coarse substrate
VSFS	Very shallow over fine substrate

1. Introduction

1.1 Study area

The study area for the Research Project on environmental flow requirements (EFRs) of the Fish River and the Orange-Senqu Estuary is the Orange River downstream of the Fish River confluence (including the estuary and immediate marine environment) and the Fish River (Technical Report 22). This report focuses on the hydrology, hydraulics and geohydrology of the Orange River downstream of Sendelingsdrift to the estuary including the Fish River in Namibia.

Three EFR sites are included in this study: two along the Fish River (Namibia), and one along the Orange River between the Fish River confluence and its mouth (Namibia-South Africa border). The locations of the sites are given in Table 1. EFR Fish 1 is located approximately 70 km upstream of the proposed Neckartal Dam wall (approximately 251 km downstream of the Hardap Dam wall), and EFR Fish 2 is located approximately 25 km downstream of the proposed Neckartal Dam wall (immediately downstream of the Seeheim Gauge (Station 0496M01), refer to Figure 1).

Table 1. Positions of sites along the Fish and Orange Rivers

Site	***Latitude (South)***	***Longitude (East)***
EFR Fish 1	26.2831°	17.7602°
EFR Fish 2	26.8221°	17.7897°
EFR O5	28.0721°	16.9602°

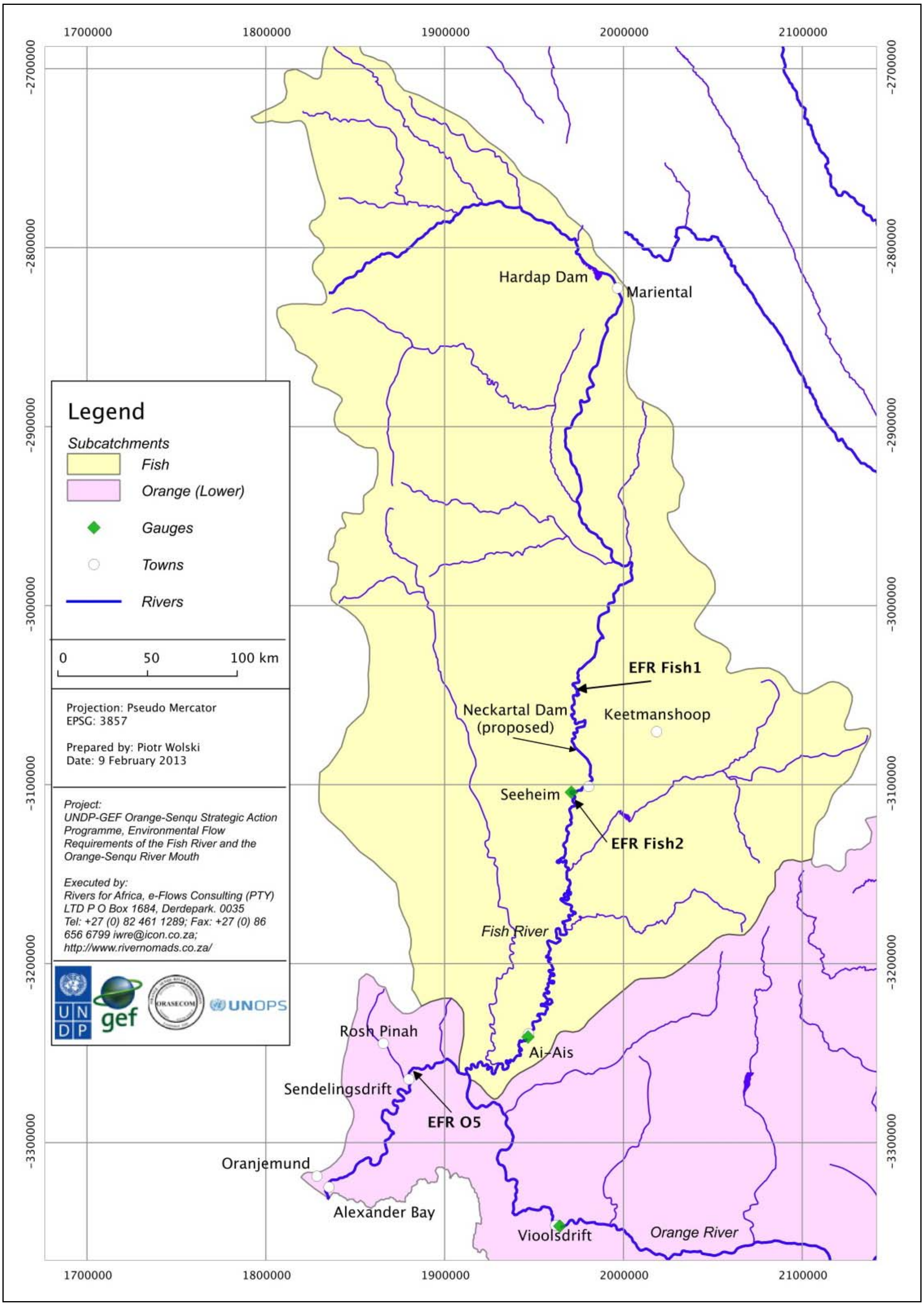

Figure 1. Study area

1.2 Aims of the report

This report documents the hydrological, hydraulic and geohydrological information used for river and estuary EFR assessments (Technical Report 27, 29 and 32).

1.3 Scope of the hydrological modelling for the Fish and Orange rivers

The hydrology of the Orange River has been modelled in detail as part of previous studies to provide natural and present day hydrology, most recently during 2010 (ORASECOM, 2010a). The Fish River hydrology was not updated during the 2010 study. Hence, the hydrology available for this EFR Study does not cover the same time period in the Fish and Orange River catchments. The hydrology for the Orange River covers the period 1920 to 2005 while the hydrology for the Fish River only covered the period 1920 to 1999. It was therefore necessary to revisit the hydrology of the Fish River.

1.4 Scope of scenario modelling for the Fish and Orange rivers

Scenarios include specific development or operational options which are referred to as drivers while the combination of drivers is referred to as a Scenario. Timing is also attached to the drivers and scenarios. The possible/likely drivers and scenarios as modelled were derived from two meetings; the first held in Pretoria on 31 August 2012 and the second held in Windhoek on 21 September 2012. The drivers and scenarios forthcoming from the first meeting related to developments envisaged by South Africa and Lesotho, while drivers and scenarios from the second meeting related to developments envisaged by Namibia.

1.5 Catchments constraints and limitations

Fish River hydrology

The hydrology for both Hardap and Neckartal dams was developed as part of the earlier Lower Orange River Management Study (LORMS), but due to funding and time constraints, the hydrological assessment could not be carried out to the level of detail generally required for the planning of large water resource developments (Republic of Namibia, Ministry of Agriculture, Water and Forestry, Directorate Rural Water Supply, 2010). The Fish River hydrology was also not updated during the 2010 Orange-Senqu River Commission (ORASECOM) Study (ORESECOM, 2010a). This EFR study required updated hydrology in a daily format and at the scale required for the EFR assessment. Therefore, due to the uncertainties in the natural hydrology used in previous studies, the hydrology of the Fish River was re-evaluated from first principles, but using the experience gained from previous studies.

Neckartal Dam

An important constraint in any environmental flow study is the limit on the flow that can be released from a dam through the outlets. In the case of Neckartal Dam, the information provided was that the outlets works would have a maximum discharge capacity of 100 m^3/s. This constraint was therefore built into the simulation carried out to establish a recommended EFR for the Neckartal Dam. This maximum design discharge capacity of 100 m^3/s is based on the assumption that the dam is full, while at lower levels of storage the flow rate through the outlet works is assumed to reduce. The relationships between storage level and outlet discharge rate (i.e. the outlet works rating curve) was estimated for use in this study.

River losses

It is well established that there are large natural losses in the Fish River and the lower reaches of the Orange River where the natural inflow from tributaries is much lower than the evaporation losses. This has a significant effect on the flow regime in the lower reaches of the river in that a zero flow is theoretically possible. Very low flows have been observed at the Vioolsdrift gauge, and taking into account further losses between the weir and the estuary as well as water use, the period of zero flow at the mouth becomes significant. It is, therefore, essential that these losses be taken into account in any hydrological modelling of the lower Orange River.

The losses in the lower Orange River have been estimated as part of previous studies and these estimates have been used in this study. The limitation is that the losses are assumed to be the same every year and not related to the river stage or climatic conditions. To improve on these simplistic assumptions would require detailed hydrodynamic modelling. This is beyond the scope of this study. The losses in the Fish River were simulated as part of the hydrological modelling using hypothetical ('dummy') small dams to represent the in-channel pool storage.

HEC-RAS

The unsteady open-source hydraulic modelling software, Hydrologic Engineering Centers River Analysis System (HEC-RAS v4.1 available at http://www.hec.usace.army.mil/software/hec-ras) was used to simulate daily flow time series at different points within the Fish River channel systems based on the disaggregated monthly outputs from the yield model (see section 3.4). Although more sophisticated hydraulic models are available, the available hydrological and topographical information for the Fish River system and resources available for this component of the study do not warrant the parameterisation of more complex models. A drawback of using HEC-RAS for the Fish River system is its inability to explicitly account for changes in pool storage during the cessation of surface flow, which is an important hydrological characteristic of the system. These, were, however, included in the HEC-RAS modelling using various other available hydraulic structures (lateral weirs) and storage systems (discrete off-channel storage areas) that are connected using linear routing (refer to Appendix A).

1.6 Report structure

The report consists of the following chapters:

Chapter 1: Introduction

This chapter provides an overview of the study area, objectives of the study as well as a discussion regarding the constraints and limitations regarding the hydrology, hydraulics and geohydrology of this study.

Chapter 2: Fish River: Modelling and hydrological characteristics

Outlines the hydrological characteristics of the Fish River and provides detail regarding the hydrology of the Fish River system.

Chapter 3: Fish River: Monthly and daily simulations

The approach to water resource modelling of the Fish River is discussed in this chapter.

Chapter 4: Fish River: Development and evaluation of drivers and scenarios

This chapter explains the process of scenario development undertaken for the Fish River.

Chapter 5: Orange River: Hydrological characteristics, modelling and scenarios

This chapter includes a discussion on the hydrological characteristics of the Orange River, as well as water resource modelling and development of scenarios.

Chapter 6: Ecohydraulics

This chapter explains how cross-sectional surveys and the results of one-dimensional hydraulic analyses were used in the EFR process.

Chapter 8: References

Details on the hydrodynamic modelling and groundwater/surface water interaction are included as appendices.

Appendix A: Seeheim gauge: Approach to implementing the double triangle method

The approach to implementing the double triangle method for the flows at Seeheim gauge is provided in Appendix A.

Appendix B: Hydraulic rating coefficients and lookup tables

The rating parameters of the hydraulic modelling are provided as well as lookup tables, which was used for ecological interpretation for fish and macro-invertebrates are provided for the EFR sites in the Fish River and Orange River.

Appendix C: Hydrodynamic modelling of the Fish River

The hydrodynamic modelling component of the hydrological study for the Fish River system is discussed.

Appendix D: Fish River hydrogeology: A hydrogeological review of interaction between aquifers and river flooding

The linkage between ground and surface water in the Fish River system is discussed.

2. Fish River: Modelling and hydrological characteristics

2.1 Modelling approach for the Fish River

Due to concerns raised by Namibia's Department of Water Affairs and Forestry about the available Fish River hydrology simulations and the inadequacy of this data for the EFR study (refer to section 1.5.1), the hydrology of the Fish River was re-evaluated as part of this study and is reported on in this chapter. The main difference between this hydrological study and previous studies is that in this analysis the channel losses in the system were approximately quantified and modelled, using hypothetical small dams to simulate evaporation losses from channel pools.

Furthermore daily disaggregation was required to assess the EFRs. The releases (and their effects on yield) from Neckartal Dam were simulated using a monthly model, but to be able to evaluate these from an EFR perspective they had to be converted to daily flows that were routed down the channel system. This was achieved by translating simulated monthly flow volumes into daily flow releases and tributary inflows which were then routed through the channel system using the HEC-RAS model.

2.2 Available data

Stream flow data

Stream flow data are available for the inflows to Hardap and Naute dams, at Seeheim gauge and at Ai-Ais gauge. Most of the records were started in 1962 although recording at Ai-Ais gauge appears to have only started in the 1970s. The records appear to be reasonably complete without any long periods of missing data. However, there was no information provided to the study team about the quality of the records. Certainly, the gauge at Seeheim is long and of a relatively uniform height along most of its length, and therefore the flow variations would not be expected to be very sensitive to changes in stage. It is also likely that many of the higher recorded flows are not very accurate given the difficulties of gauging in such wide channels.

In addition to the channel stream flow observations there are also some data for managed releases made from Hardap and Naute dams. The Hardap Dam releases are very important for understanding the extent and magnitude of incremental inflows between Hardap and Seeheim gauge. According to the records, the dam releases (including spillage) have only occurred during exceptionally wet years.

Rainfall data

There are a number of rain gauges within the catchment (Figure 2) that have recorded rainfall during the past, however, based on the data that were made available, many of these are no longer active. The period selected as having the best spatial coverage of available data with which to estimate sub-basin average rainfall time series was October 1930 to September 1995. Extending the rainfall estimates into the 2000s would have been useful to match the available stream flow data, but would have resulted in unreliable and potentially inconsistent estimates for the last ten or so years.

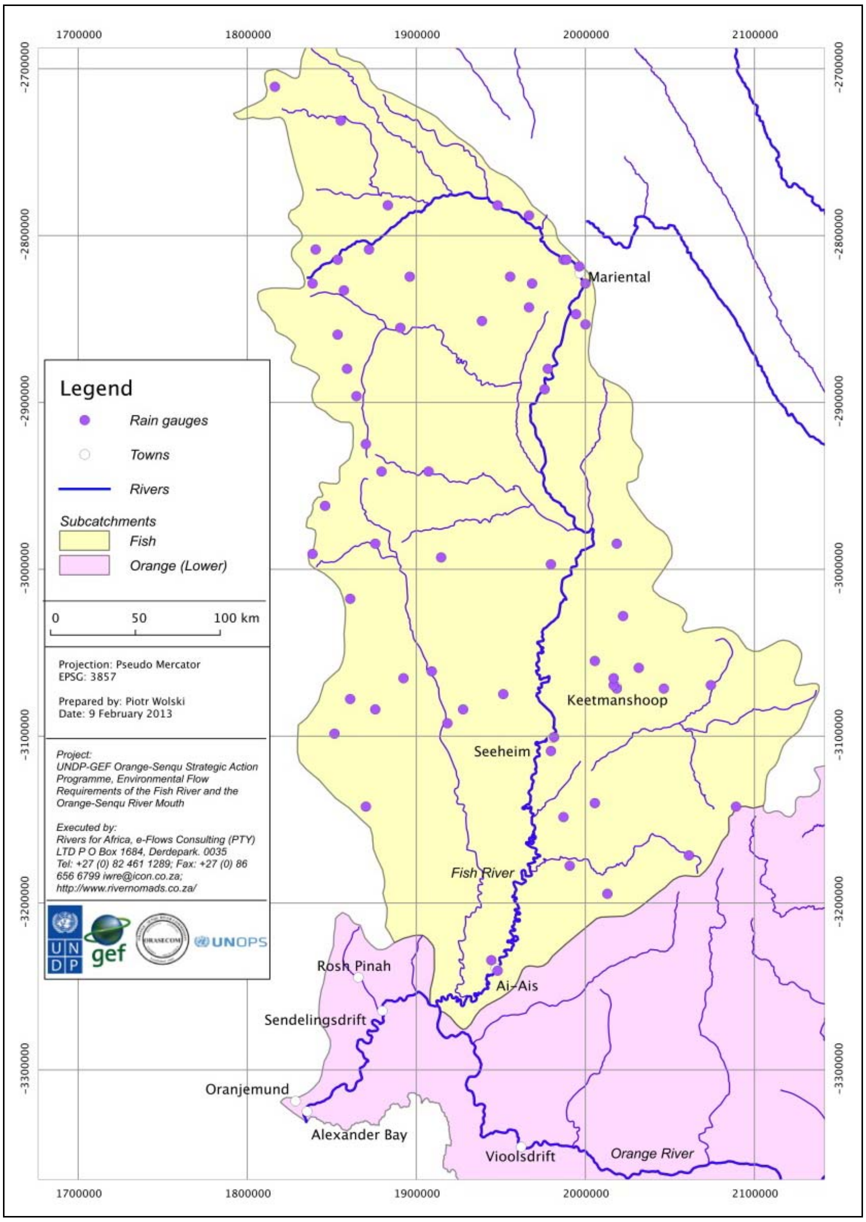

Figure 2. Rain gauges in the Fish River catchment

2.3 Daily stream flow characteristics

The flow regime of the Fish River (and tributaries) is characterised by high variability. Seeheim Gauge has a maximum observed mean daily flow of 6,270 m^3/s, while the flow equalled or exceeded 10% of the time is approximately 8 m^3/s. Zero flow conditions are experienced 70% of time (based on daily flows). At Ai-Ais gauge, the equivalent values are a maximum of 3,470 m^3/s, a flow exceeded 10% of the time of 1.5 m^3/s and zero flows for about 78% of the time. However, this is based on a shorter record that does not include two wet years in 1972 and 1974.

There are strong similarities in the shapes of the observed hydrographs at Hardap (inflows) and Seeheim Gauge, despite the fact that no releases were made from Hardap Dam in most years (only nine times in the years between 1963 and 2006). This suggests that the flows at Seeheim are not totally dependent upon flows from the upper parts of the catchment above Hardap Dam. There is, however, evidence for quite substantial attenuation and loss of flow between Seeheim gauge and Ai-Ais gauge in most years, partly influenced by the limited number (and magnitude) of spills and releases from Naute Dam. These patterns of attenuation and loss are difficult to generalise and it is clear that the contribution of the lower and western tributaries is highly variable. The attenuation of high flows between Seeheim and Ai-Ais gauges could also result in longer durations of baseflow following large floods. While there are not sufficient data to reach definitive conclusions, the additional duration of flow after large events at Ai-Ais gauge may compensate for the total loss of smaller flow events along the channel between these two sites. The result being quite similar durations of zero flow as noted from the available observed records.

It is reasonable to assume that the pattern of daily flows represented by the observed data at Seeheim gauge is relatively natural, while the actual magnitudes may be lowered through storage and use in Hardap Dam. Similarly, the patterns of flow at Ai-Ais gauge are also likely to be relatively natural, but it is distinctly possible that the attenuation and channel loss effects may be exaggerated by the loss of some inflows from the Löwen River (Naute Dam), as well as somewhat reduced flow magnitudes at Seeheim gauge.

Characteristic hydrographs (high flows with peaks exceeding 2,000 m^3/s) at Seeheim gauge

There are six of these in the observed record up to 2010. There are generally multiple peaks within the whole flow period which can last for over six months, but the total flow period is quite variable. The peaks typically occur at the beginning (January to March) of the year. The main hydrograph (flows above 5 to 10 m^3/s) typically lasts for less than three months, followed by a highly variable period of low flows. There is a relatively poor relationship between the period of low flows and the size of the peak.

Characteristic hydrographs (high flows with peaks of 250 to 2,000 m^3/s) at Seeheim gauge

These events occurred during 13 of the 50 years of observations. The duration of these events is typically less than six months depending on the size of the peak and the number of peaks that occur within a single season.

Characteristic hydrographs (high flows with peaks of less than 250 m³/s) at Seeheim gauge

These events occurred during the remaining years of the record, with the exception of three years (1982, 2003, and 2004) when there were no flows. The peaks can be as low as 5 m³/s and the durations less than one month. It is possible to find more than one such event in a single year (extending the total flow duration) and these events can occur together with events of a higher magnitude (superimposed on somewhat more continuous baseflows).

3. Fish River: Monthly and daily simulations

The Pitman and Water Resources Modelling Platform (WReMP) (Mallory et al., 2011) models were used to simulate the monthly hydrology of the Fish River and develop various scenarios of future development. The Pitman rainfall-runoff model was used to generate the natural incremental flows at 17 nodes within the whole basin (Figure 3). The nodes were established to represent key points on the main river (EFR sites and existing or planned reservoirs), as well as the main tributaries. Pool storage was approximately quantified for each of the nodes on the basis of the length of the main channel above the node (up to the previous node or the catchment boundary) together with assumptions about the average width and depth of the pools and the proportion of the channel length having pools (Table 2). The estimated pool-storage volume was used to establish 'dummy' dams within the model in an attempt to account for in-stream losses.

Table 2. Catchment area and channel pool characteristics for the nodes

Node	Area (km^2)	Flows into	Pool length (km)	Pool width (m)	Pool depth (m)	Pool surface area (km^2)	Pool volume (Mm^3)*
F1	6657	F2	150	30	1.5	1.8	2.7
F2	6764	F3	125	40	2	2	4
F3	2722	F5_3	140	60	2	3.36	6.72
F4_1	7537	F4_3	50	20	1	0.4	0.4
F4_2	2000	F4_3	30	20	1	0.24	0.24
F4_3	2200	F5_3	65	35	2	0.91	1.82
F5_1	4700	F5_3	100	20	1	0.8	0.8

* Mm^3 million cubic metres

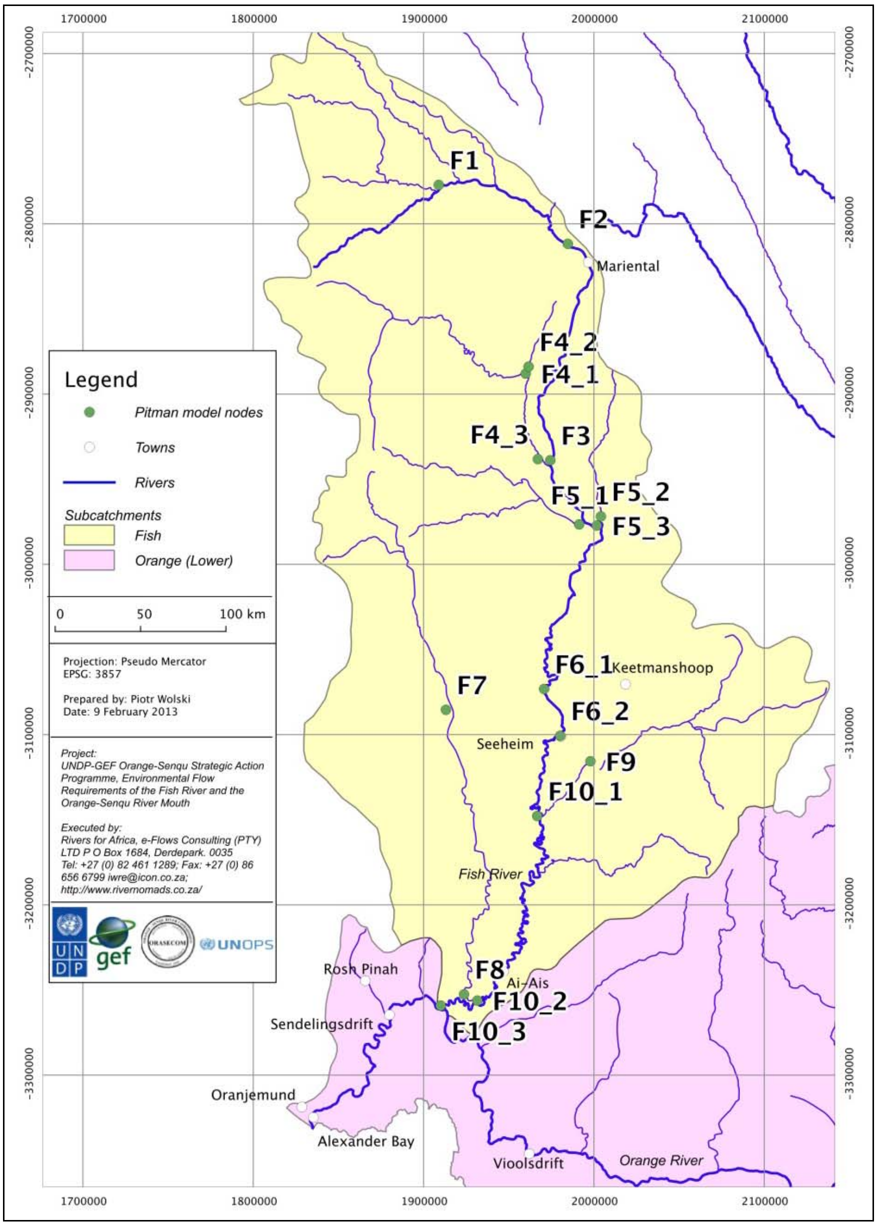

Figure 3. Pitman model simulation nodes within the Fish River basin

3.1 Understanding the dynamics of flow within the Fish River

One of the objectives of setting up the Pitman model is to represent the actual dynamics of runoff generation and channel flow as far as possible given the limitations of the model's conceptual simplifications as well as our understanding of the real processes. There seems to be little doubt that the main flood responses (even relatively small events) will be largely derived from surface runoff processes. The complicating factor is that these could be highly spatially variable, depending upon the rainfall variability. While runoff may therefore be generated within some parts of the catchment, this may not necessarily lead to stream flow within the main Fish River channel due to attenuation and losses within the channel system. The large observed runoff events are assumed to be caused by more widespread rainfall (and therefore runoff) over the whole basin (albeit with substantial spatial variability in depth), such that the storage deficits in pools and dry channels are quickly filled. Our ability to model the variation of response therefore depends strongly on the degree to which the available rainfall data represent real spatial patterns.

With respect to low flows and the extent to which static pools within the system are likely to be maintained between flow events, there is insufficient information available to make firm conclusions. However, field work during the dry season of 2012 suggests that there is a groundwater gradient towards the channel and that there exist a number (but the actual number is not known) of localised springs that are semi-permanent. The correspondence between the number of recorded events at Hardap and Seeheim also suggest that the pools will be replenished by channel flow during most years. It is therefore concluded that the pools are partially sustained by annual stream flow contributions and partly by small localised groundwater seepages into the channel zone. It is more than possible that some pools are dominated by one of these processes and others by the other process or a combination of both.

Field observations suggest that some of the pools in the gorge area near the proposed Neckartal Dam (Figure 4) are more than 3 m deep, while the potential evaporation depth over the six main dry season months (May to October) is approximately 0.85 m. Seasonal replenishment through channel flow is therefore more than sufficient to sustain the pools over all dry seasons. Even during years when there is no channel flow the total evaporative loss is likely to be a maximum of 2,3 m, and therefore the deeper pools can be expected to be sustained through one such year as well. Many of the shallower pools, however, may disappear during years when the duration of flow is short and when there are years with zero flow. The flow records do not include any periods where there are two or more consecutive years experiencing zero flow. This situation could of course be changed with the construction of Neckartal Dam, depending on the operational management of controlled releases.

The lessons to be learnt from this (limited) understanding of the system are that:

- It is important to realistically simulate the frequency of channel flow (i.e. do not simulate extended periods of zero flow).
- It is less important to be able to simulate the dynamics of interaction between the groundwater and the channel, although this could be beneficial from a water quality perspective. The basis for this conclusion is that most of the more important (deeper) pools can be sustained by at least some flow in most years as long as a sequence of zero flows does not extend beyond a single wet season.

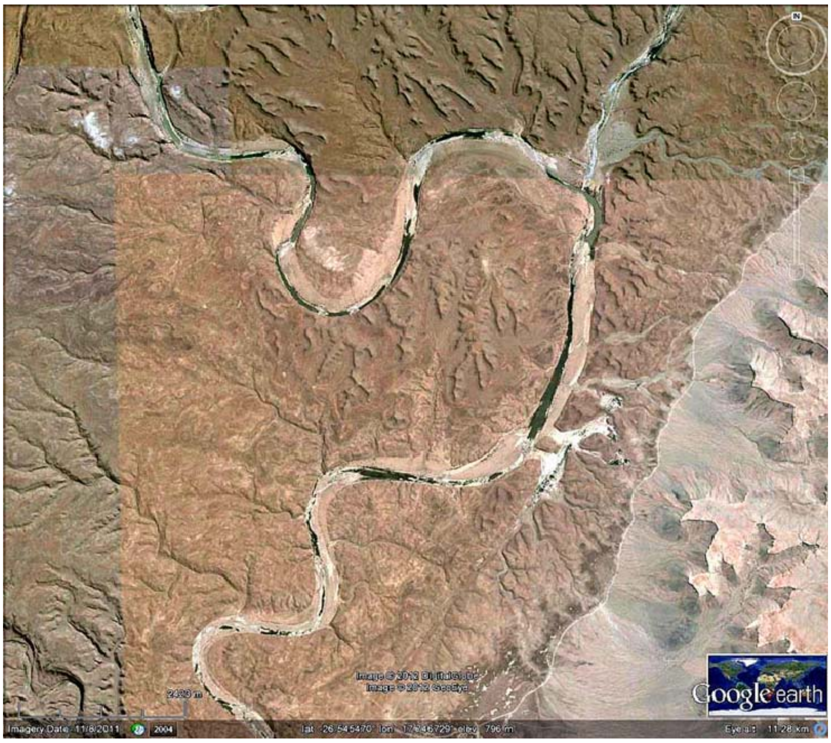

Figure 4. Pools within the gorge area near the proposed Neckartal Dam site

3.2 Calibration of the Pitman model for the Fish River

For the purposes of calibration against the available observed flow data (inflows to Hardap Dam, flows at Seeheim gauge and Ai-Ais gauge) the model was run with an approximate representation of both Hardap and Naute dams. Few releases are made from Naute Dam and most of the releases from Hardap Dam are during very wet periods (when the dam is expected to spill anyway) to avoid excessive downstream flooding. No releases were included in the Pitman model and it was assumed that this would be adequate when modelling at a monthly time step.

It is known to be very difficult to accurately simulate individual months within semi-arid catchments, partly because of the highly variable nature of the rainfall characteristics that are typically inadequately represented by the available rainfall data. This problem is exacerbated by the highly variable nature of the hydrological response in semi-arid areas. The objective of modelling semi-arid areas is therefore usually to reproduce the observed magnitude-frequency characteristics as reflected in the shapes of flow duration curves. Table 3 indicates that the low flow inputs into Hardap Dam are not very well simulated (and could be improved), however, this is not very important as they do not form part of the downstream flow regime under the current system of operating the dam. The results for low flows at Seeheim gauge are much better (partly because this was the focus of the calibration exercise). Unfortunately, there are not enough observed flow data that are coincident with the modelling period of 1930 to 1995 to perform the same model assessments at Ai-Ais gauge.

The overall conclusion was that the simulations in the main channel of the Fish River downstream of Hardap Dam are sufficiently representative of the observed flow regime for the purposes of this study. However, it should also be recognised that the simulations are heavily dependent upon how representative the input rainfall data is compared to real conditions, as well as the assumptions that have been made about pool storage volume and therefore the effects of pools on the downstream continuity of flow during relatively dry years.

Table 3. Observed and simulated flows ($m^3 * 10^6$) for several duration curve percentage points at Hardap (inflows) and Seeheim gauge

FDC* % Point	***Hardap Dam Observed***	***Hardap Dam Simulated***	***Seeheim gauge Observed***	***Seeheim gauge Simulated***
5%	58	60	105	123
10%	29	17	35	61
15%	14	7	26	22
20%	4	1	12	10
25%	1.6	0	5	5
30%	0	0	2.5	2.2

Notes: The observed flows are based on all the available data, while the simulated flows represent the total simulated period of 1930 to 1995.
* Flow Duration Curve.

The yield of Neckartal Dam will be highly dependent upon the sequences of flow of different magnitudes, as well as the length of the periods of much lower flows between major wet periods. These wet periods (when the dams can be assumed to have filled, had they existed) occurred in the mid-1930s, mid-1950s, mid 1970s and again in the 1999/2000 wet season. The latter is beyond the simulation period, but the relatively long dry period between the end of the 1970s and the late 1990s has been captured by the simulations. This is important from the perspective of the yield analysis and the analysis of the impacts on the yield of any managed EFR releases from Neckartal Dam.

3.3 System simulations and release options using the Water Resources Modelling Platform Model

The incremental flows generated by the Pitman model (i.e. not including any reservoir or main channel pool storage effects) were used as input to the WReMP system yield model. Within WReMP the same 'dummy dam' volumes were used together with the storages represented by Hardap, Naute and Neckartal dams. The WReMP was used to generate representative time series of present day conditions (i.e. no Neckartal Dam) and five options of managed EFR releases. The first of these release options represents a condition of no releases from Neckartal (release option (RO) 0%), while the other release options were based on progressively higher releases relative to the simulated monthly inflows to Neckartal Dam (RO 20%, RO 30%, RO 40% and Sc 50%). All of the release options were constrained under the assumption that the maximum instantaneous release will be limited to 100 m^3/s, based on the design of the outlet works. As the monthly releases were disaggregated into daily flow patterns using the double triangle approach explained below, the maximum release volume allowed in the model was the volume that resulted in a main daily peak flow of 100 m^3/s, which is equivalent to 35 $m^3 * 10^6$ per month.

The consequences of this approach are that:

- there are much longer periods of no flow below Neckartal dam under RO 0%, which are only mitigated by tributary inflows downstream;
- the storage projections under the higher releases (RO 40% and RO 50%) suggest much lower storage levels than under RO 0% and say RO 20% (see Table 4);
- one of the consequences of the previous point is that there are more frequent and earlier (in some wet seasons with relatively high inflows) spills under RO 0% than the other scenarios;
- most of the higher flow releases are identical for RO 20% to RO 50% because of the 100 m^3/s maximum release restriction;
- the available yield reduces substantially as the releases are increased from RO 0% to RO 50%;
- there are potential 'trade-offs' between relatively low flow and higher flow conditions downstream of the dam that will need to be considered by the ecological specialists.

Table 4. Comparison of storage levels at different frequencies of exceedence under RO 20% and RO 50%

Frequency of Exceedance	***Storage (Mm^3): RO 20%***	***Storage (Mm^3): RO 50%***
90%	270	130
70%	487	408
50%	676	634
20%	816	795

3.4 Monthly to daily disaggregation

Because of the importance of pool storage downstream of Neckartal Dam and the effects on flow attenuation and in-stream channel losses, it was considered necessary to disaggregate the monthly flow volumes simulated by the Pitman and WReMP models into representative daily flow sequences (which could also be used to specify daily, or sub-daily, patterns of release for reservoir management purposes). It was also recognised that some daily flow characteristics are required by the ecological specialists as part of their interpretation of the impacts of the different scenarios.

The daily flow characteristics have been used to develop a simple approach to converting monthly flow volumes into representative daily flow hydrograph shapes. The basis of the approach is a double triangle (Figure 5) that is used to represent the peak response and the baseflow 'tail'.

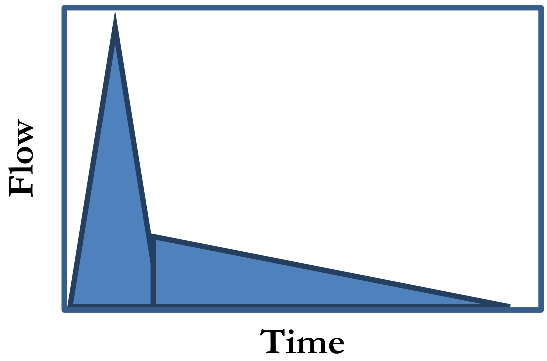

Figure 5. Basic concept of the double triangle monthly disaggregation method

The approach to implementing the double triangle method for the flows at Seeheim gauge is provided in Appendix A.

The outputs from the WReMP model for key locations within the basin have been disaggregated using the double triangle approach explained in Appendix A and the daily flow time series have been routed through an approximately calibrated (using observed flows at Seeheim gauge and Ai-Ais gauge) version of the HEC-RAS model. The daily flow sequences simulated by the HEC-RAS model represent the scenario data (present day conditions, RO 0% and RO 20% to RO 50%) that can be used by the ecological specialists to determine the ecological impacts of different flow management practices.

4. Fish River: Evaluation of drivers and release options

4.1 Background

As discussed in section 1.3, development scenarios are made up of drivers which were identified in both the Fish and Orange River catchment. This chapter describes the Fish River drivers.

By far the most significant driver in the Fish river is the imminent construction of the Neckartal Dam which will have a major influence on the flow regime of the lower Fish River and hence the flows entering the lower Orange River. The impact that the Neckartal Dam has on the downstream flow regime will in turn depend very much on the Environmental flow releases made from the dam.

4.2 Assessment of release options from the Neckartal Dam

The monthly release time series derived from WReMP for each release option were disaggregated into daily flow time series using the methodology described in Appendix A. In order to allow for the attenuation of the release out of Neckartal Dam, the release flow was simulated using HEC-RAS, from the Neckartal Dam down to the confluence with the Orange River. The resulting flow time series at EFR Fish 2 and at EFR Fish Ai-Ais were then analysed by ecological specialists in various fields (geomorphology, water quality, fish, macro-invertebrates, riparian vegetation and riverine fauna). Based on this evaluation, the recommendation was made for an EFR release of between 30% and 40% of the inflow. The final recommended EFR (referred to as RO Opt) entails releasing 40% of the inflow while the storage in the dam is above 60% of its full supply capacity, dropping to 30% of the inflow should the storage in the dam drop below 60%.

4.3 Identification of Fish River drivers

The following drivers were identified during the meeting of 21 September 2012 but were not assessed further as these drivers were unlikely to be implemented or developed.

- Increase in current 2200 ha of irrigation.
- Raising of Hardap Dam wall.
- Broekaros Dam.
- Social issues as potential drivers.
- Political issues as potential drivers (focus on drought alleviations).

The drivers that would be considered are:

- Neckartal Dam with abstraction for irrigation;
- Neckartal Dam with abstraction for irrigation and an EFR release options;
- increase in Naute Dam irrigation.

As explained in section 4.2, the Neckartal Dam with abstraction for irrigation and EFR releases were divided into various release options. Increased irrigation from Naute Dam was included as part of the release options.

- EFR RO 0%
- EFR RO 10%
- EFR RO 20%
- EFR RO 30%
- EFR RO 40%
- EFR RO 50%

Once the release options were assessed, an optimised EFR release option was identified (referred to as RO Opt) which will be the driver that is considered as part of the joint Orange and Fish scenarios for EFR assessment on the Orange River and estuary.

4.4 Yield of Neckartal Dam

The yield of Neckartal Dam will inevitably reduce with increasing releases for the EFR. Table 5 summarises the impact of all the release options on the yield of the Neckartal Dam. Yield in this context refers to the historical yield.

Table 5. Yield of Neckartal Dam under various release options

Release option as % of inflow released	***Releases (Mm3/a)***	***Yield (Mm3/a)***	***Yield as % of no release option***
0	0	81	100.0
10	27.8	74	91.4
20	40.7	68	84.0
30	51.3	61	75.3
40	59.8	55	67.9
50	67.1	49	60.5
Opt	56	61	75.3

4.5 Evaluating the release options of the Fish River

This section provides some recommendations on the approaches that should be used to interpret the daily flow time series of the release option

Continuity of flow

This section refers to not only the continuity of any flow (greater than zero), but also the continuity of critical low flows. These analyses can be performed using both flow duration curves (for all months of the year, as well as for the main wet season period, identified as January to March) and run-analysis methods.

The flow duration curve approach simply entails identifying the percentage of time that the flows are greater than certain flow thresholds defined to be ecologically important. Comparisons can then be made between the different release options. For example, zero flows are exceeded 65% of the time at Seeheim gauge (representative of EFR site EFR Fish 2) under the simulated present day condition in the wet season, while this reduces to 34%, 45% and 53% of the time under RO 0%, RO 20% and RO 50%, respectively. At the same site, a flow of 10 m^3/s is exceeded during the wet season 37% under present day (PD) and 16%, 20% and 26% under RO 0%, RO 20% and RO 50%, respectively.

The flow duration curve analysis does not take into account the continuous length of time that flows will be below (or above) the defined threshold (i.e. the analysis is independent of sequences of flow). However, it is possible to perform run-analyses to determine these differences between scenarios.

High flow event frequency

The run-analysis approach is appropriate for assessing differences in the number and frequency of high flow events by setting critical high flow thresholds and determining the differences in number of events of a specified duration that occur between scenarios. For example, a flow event that has flows exceeding 150 m^3/s for 4 days might be considered important. For the Ai-Ais reach (management resource unit (MRU) Fish B.2) this occurs on 36 occasions in the simulated period of 1930 to 1995 (66 years). The number of occasions reduces to 27 for RO 0% and RO 20% and 25 for the RO 40% and RO 50%. The slightly larger number of events in the lower release scenarios is a result of more spills from Neckartal Dam consequent on higher storage conditions associated with smaller releases (Table 4).

Pool storage conditions

It should be recognised that all of the models used are simulating the pool-storage conditions in a very simplified way and at very coarse (channel reach) scales, and no attempts have been made to simulate individual pools. During the periods when the HEC-RAS model simulates zero flow conditions at the end of any specific channel reach, it is inevitable that the pools will be less than full. Part of the model output is an estimate of the average pool storage condition within the reach.

However, this also means that the shallower and smaller pools will have storage conditions below that average, while the larger and deeper pools will be above average. During wetting sequences, it is also inevitable that the pools in the upstream parts of the reach will become full before those in the downstream parts (unless tributary inflows in the downstream areas play a major role).

The pool storage states are therefore simulated in a relatively coarse manner within the model and it would not be appropriate to quantitatively interpret the model outputs in too literal a manner. It is better to interpret the outputs in a more probabilistic way. For example, the HEC-RAS simulations for present day conditions in the EFR Fish 2 reach below Seeheim gauge (see Appendix B) include a single short period of zero pool storage at the end of the extreme and extended dry period in the 1980s, while RO 0% results contain many periods of simulated zero pool storage. The probability of getting totally dry pools under present day conditions is therefore very small (consistent with observations made by local inhabitants during the field trips), while there is a very high probability that pools will dry up frequently during RO 0%. RO 20% represents a substantial reduction in the probability of pool drying, but there remains a significant risk that this could occur. The other release options reduce this risk and the probability of pool drying under the RO 50% is not considered to be substantially greater than under present day conditions.

For the reach above EFR Fish Ai-Ais, the situation is similar, but the probability (and therefore risk) of pool drying might be greater for the lower release scenarios (i.e. RO 20% and RO 30%). This is associated with the longer distance from the Neckartal Dam release point, and the possibility of lower tributary inflows in this drier part of the basin and therefore the greater attenuation effects on the releases.

5. Orange River: Hydrological characteristics, modelling and scenarios

5.1 Modelling approach for the Orange River

The hydrology of the Orange River is well understood and documented as part of previous ORASECOM projects and was not re-analysed as part of this study. However, all previous hydrological analyses produced monthly flow time series while ecological evaluation ideally required daily flow time series. The existing water resources model of the Orange River (the Water Resources Planning Model, (WRPM)) is also a monthly model and hence all development scenarios are expressed as monthly flow time series. As with the Fish River, a disaggregation technique was therefore used to produce daily flow time series for all scenarios. This technique, described in section 5.5, differs from that used on the Fish River (Appendix A) due to the different flow characteristics of the two rivers.

The flow at the Orange Estuary consists of the combination of the flow from the Orange River and the flow from the Fish River with minor influences such as losses and water use along the 150 km river reach from the confluence of these two rivers to the estuary. Scenarios at the estuary were, therefore, derived from three separate modelling processes consisting of the following:

- the Fish River release options, as described in the chapter 4;
- Orange River scenario modelling up to the confluence of the Fish River using the WRPM;
- combining flows from the Fish and the Orange rivers and extrapolation to the EFR O5 site and the estuary as well as disaggregation into daily flows.

5.2 Available data

Stream flow data

Stream flow data for the Orange River was obtained from previous studies undertaken by ORASECOM, specifically the study referred to as Support to Phase 2 of the ORASECOM basin-wide integrated water resources management plan (ORASECOM, 2010a, b, c). These data consist of naturalised flow time series at numerous sub-catchments within the Orange River.

It is important for the estimation of ecological flow requirements to quantify the natural flow since this is used as a reference condition. The natural flow of the Orange River basin is complicated by the large natural losses in the lower reaches of the Orange River. While there is substantial runoff in the upper reaches of the Orange and Vaal River basins, the incremental runoff in the lower reaches is negative due to the evaporation and bed losses. Hence there is a natural reduction in runoff. These losses are difficult to quantify accurately since they are dependent on daily weather conditions as well as the river flow. Greater flow rates result in larger surface areas and hence larger losses, while at low flow rates the small surface area results in decreased losses.

While in reality losses vary from day to day and month to month, this level of detailed modelling has not yet been achieved successfully on the lower Orange River. The best estimates currently available are monthly losses, assumed to be constant from one year to the next. These losses are summarised in Table 6.

Table 6. Evaporation and bed losses in the lower Orange River (ORASECOM, 2010a)

Month	***Loss m^3/s***	***Loss Mm^3/s***
Oct	24.01	64.3
Nov	30.59	79.3
Dec	32.18	86.2
Jan	32.08	85.9
Feb	26.35	64.3
Mar	19.23	51.5
Apr	13.49	35.0
May	9.88	26.5
Jun	7.33	19.0
Jul	8.18	21.9
Aug	12.11	32.4
Sep	18.80	48.7
Annual	19.52	614.5

The natural flow at the Orange River Estuary is therefore the sum of the natural incremental inflows less the natural evaporation and bed losses indicated in Table 7 and are presented in Table 8. Note that this natural flow does not include flow from the Molopo River since bed losses from this catchment exceed the runoff.

Table 7. Summary of natural flow at the Orange Estuary (Mm³ per annum (Mm³/a)

Month	***Orange River***	***Losses***	***Fish River***	***Resulting natural flow***
October	708	64	1	645
November	1,061	79	3	985
December	1,216	86	10	1,139
January	1,699	85	93	1,706
February	2,198	64	158	2,292
March	1,850	52	181	1,981
April	1,078	35	99	1,143
May	525	27	16	515
June	245	19	4.1	230

Month	Orange River	Losses	Fish River	Resulting natural flow
July	203	22	2	183
August	228	32	0.7	197
September	341	49	0.5	293
Annual	11 353	615	569	11 307

EFR O5

EFR O5 is located on the lower Orange River downstream of the confluence with the Fish River at Sendelingsdrift (Figure 1). The natural flow at this point is very similar to that of the natural flow at the estuary, the only difference being the natural losses in the river reach from EFR O5 to the mouth. This is estimated to be approximately 67 million m^3/annum (Mm^3/a). The incremental runoff along this stretch of river is negligible.

The estimated natural flow at EFR O5 is given in Table 9.

Table 8. Summary of natural flow at EFR O5

Month	Average monthly natural flow after losses (Mm^3/a)
Oct	652.1
Nov	993.5
Dec	1,148.6
Jan	1,715.1
Feb	2,298.8
Mar	1,986.2
Apr	1,146.3
May	517.7
Jun	232.4
Jul	184.9
Aug	200.0
Sep	298.0
Annual	11,373.3

5.3 Daily stream flow characteristics

The Orange River catchment is much larger than the Fish River catchment and is characterised by high rainfall and runoff in the upper reaches of the catchment. Flood events in the Orange River are therefore of a much longer duration than flood events in the Fish River. The disaggregation technique used on the Fish River flows assume that a flood event occurs over a period of less than a month and this is not the case in the Orange River. Floods in the Fish River also do not necessarily coincide with the floods in the Orange River.

The maximum flood recorded in the Orange River was 8 137 m³/s and occurred in March 1988. It is interesting to note that this is long after the construction of the Vanderkloof and Gariep dams. This raised the question as to what extent these dams (and others on the Vaal River and in the Lesotho) are changing the flooding regime of the Orange River. A flood frequency analysis was therefore carried out to estimate this, using two periods. The 'natural' or reference period was from 1935 to 1970 (before river closure due to the Gariep and Vanderkloof dams) and the second period from 1977 to 2012. The flood frequency analysis is shown in Figure 6.

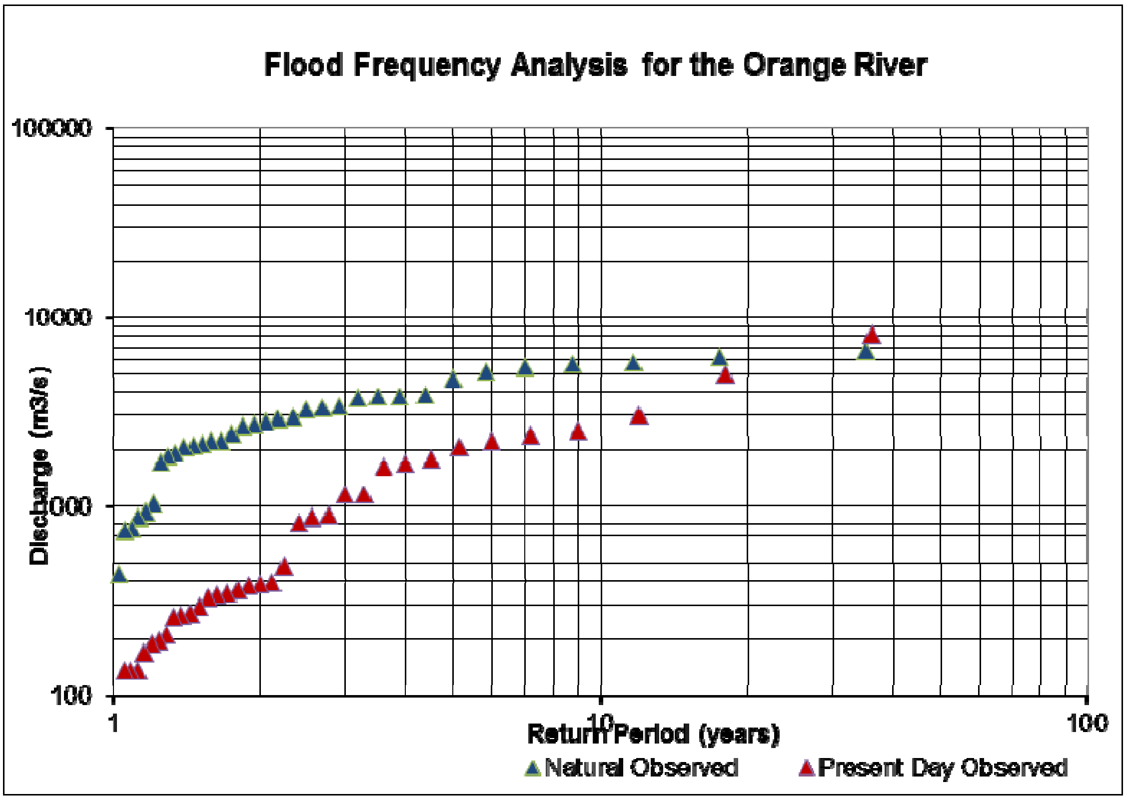

Figure 6. Flood frequency analysis of the Orange River catchment over selected periods

Figure 6 shows that many of the floods have been substantially reduced due to upstream development.

5.4 Monthly simulations

The WRPM was used to generate flows up to the confluence of the Fish River. These simulations were carried out as part of the Orange River Reconciliation Strategy Study commissioned by South Africa's Department of Water Affairs. These simulations are only valid up to the confluence of the Fish River. Previous Fish River hydrology covers the period of 1930 to 1995 while the WRPM has been set up with hydrology from 1920 to 2005. Furthermore the updated Fish River hydrology has only become available during this study. In order to derive scenario time series at the EFR site

(EFR O5) and the Orange River Estuary, an Excel spread sheet was used to add flows and subtract losses and water use. This spread sheet allowed for the following:

- EFR O5: Add flow from the Fish River.
- Estuary:
  - Add flow from the Fish River.
  - Subtract losses (67 Mm^3/a).
  - Subtract water use (39 Mm^3/a under present day conditions, 58 million m^3/annum for future scenarios).

The outcome of these simulations is monthly flow time series at EFR O5 and the Orange River Estuary for each scenario modelled.

5.5 Daily flow evaluation

While the modelling tools that have been set up for the Orange River basin on behalf of ORASECOM as part of several previous projects are monthly time step models, ecologists require an indication of the daily variation of the flow. This is especially important for the estuarine specialists who need to correlate periods of low flow with mouth closure events in order to understand the estuary dynamics. Two approaches were used to develop daily flow time series. Firstly, for the estuary, the observed flow at the Vioolsdrift gauge was extrapolated to the estuary over the period of 1992 to 2012 by adding in the observed flow from the Fish River (accepted as the observed flow at Ai-Ais gauge) and subtracting estimated losses and water use between Vioolsdrift and the mouth. While this is an approximation, it provided an indication of the low flow periods for the estuarine ecologists.

Monthly time series for each scenario at EFR O5 were disaggregated into daily time series using the method described by Mallory and Sawunyama in their report for the Water Research Commission (Mallory and Sawunyama, 2012). The method uses a daily flow time series, in this case the observed flow at Vioolsdrift, as an indicator of the flow pattern in each month. Using duration curves derived from the monthly flow time series and the daily flow time series, the daily flow from the indicator site is scaled up or down to maintain the monthly volume from the monthly time series. The limitation of this is that the daily time series is not an accurate representation of actual daily flows but rather a statistical representation of daily flow. This is, however, adequate as an indication of flood frequencies and how these change from one scenario to the next.

5.6 Driver description

Orange and Vaal River drivers

- Metolong Dam: Construction of the Metolong Dam in Lesotho.
- Optimised releases from dams: This includes the hydropower generation by Eskom and how this is likely to change in future as well as improved operation of the dams for purposes of irrigation releases.
- Polihali Dam: Construction of the Polihali Dam in Lesotho.

- Vioolsdrift Balancing Dam: Construction of a small flow regulating structure to supply possible irrigation projects or shortfalls to existing irrigators due to upstream development.
- Vioolsdrift Large Dam: Construction of the Vioolsdrift Dam to supply possible irrigation projects or shortfalls to existing irrigators due to upstream development.
- Boskraai Dam Construction of the Boskraai Dam at the confluence of the Orange and the Kraai River.
- AMD treated: Desalination of acid mine drainage (AMD) emanating from the Upper and Middle Vaal River catchment.
- Increased domestic and irrigation demands in South Africa (applicable to all scenarios).
- Increased Namibian irrigation: Increased irrigation along the Lower Orange River (with water from the Orange River) in Namibia.
- Tandjieskoppe: Development of irrigation in Namibia at Tandjieskoppe.

Fish River drivers

The Fish River drivers are provided in Chapter 4. These drivers or EFR release options were tested and minimised to ensure a reasonable number of options. Only one EFR release option was included, i.e. the recommended EFR referred to as the REC EFR. The only Fish River drivers combined with the above Orange River drivers were the:

- Neckartal Dam with the planned irrigation from this dam and no EFR releases;
- Neckartal Dam with the planned irrigation and the REC EFR option;
- increased irrigation from the Naute Dam.

5.7 Scenario description

The drivers were combined within the likely time-frame that these developments could take place so as to derive plausible development scenarios. The combination of drivers that result in scenarios (Sc) are illustrated in the two tables below. Table 9 illustrates the time-line and list the drivers, whereas Table 10 shows explicitly which driver is activated in each scenario. The scenarios name includes OF, referring to Orange-Fish.

Table 9. Time lines, scenario and driver combinations

Time frame	***Scenario***	***Orange River drivers***	***Fish River drivers***
Recent Past	Sc OF 1	Modelled present day current releases and use included.	
Immediate future 2013 - 2020	Sc OF 2	Metolong Dam, Tandjieskoppe, AMD treated.	Neckartal Dam. Increase in Naute Dam irrigation.
	Sc OF 3	Metolong Dam, Tandjieskoppe, AMD treated.	Neckartal Dam with EFR release. Increase in Naute Dam irrigation.
	Sc OF 4	Metolong Dam, Tandjieskoppe, AMD treated, 2010 EFR flows released. Optimised releases from dams.	Neckartal Dam with EFR release. Increase in Naute Dam irrigation.

Time frame	***Scenario***	***Orange River drivers***	***Fish River drivers***
2020 - 2040	Sc OF 5	Metolong Dam, Tandjieskoppe, AMD treated, 2010 EFR flows released, Polihali Dam, Vioolsdrift Balancing Dam (small). Optimised releases from dams.	Neckartal Dam with EFR release. Increase in Naute Dam irrigation.
Post 2040 - maximum foreseeable development	Sc OF 6	Metolong Dam, Tandjieskoppe, AMD treated, Polihali Dam, Large Vioolsdrift Dam (no EFR), Boskraai Dam. Optimised releases from dams.	Neckartal Dam. Increase in Naute Dam irrigation.
	Sc OF 7	Metolong Dam, Tandjieskoppe, AMD treated, Polihali Dam, Large Vioolsdrift Dam (no EFR), Boskraai Dam. Optimised releases from dams.	Neckartal Dam with EFR release. Increase in Naute Dam irrigation.
	Sc OF 8	Metolong Dam, Tandjieskoppe, AMD treated, Polihali Dam, Large Vioolsdrift Dam (EFR O4 released), Boskraai Dam. Optimised releases from dams.	Neckartal Dam with EFR release. Increase in Naute Dam irrigation

Table 10. Drivers that are activated or deactivated under different scenarios

	Orange River Drivers										***Fish River Drivers***		
Scenario	***Metolong Dam***	***AMD treated***	***EFR flows 2010***	***Optimised releases***	***Tandjieskoppe***	***Additional Namibian irrigation***	***Polihali Dam***	***Vioolsdrift balancing dam***	***Vioolsdrift large dam***	***Boskraai Dam***	***Neckartal Dam***	***Neckartal with REC EFR***	***Increased Naute irrigation***
Sc OF 2	Yes	Yes			Yes						Yes		Yes
Sc OF 3	Yes	Yes			Yes							Yes	Yes
Sc OF 4	Yes	Yes	Yes	Yes	Yes							Yes	Yes
Sc OF 5	Yes	Yes	Yes	Yes	Yes		Yes	Yes				Yes	Yes
Sc OF 6	Yes	Yes		Yes	Yes	Yes	Yes		Yes	Yes	Yes		Yes
Sc OF 7	Yes	Yes		Yes	Yes	Yes	Yes		Yes	Yes		Yes	Yes
Sc OF 8	Yes	Yes	Yes	Yes	Yes	Yes	Yes		Yes	Yes		Yes	Yes

The scenario modelling results are summarised in Table 11. At times, especially under the future development scenarios, theoretical river losses can exceed the river flow which within the modelling process results in negative flow. These negative flows were set to zero, the implication of this being that under very low flow conditions the losses are not fully realised. For this reason, the mean annual runoff (MAR) in Table 12 cannot simply be added to obtain a total MAR at the Orange River Estuary.

These monthly flow time series were then disaggregated into daily time series using the method described in Section 5.5.

Table 11. Summary of scenario modelling results (volume in Mm³/a)

Scenario	*Orange River* MAR*	*Fish River MAR*	*EFR O5 MAR*	*Estuary MAR*
Natural	10,738	569	11,373	11,306
Sc OF 1(PD)	4,143	474	4,617	4,508
Sc OF 2	4,158	355	4,513	4,404
Sc OF 3	4,158	362	4,520	4,412
Sc OF 4	4,109	362	4,471	4,362
Sc OF 5	3,599	362	3,849	3,837
Sc OF 6	2,078	355	2,433	2,314
Sc OF 7	2,078	362	2,440	2,322
Sc OF 8	2,692	362	3,067	2,930

* Orange River at Fish River confluence.

6. Ecohydraulics

6.1 Methodology

The application of holistic methods for ecological flow determination (refer to Tharme, 1996) requires environmental flow requirements to be expressed as discharge rates (including their temporal characteristics) through assessments of the presence of suitable habitat for certain biota at different flows. The interface between the way in which flow requirements are assessed and expressed is through the results of hydraulic measurements, analyses and modelling at sites along rivers. The primary product of these hydraulic analyses are relationships between discharge and the following determinants, which have been found over the course of numerous flow assessments, to be the most useful: depth (maximum and average), velocity (average), wetted perimeter, and width of the water surface. The discharge-depth (or rating) relationship is fundamental to hydraulic analysis, and is generally derived from a combination of measured and synthesised data (refer to Rowlston et al., 2000; Birkhead, 1999; Jordanova et al., 2004; Hirschowitz et al., 2007 and Birkhead, 2010 for descriptions of procedures for deriving hydraulic information for use in EFRs in South Africa). Once the rating relationship for a river section has been developed, the relationships between discharge and the other hydraulic parameters (listed above) may readily be computed using the cross-sectional geometry, and are generally provided in tabular format using look-up tables (refer to section 6.5).

The cross-sectional profile plots and look-up tables comprise the "standard hydraulic data" used in EFR determinations in South Africa. Ecologists use these standard hydraulic data with the aid of site assessments and photographs to determine the quantity and quality of hydraulic habitat at different flows. Substantial experience and interpretation are required to provide assessments of site-based and reach-based biological habitats using cross-sectional surveys and the results of one-dimensional hydraulic analyses (biological habitat refers to the integration of the different components defining habitat, e.g. hydraulic, substrate and cover attributes for fish). Procedures have therefore been developed for using standard hydraulic information as the basis for quantifying hydraulic habitat for fish (refer to Hirschowitz et al., 2007 and Birkhead, 2010 for an explanation of the method). The method allows the assessment of abundance of different flow classes to be applied more consistently in EFRs, and has been used in this study.

6.2 Data collection

Fish River: EFR Fish 1 and EFR Fish 2

Field trips to the two Fish River sites took place in February and June 2012. Water levels were marked along the reaches corresponding to a measured discharge at the Seeheim gauge of 10 m^3/s on 16 February 2012 (Figure 7). Strand lines (Figure 8) were measured corresponding to a recent flow event (peak at the Seeheim gauge of 133 m^3/s on 9 February 2012). During the second field trip, cross-sections and water levels were surveyed along reaches at the sites (figures in Appendix B) and discharges were measured (Table 12). Strand lines corresponding to the highest flood event (peak at the Seeheim gauge of 535 m^3/s on 30 March 2012) were also surveyed.

Figure 7. Examples of stages marked on 16 February 2012 (for subsequent surveying during June 2012), corresponding to a discharge of 10 m^3/s measured at the Seeheim gauge

Figure 8. Examples of strand lines marked on 16 February 2012 and corresponding to a peak discharge of 133 m^3/s measured at the Seeheim gauge on 9 February 2012

In Figure 9 the flow direction at both sites is from top-right to bottom-left. The reach lengths (distances between the upstream and downstream cross-sections) at EFR Fish 1 and EFR Fish 2 are 1.7 and 1.9 km, respectively.

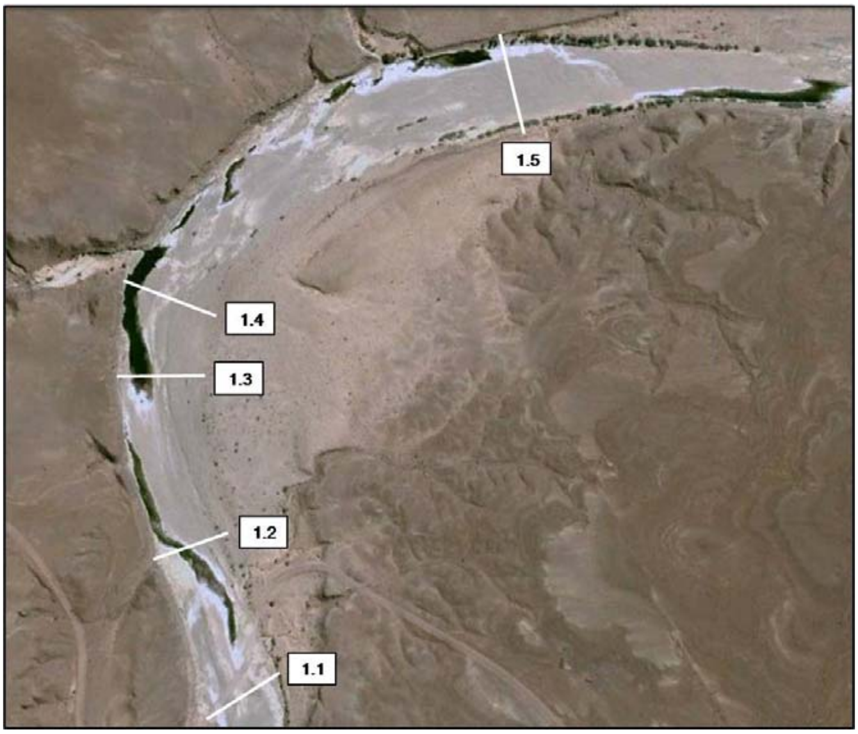

Figure 9. Locations of surveyed cross-sections at EFR Fish 1 (top) and EFR Fish 2 (bottom)

Table 12. Hydraulic data collected at the Fish River sites

Site	***Cross-section[1]***	***Date***	***Discharge (m^3/s)***	***Stage[2] (m)***
EFR Fish 1	1.1	09/02/2012	133	98.38
		30/03/2012	0.15	96.32
		16/06/2012	535	99.32
	1.2	09/02/2012	133	98.38
		30/03/2012	0.15	96.50
	1.3	30/03/2012	0.15	96.49
		16/06/2012	535	99.81
	1.4	09/02/2012	133	98.89[3]
		30/03/2012	0.15	96.47
		16/06/2012	535	99.98
	1.5	09/02/2012	133	99.95
		30/03/2012	0.15	97.46
		16/06/2012	535	101.65
EFR Fish 2	2.1	09/02/2012	133	99.08
		16/02/2012	10	97.67
		30/03/2012	535	99.61
		16/06/2012	0.06	97.23
	2.2	09/02/2012	133	98.33[4]
		16/02/2012	10	96.90[4]
		16/06/2012	0.06	96.44
	2.3	16/06/2012	0.06	96.45
	2.4	16/06/2012	0.06	96.42
	2.5	16/06/2012	0.06	96.43
	2.6	09/02/2012	133	97.42
		16/02/2012	10	96.85
		30/03/2012	535	98.4
		16/06/2012	0.06	96.41

1 Refer to Figure 9. 2 Relative to local datum.
3 Upstream of cross-section above rapid. 4 140 m upstream.

Orange River: EFR O5

A field trip to the Orange River site took place in June 2012, during which a cross-section and water level were surveyed (Figure 10 and Appendix B). A discharge (Table 13) and a strand line corresponding to a recent flood event (attenuated peak of 590 m^3/s on 1 April 2012 at the Ai-Ais gauge (Station 0499M02) located approximately 90 km upstream was measured. The corresponding flow at the Vioolsdrift Gauge (Station D8H003), located approximately 155 km upstream of the

Orange River site, was substantially lower during the same period (up to 69 m^3/s on 31 March 2012). The Gamchab River enters the Fish River approximately 36 km upstream of the Orange River confluence, but is ungauged. The flood event experienced in April 2012, however, appears to be largely in response to a release from Hardap Dam, peaking at between 800 m^3/s and 880 m^3/s over a two-day period (refer to Figure 11).

Figure 10. Locations of the surveyed cross-section at the EFR O5. The flow direction is from top-right to bottom-left.

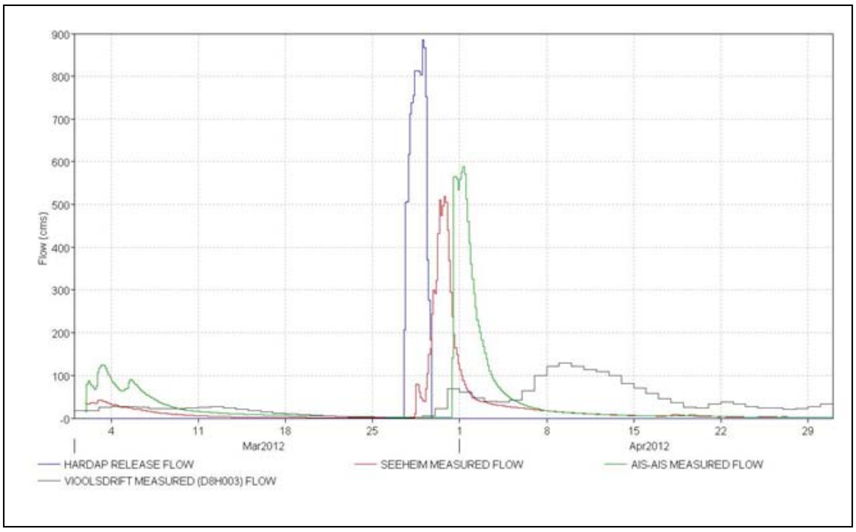

Figure 11. Discharge time series of releases from Hardap Dam between 27 and 29 March 2012 and corresponding gauged flows at the Seeheim and Ai-Ais gauges on the Fish River and Vioolsdrift gauge on the Orange River (cms = m^3/s).

Table 13. Hydraulic data collected at EFR O5

Date	Discharge (m^3/s)	Stage[1] (m)
15/06/2012	29.1	96.28
01/04/2012	550[2]	98.65

1 Relative to local datum.

2 Approx. discharge in response to a release at Hardap Dam (gauged peak of 590 m^3/s on 1 April 2012 at the Ai-Ais Gauge (Station 0499M02)).

6.3 Hydraulic modelling

Fish River: EFR Fish 1 and EFR Fish 2

Steady-state HEC-RAS models were calibrated for the two Fish River sites, using the surveyed cross-sectional profiles (Appendix B) and hydraulic data collected during the field trips (refer to Table 12). The HEC-RAS modelling provided additional rating data to augment the observed data, to which continuous relationships were fitted by regression. The rating parameters and the stage-discharge plots are provided in Appendix B.

For cross-section 2.1 at EFR Fish 2 (a riffle at low flows) the hydraulic modelling software, HABFLO (refer to Birkhead, 2010) was used to prepare a lookup table (refer to Appendix B) for ecological interpretation.

Orange River: EFR O5

A continuous rating relationship was fitted by regression to the stage-discharge data collected for EFR O5. The rating parameters and the stage-discharge plots are provided in Appendix B. The lookup table for the cross-section at EFR O5 is provided in Appendix B.

6.4 Confidences in modelling results

Confidences are evaluated on a scale of 0 - 5 with 5 referring to very high confidence.

For the Fish River EFR sites, the hydraulic characterisations include measured rating data in the approximate range 0,1 m^3/s to 535 m^3/s, and steady-state non-uniform hydraulic analyses have been used with multiple (surveyed) cross-sections. Consequently, the site hydraulic characterisations are medium-high (4). Taking account, however, of the approximate simulation of changes in dead storage in pools, the confidence in the hydraulic characterisations reduces to medium (3).

For EFR O5, the recommended low flows (drought and maintenance) are in the range 1.9 m^3/s to 37 m^3/s, and the floods range from 70 m^3/s to 1,000 m^3/s. The confidence in the hydraulic characterisations for both low and high flows is medium (3). This is because although measured rating data include 29,1 m^3/s and approximately 550 m^3/s, and zero flow depth is expected at the cessation of flow (section lies through a rapid), a non-horizontal cross-channel water surface profile (refer to Figure B12) occurs at low to medium flows, thus reducing the accuracy of the hydraulic characterisation.

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Appendix A Seeheim gauge - Approach to implementing the double triangle method

A.1 Step 1: Quantify the peak value

If monthly volume (MV) < $1.2 * 10^6$ m^3 then peak daily = MV/0.216 $m^{3/}$s.

This is based on the assumption of distributing the monthly flow volume using a single triangle with a base width of 5 days, i.e. by simple geometry, volume = peak * 5 days / 2 or peak ($m^{3/}$s) = volume * 10^6 * 2 / (5 * 3600 * 24) = volume / 0.216 (assuming that the volume is expressed in million m^3.

If MV ≥ $1.2 * 10^6$ m^3 then three empirical relationships were derived to estimate the width of the peak triangle (P1), the width of the baseflow triangle (P2) and the height of the baseflow triangle (P3) relative to the main peak (see figure 4, section 3.4):

P1 = integer (ln(MV) * 0.6 + 0.5) (Width in days of the peak triangle)

P2 = integer (7 * P1 +0.5) (Width in days of the baseflow triangle)

P3 = 1 / $MV^{0.4}$ (Relative height of the baseflow triangle)

From simple geometry:

Total volume = Peak triangle volume + Baseflow triangle volume

Total Volume ($m^3 * 10^6$) = (Peak * P1 / 2 + Peak * P3 * P2 / 2) * 3600 * 24 / 10^6

With the peak value expressed in $m^{3/}$s. The last three constants in the equation are used to convert days to seconds and million m^3 to m^3. Rearranging the equation allows the peak daily flow to be estimated, while the maximum baseflow rate ($m^{3/}$s) is simply the peak daily * P3.

Peak daily ($m^{3/}$s) = MV ($m^3 * 10^6$) / (0.024 * 3.6 * 0.5 * (P1 + P2 * P3)

A.2 Step 2: Estimate the daily flows within the main peak triangle

This is a relatively trivial calculation to determine the shape of the triangle based on the daily peak (2nd day) and the base length (P2).

A.3 Step 3: Estimate the daily flows in the baseflow triangle

This is also trivial given the height of the right-angle triangle (maximum baseflow) and the duration of the baseflow triangle (P2).

Figure A1 illustrates the relationships between the monthly flow volume and the widths of the two triangles. The stepped nature of the relationships is associated with the integer rounding in the estimation equations for P1 and P2. Figure A2 illustrates the relationships between the monthly flow volume and the peak daily flow and the ratio of maximum baseflow to daily peak. Figure A3 illustrates the results for a range of events at Seeheim gauge. These results are based on aggregating the observed daily flows to monthly time series and then applying the disaggregation method to generate simulated daily flows.

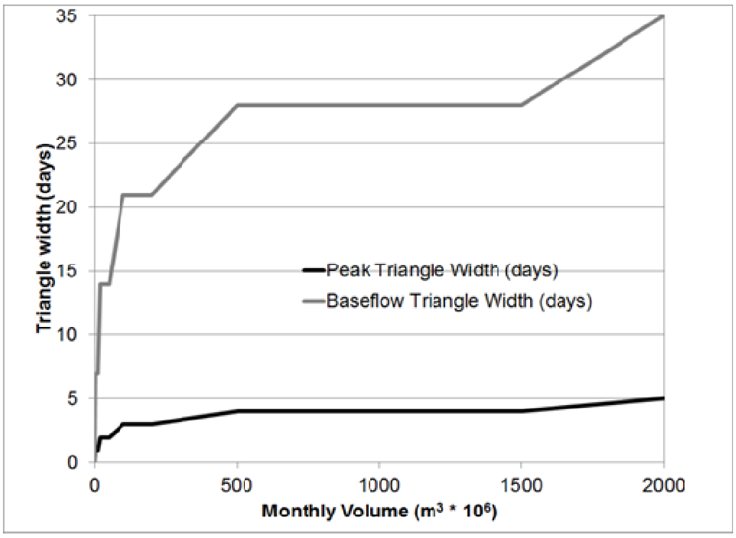


Figure A1. Relationships between the monthly flow volume and the widths of the two triangles

The results of such a simple procedure appear to be quite successful for the Fish River at Seeheim for a wide range of different events and the flow duration curves (Figure A4) are reasonably well matched for the full range of flows. The frequency characteristics of the daily flows have therefore been well represented.

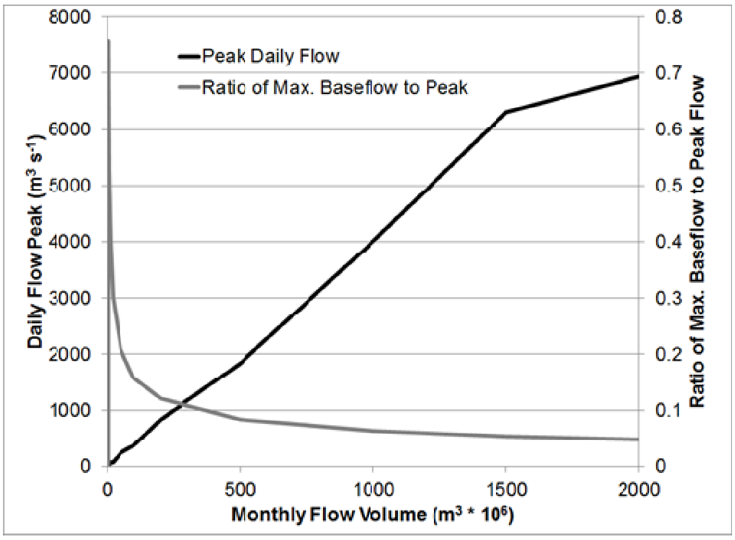
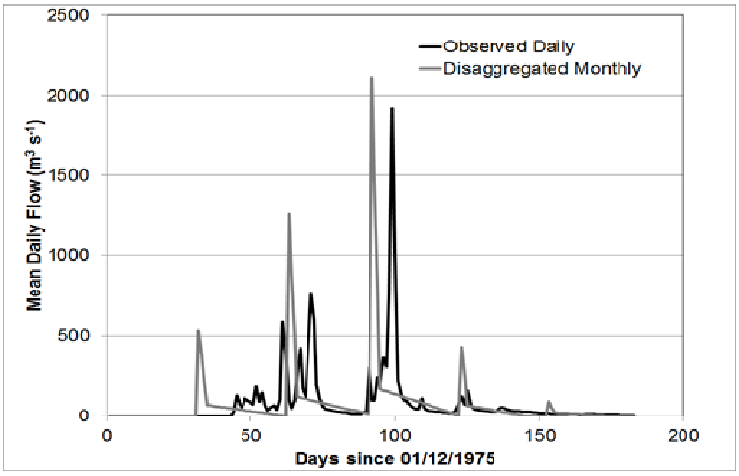
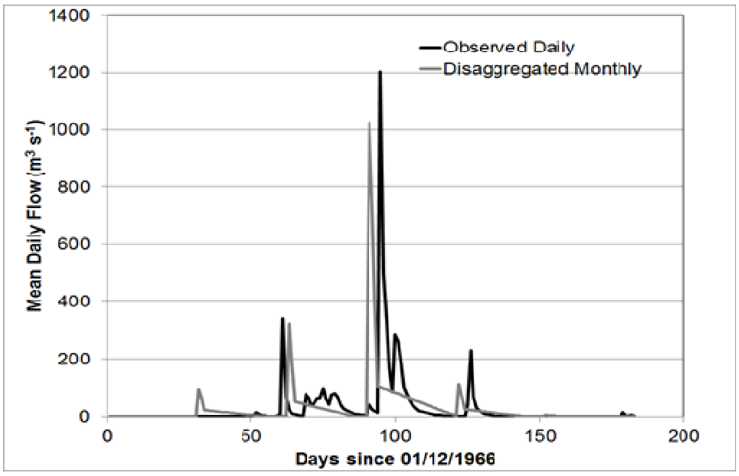


Figure A2. Relationships between the monthly flow volume and the peak daily flow and the ratio of maximum baseflow to daily peak





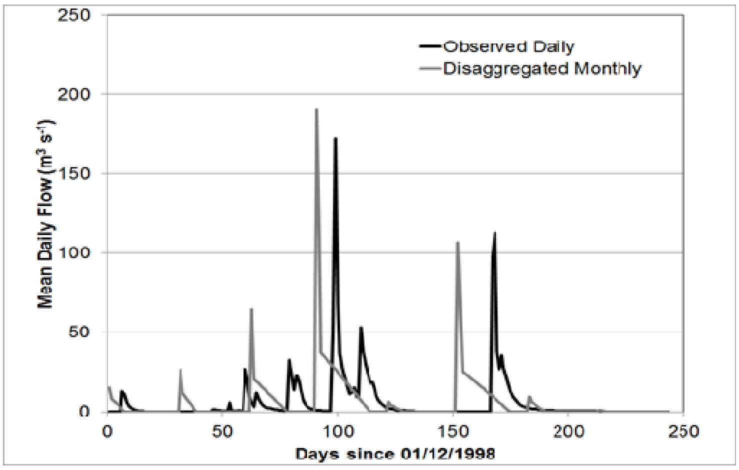


Figure A3. Example daily flow hydrographs for Seeheim gauge (observed and disaggregated monthly) for different ranges of events

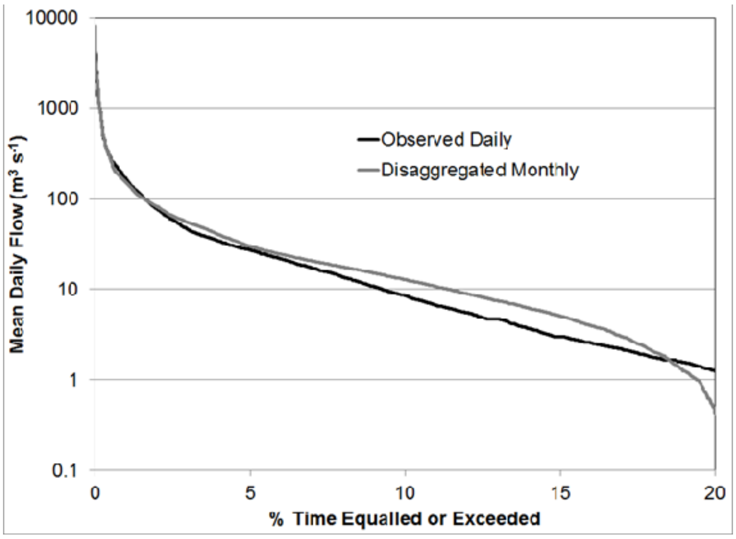


Figure A4. Flow duration curves for the observed daily and disaggregated monthly (full time series from 1960 to 2004)

Appendix B Hydraulic cross-sections, rating coefficients, lookup tables and graphs

B.1 Cross-sections at EFR Fish 1 and EFR Fish 2

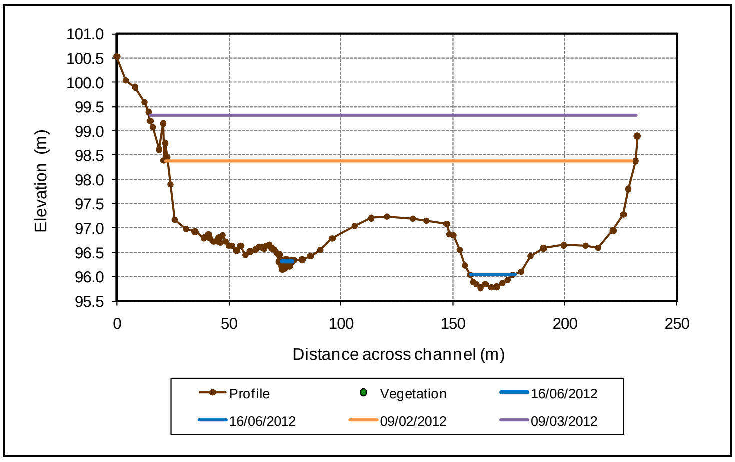


Figure B1. Cross-sectional profile 1.1 surveyed at EFR Fish 1 along the Fish River

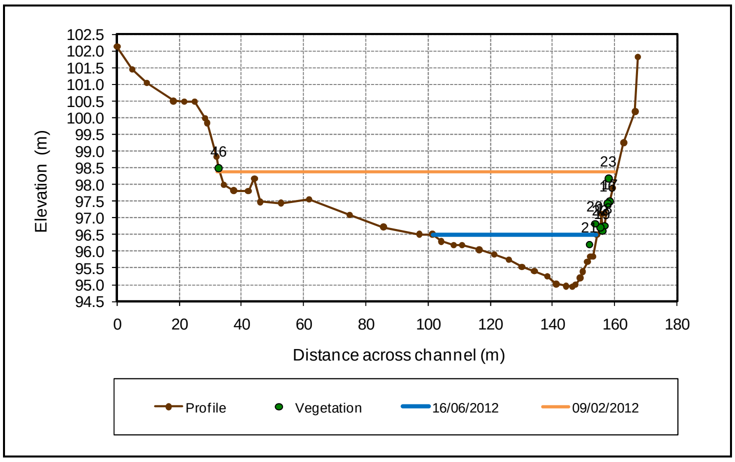


Figure B2. Cross-sectional profile 1.2 surveyed at EFR Fish 1 along the Fish River

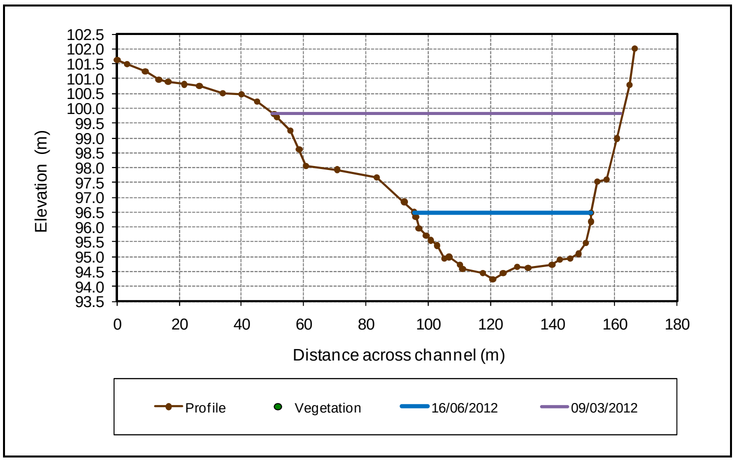


Figure B3. Cross-sectional profile 1.3 surveyed at EFR Fish 1 along the Fish River

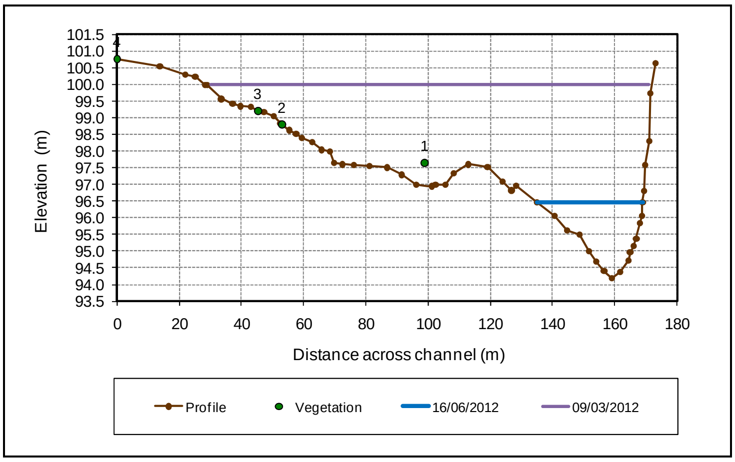


Figure B4. Cross-sectional profile 1.4 surveyed at EFR Fish 1 along the Fish River

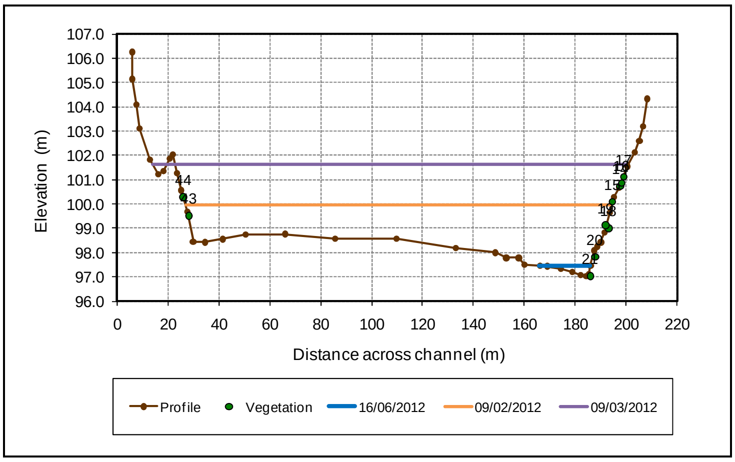


Figure B5. Cross-sectional profile 1.5 surveyed at EFR Fish 1 along the Fish River

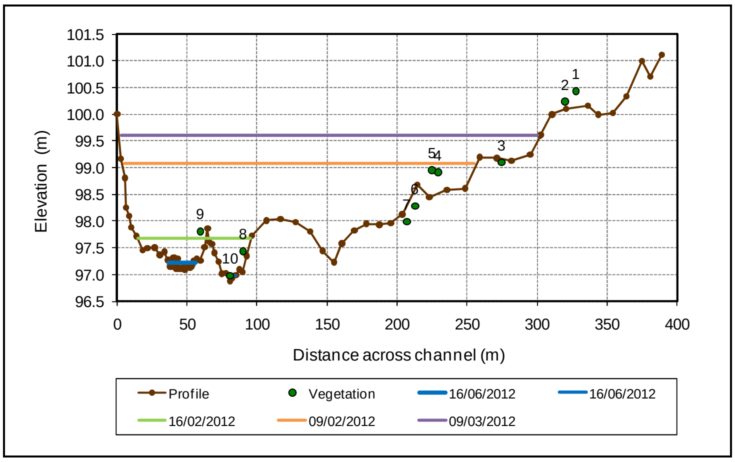


Figure B6. Cross-sectional profile 2.1 surveyed at EFR Fish 2 along the Fish River

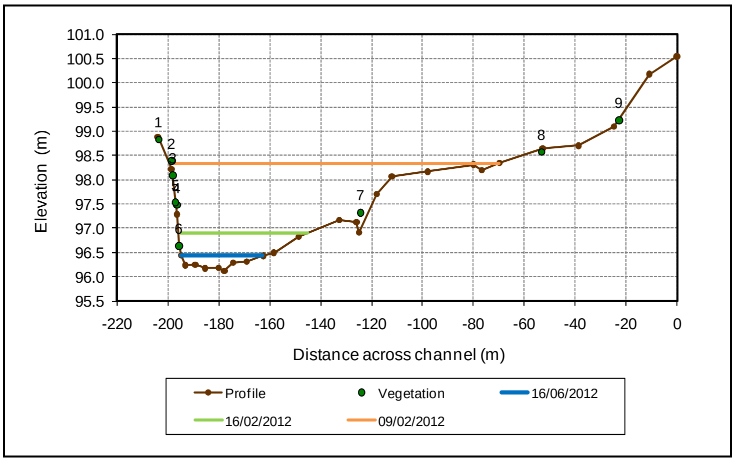


Figure B7. Cross-sectional profile 2.2 surveyed at EFR Fish 2 along the Fish River

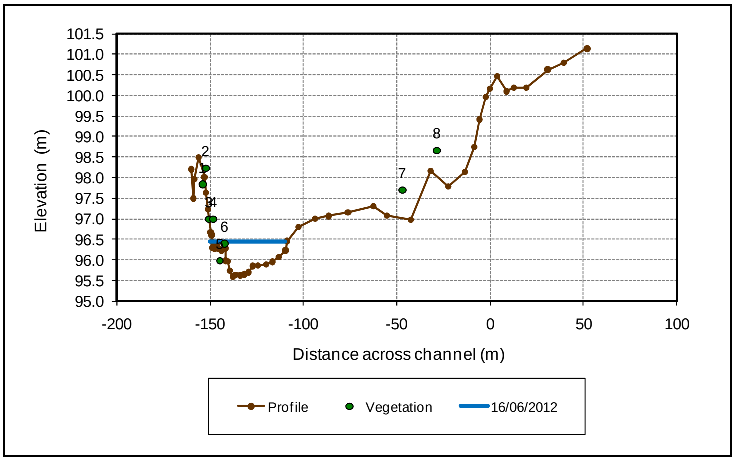


Figure B8. Cross-sectional profile 2.3 surveyed at EFR Fish 2 along the Fish River

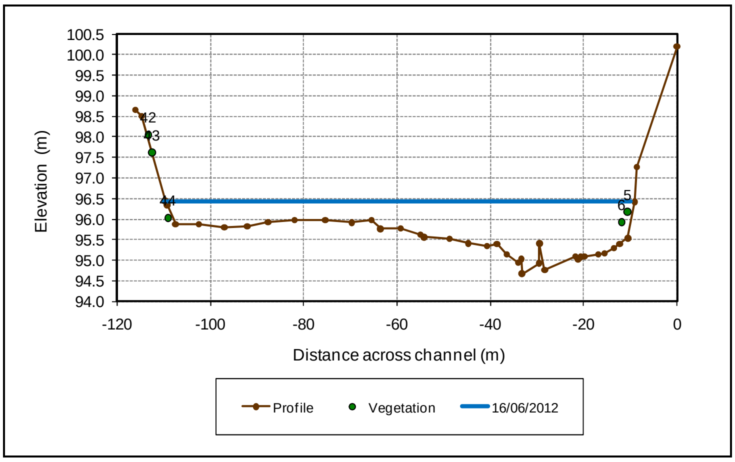


Figure B9. Cross-sectional profile 2.4 surveyed at EFR Fish 2 along the Fish River

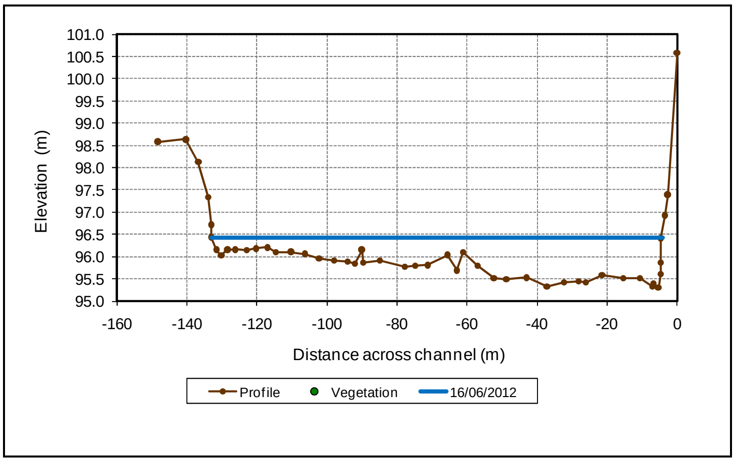


Figure B10. Cross-sectional profile 2.5 surveyed at EFR Fish 2 along the Fish River

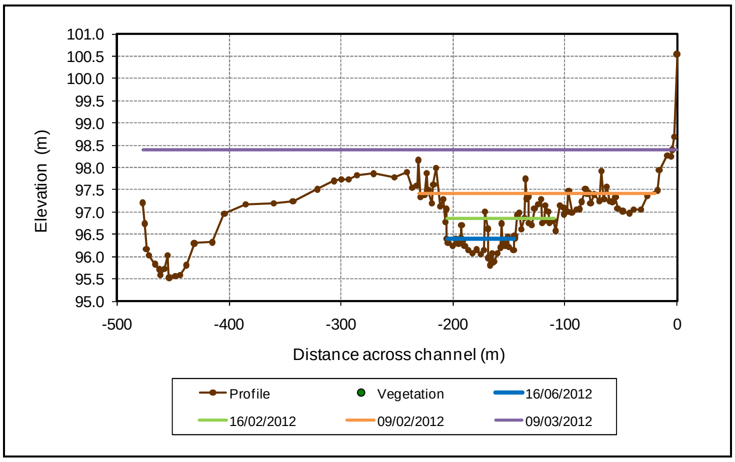


Figure B11. Cross-sectional profile 2.6 surveyed at EFR Fish 2 along the Fish River

B.2 Cross-sections at EFR O5

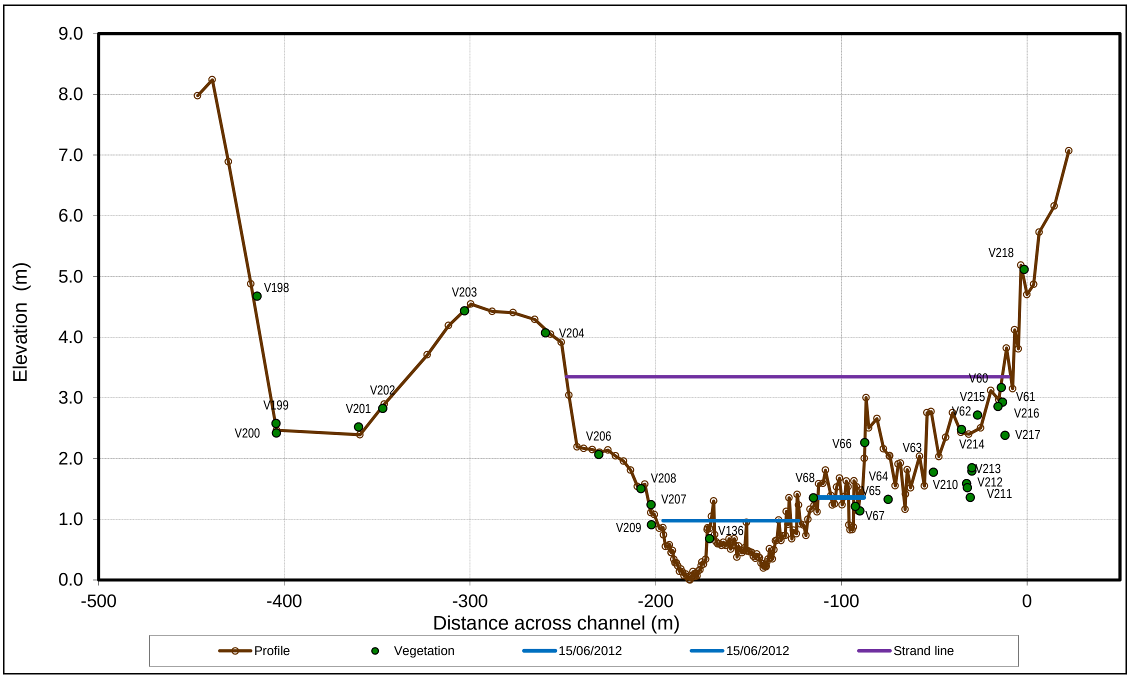


Figure B12. Cross-sectional profile surveyed at Site 5 along the Orange River

B.3 Rating coefficients

The rating coefficients for the Fish River EFR sites and Orange River EFR site are provided in Table B1 and Table B2 respectively.

Table B1. Rating coefficients in $z = aQb + c$ for the cross-sections surveyed at the two EFR sites in the Fish River, where z is stage (m) and Q is discharge (m^3/s)

Cross-section	***EFR Fish 1: 1.1***	***EFR Fish 1: 1.2***	***EFR Fish 1: 1.3***	***EFR Fish 1: 1.4***	***EFR Fish 1: 1.5***
a1	0.857	0.592	0.580	0.543	0.508
b1	0.227	0.278	0.294	0.312	0.346
c1	95.770	96.110	96.110	96.110	97.200
Bed elevation	95.77	94.94	94.23	94.19	97.02
Pool depth[1]	0.00	1.17	1.88	1.92	0.18

Cross-section	***EFR Fish: 22.1***	***EFR Fish: 22.2***	***EFR Fish: 22.3***	***EFR Fish: 22.4***	***EFR Fish: 22.5***	***EFR Fish: 22.6***
a1	0.539	0243	0.195	0.197	0.208	0.206
b1	0.174	0.410	0.414	0.400	0.379	0.367
c1	96.880	96.300	96.300	96.300	96.300	96.300

Cross-section	EFR Fish: 22.1	EFR Fish: 22.2	EFR Fish: 22.3	EFR Fish: 22.4	EFR Fish: 22.5	EFR Fish: 22.6
a2	0.446					
b2	0.300					
c2	96.880					
Q 1-2	4.50					
z 1-2	97.58					
Bed elevation	96.88	96.12	95.60	94.67	95.31	95.81
Pool depth[1]	0.00	0.18	0.70	1.63	0.99	

1 Depth at the cessation of surface flow.

B.4 Stage discharge relationships EFR Fish 1 and EFR Fish 2

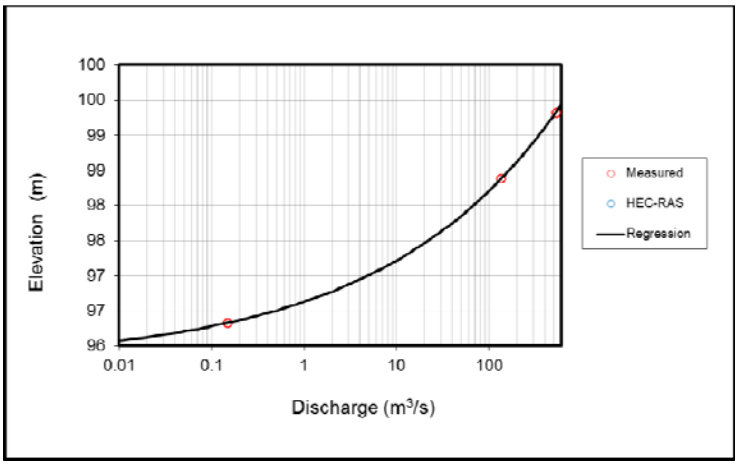


Figure B13. Stage-discharge relationships for cross-section 1.1 at EFR Fish 1 along the Fish River

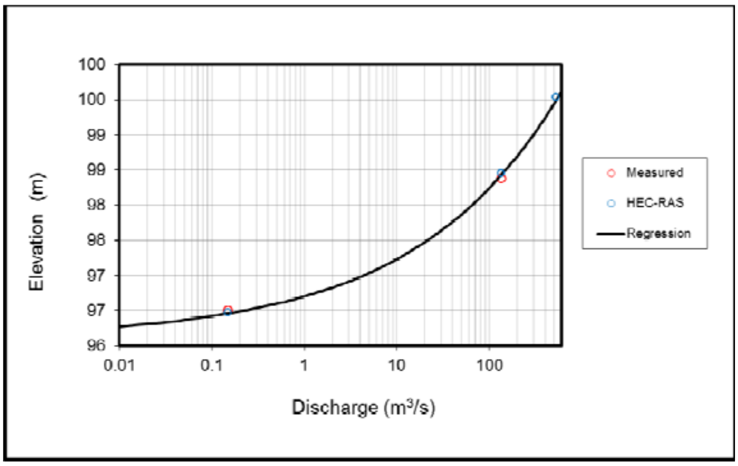


Figure B14. Stage-discharge relationships for cross-section 1.2 at EFR Fish 1 along the Fish River

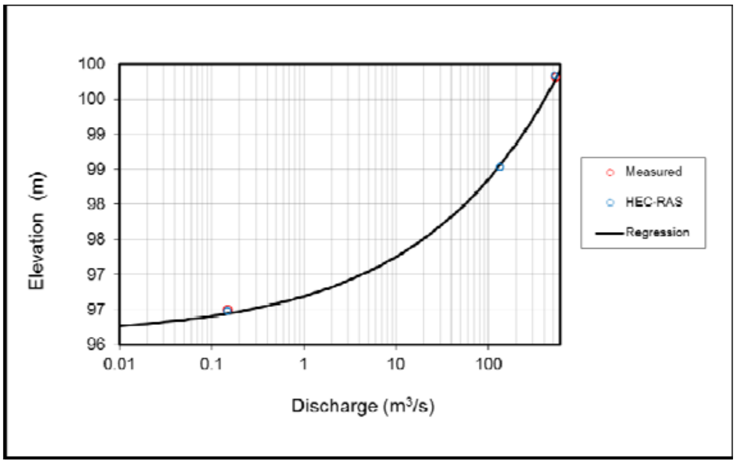


Figure B15. Stage-discharge relationships for cross-section 1.3 at EFR Fish 1 along the Fish River

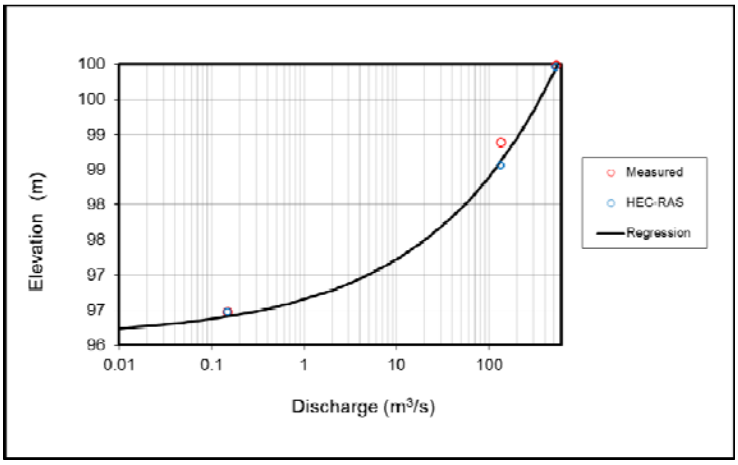


Figure B16. Stage-discharge relationships for cross-section 1.4 at EFR Fish 1 along the Fish River

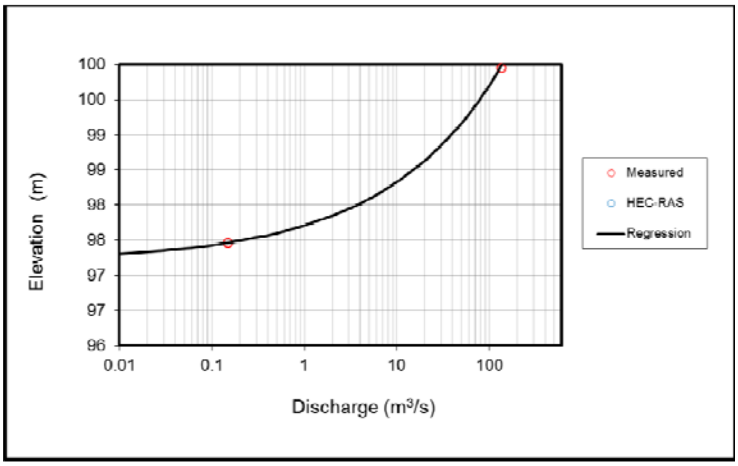


Figure B17. Stage-discharge relationships for cross-section 1.5 at EFR Fish 1 along the Fish River

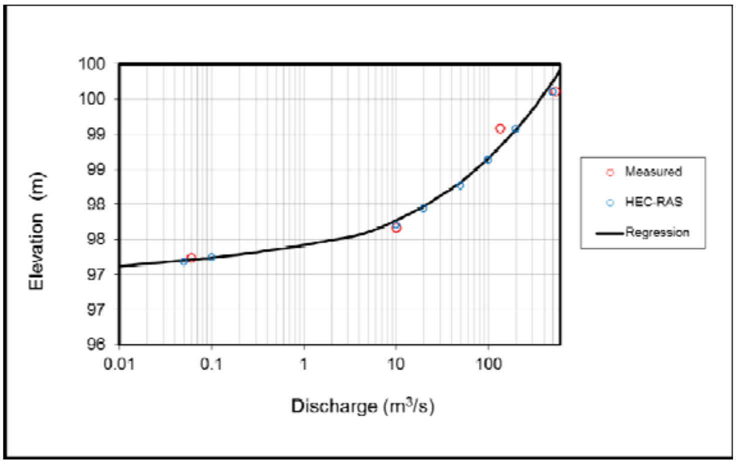


Figure B18. Stage-discharge relationships for cross-section 2.1 at EFR Fish 2 along the Fish River

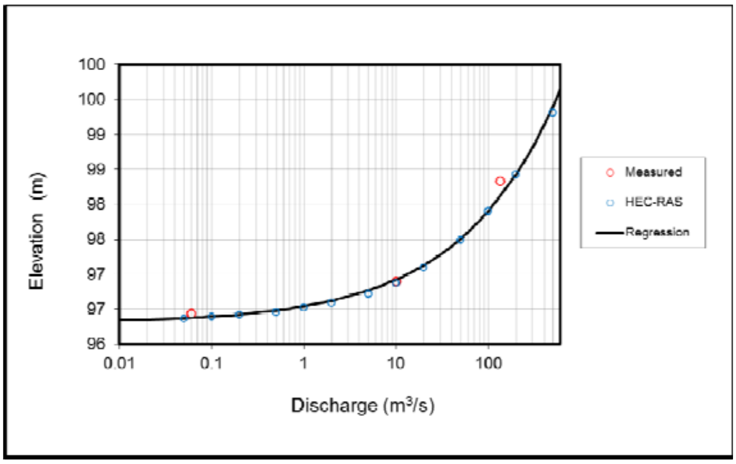


Figure B19. Stage-discharge relationships for cross-section 2.2 at EFR Fish 2 along the Fish River

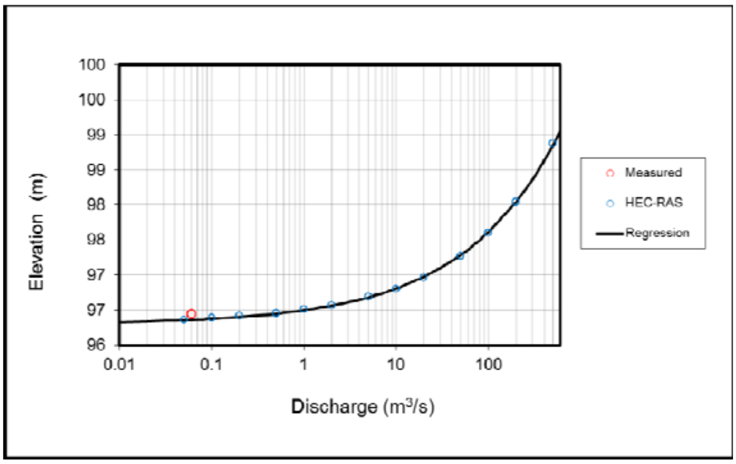


Figure B20. Stage-discharge relationships for cross-section 2.3 at EFR Fish 2 along the Fish River

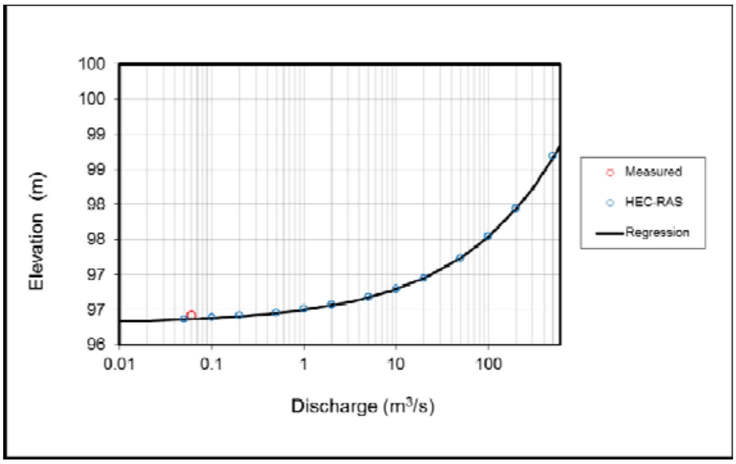


Figure B21. Stage-discharge relationships for cross-section 2.4 at EFR Fish 2 along the Fish River

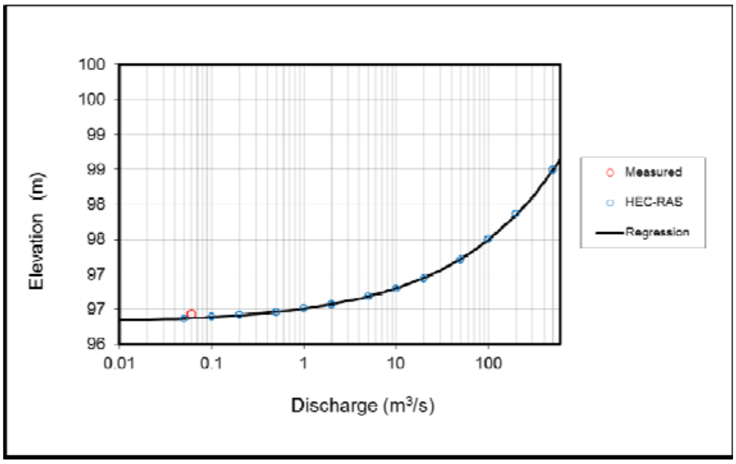


Figure B22. Stage-discharge relationships for cross-section 2.5 at EFR Fish 2 along the Fish River

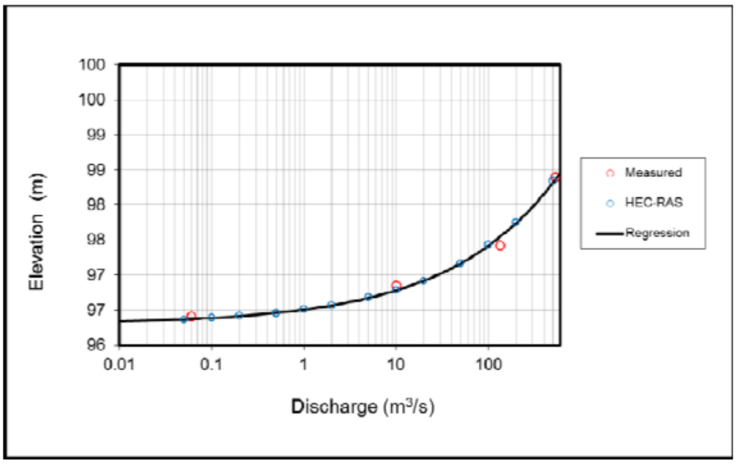


Figure B23. Stage-discharge relationships for cross-section 2.6 at EFR Fish 2 along the Fish River

B.5 Orange River: EFR O5

Although only the two (measurement-based) rating points are indicated in the figure below, Manning's resistance equation was used (with estimated flow resistances and slopes) to confirm the shape of the fitted power function.

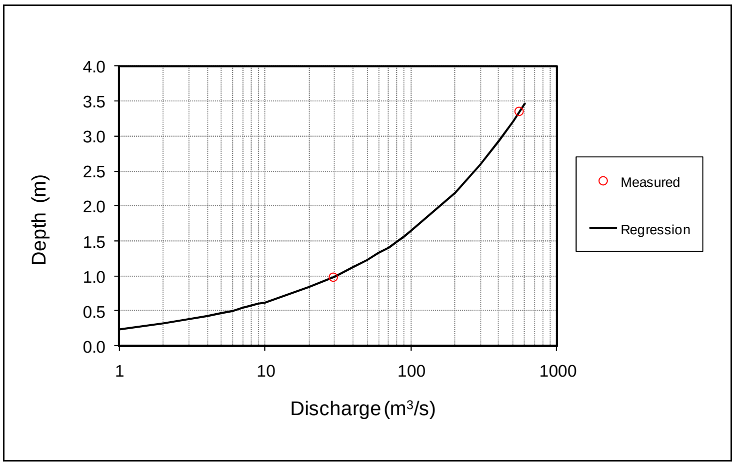


Figure B24. Stage-discharge relationship for the cross-section at EFR O5 on the Orange River

B.6 Lookup tables

Lookup tables for fish and macro-invertebrates for the Fish River EFR sites and Orange River EFR site are provided below (Table B2-B5).

Abbreviations for the fish and macro-invertebrate flow classes used in the tables are as follows:

SVS: Slow very shallow

S: Slow shallow

SD: Slow deep

VS: Fast very shallow

FS: Fast shallow

I: Fast intermediate

FD: Fast deep

SCS: Very shallow over coarse substrate

SCS: Shallow over coarse substrate

CS: Fast over coarse substrate

VFCS: Very fast over coarse substrate

VSFS: Very shallow over fine substrate

SFS: Shallow over fine substrate

FFS: Fast over fine substrate

VFFS: Very fast over fine substrate

Table B2. Fish: Lookup table providing relevant hydraulic parameters and flow classes for used for ecological interpretation at cross-section 2.1 at EFR Fish 2 on the Fish River

Max. depth (m)	***Stage (m)***	***Ave depth (m)***	***Discharge (m^3/s)***	***Width (m)***	***Perim (m)***	***Ave vel (m/s)***	***Max vel (m/s)***	***Slope (m/m)***	***Fish flow class (%)***						
									SVS	***SS***	***SD***	***FVS***	***FS***	***FI***	***FD***
0.05	97.1	0.03	0.02	11	11	0.05	0.18	0.0039	100	0	0	0	0	0	0
0.1	97.2	0.05	0.04	19	19	0.04	0.14	0.0039	95	5	0	0	0	0	0
0.15	97.2	0.07	0.1	30	30	0.05	0.16	0.0039	62	38	0	0	0	0	0
0.2	97.3	0.09	0.21	42	43	0.05	0.19	0.0039	56	44	0	0	0	0	0
0.25	97.3	0.12	0.4	53	53	0.06	0.23	0.004	47	53	0	0	0	0	0
0.3	97.4	0.15	0.73	60	60	0.08	0.28	0.004	28	70	0	1	1	1	0
0.35	97.4	0.18	1.2	69	69	0.1	0.36	0.004	23	71	0	1	2	2	1
0.4	97.5	0.21	2	77	78	0.13	0.44	0.004	19	71	0	2	2	3	2
0.45	97.5	0.23	3.2	88	88	0.16	0.56	0.004	19	66	0	3	3	5	5
0.5	97.6	0.27	4.7	93	93	0.19	0.65	0.0041	12	65	3	3	4	4	9
0.55	97.6	0.3	5.9	99	99	0.2	0.67	0.0041	8	61	9	2	4	4	12
0.6	97.7	0.33	7.3	104	104	0.21	0.71	0.0041	7	55	13	2	4	4	14
0.65	97.7	0.37	8.9	109	109	0.22	0.74	0.0041	7	46	20	3	2	5	17
0.7	97.8	0.39	11	115	116	0.24	0.79	0.0041	7	35	27	3	2	5	20
0.75	97.8	0.42	13	123	123	0.25	0.83	0.0041	8	30	28	4	3	3	24
0.8	97.9	0.44	15	133	133	0.26	0.87	0.0041	9	25	29	5	3	2	26
0.85	97.9	0.43	18	149	149	0.28	0.9	0.0041	10	22	29	7	4	3	25
0.9	98.0	0.43	21	168	168	0.29	0.92	0.0041	12	20	27	8	4	3	25
0.95	98.0	0.43	24	190	191	0.3	0.94	0.0041	11	20	27	8	7	3	24

Max. depth (m)	***Stage (m)***	***Ave depth (m)***	***Discharge (m^3/s)***	***Width (m)***	***Perim (m)***	***Ave vel (m/s)***	***Max vel (m/s)***	***Slope (m/m)***	***Fish flow class (%)***						
									SVS	***SS***	***SD***	***FVS***	***FS***	***FI***	***FD***
1	98.1	0.47	28	193	194	0.31	0.98	0.0041	8	20	27	7	8	4	27
1.05	98.1	0.52	32	196	196	0.32	1	0.0041	2	24	27	2	8	7	29
1.1	98.2	0.56	36	198	198	0.33	1.05	0.0041	2	23	27	2	6	8	33
1.15	98.2	0.61	41	199	200	0.34	1.05	0.0041	0	23	27	0	3	8	39
1.2	98.3	0.65	46	201	201	0.35	1.11	0.0041	1	20	27	1	2	7	44
1.25	98.3	0.7	52	202	202	0.37	1.14	0.0041	0	18	27	0	1	3	51
1.3	98.4	0.74	58	203	203	0.39	1.18	0.0042	0	14	29	0	1	2	54
1.35	98.4	0.79	65	204	204	0.4	1.24	0.0042	1	10	29	1	1	1	57
1.4	98.5	0.81	72	211	211	0.42	1.25	0.0042	1	6	32	2	1	1	58
1.45	98.5	0.83	80	218	219	0.44	1.33	0.0042	2	4	30	4	1	1	58
1.5	98.6	0.84	88	229	230	0.46	1.36	0.0042	3	3	29	5	2	1	57
1.55	98.6	0.85	97	241	242	0.47	1.39	0.0042	3	3	28	5	4	2	56
1.6	98.7	0.89	107	244	245	0.49	1.43	0.0042	2	4	26	5	4	2	57
1.65	98.7	0.94	117	245	246	0.51	1.46	0.0042	1	5	26	1	5	4	59
1.7	98.8	0.98	128	246	247	0.53	1.52	0.0042	0	5	24	1	4	5	60
1.75	98.8	1.03	139	247	248	0.55	1.56	0.0042	0	5	23	1	3	4	63
1.8	98.9	1.07	151	249	249	0.57	1.58	0.0042	0	5	23	0	1	3	68
1.85	98.9	1.12	164	250	251	0.59	1.63	0.0042	0	4	22	1	1	2	70
1.9	99.0	1.16	178	251	252	0.61	1.68	0.0042	0	4	21	1	1	1	72
1.95	99.0	1.2	192	253	253	0.63	1.7	0.0042	0	2	22	1	1	1	74
2	99.1	1.25	207	254	255	0.65	1.77	0.0042	0	2	21	1	1	1	74

Max. depth (m)	***Stage (m)***	***Ave depth (m)***	***Discharge (m^3/s)***	***Width (m)***	***Perim (m)***	***Ave vel (m/s)***	***Max vel (m/s)***	***Slope (m/m)***	***Fish flow class (%)***						
									SVS	***SS***	***SD***	***FVS***	***FS***	***FI***	***FD***
2.05	99.1	1.26	223	261	262	0.68	1.8	0.0044	0	2	20	2	1	1	74
2.1	99.2	1.19	240	287	288	0.7	1.82	0.0046	2	2	17	6	4	1	69
2.15	99.2	1.22	258	293	294	0.72	1.87	0.0047	2	2	17	7	4	0	69
2.2	99.3	1.27	277	294	295	0.74	1.89	0.0049	1	1	16	6	4	1	70
2.25	99.3	1.31	296	295	296	0.77	1.96	0.0051	1	2	15	4	4	3	70
2.3	99.4	1.36	317	296	297	0.79	1.99	0.0053	0	3	15	1	3	6	72
2.35	99.4	1.4	339	298	298	0.81	2.02	0.0054	0	3	14	1	2	6	74
2.4	99.5	1.45	361	299	299	0.84	2.05	0.0056	0	2	14	0	2	5	76
2.45	99.5	1.49	385	300	301	0.86	2.1	0.0058	0	2	13	1	1	3	79
2.5	99.6	1.53	409	301	302	0.89	2.08	0.0059	0	2	13	0	0	0	84
2.55	99.6	1.58	435	302	303	0.91	2.15	0.006	0	1	13	0	0	0	84
2.6	99.7	1.62	462	304	304	0.94	2.2	0.006	0	1	12	0	0	0	85
2.65	99.7	1.66	490	305	306	0.97	2.25	0.006	0	1	12	1	1	0	85
2.7	99.8	1.71	519	306	307	0.99	2.27	0.006	0	0	12	1	1	0	85
2.75	99.8	1.75	549	307	308	1.02	2.34	0.006	0	0	11	1	1	0	86

Table B3. Macro-invertebrates: Lookup table providing relevant hydraulic parameters and flow classes for used for ecological interpretation at cross-section 2.1 at EFR Fish 2 on the Fish River

Max. depth (m)	***Stage (m)***	***Ave depth (m)***	***Discharge (m^3/s)***	***Width (m)***	***Perim (m)***	***Ave vel (m/s)***	***Max vel (m/s)***	***Slope (m/m)***	***Macro-invertebrate flow class (%)***							
									VSCS	***SCS***	***FCS***	***VFCS***	***VSFS***	***SFS***	***FFS***	***VFFS***
0.05	97.1	0.03	0.02	11	11	0.05	0.18	0.0039	43	7	0	0	43	7	0	0
0.1	97.2	0.05	0.04	19	19	0.04	0.14	0.0039	45	5	0	0	45	5	0	0
0.15	97.2	0.07	0.1	30	30	0.05	0.16	0.0039	43	7	0	0	43	7	0	0
0.2	97.3	0.09	0.21	42	43	0.05	0.19	0.0039	41	9	0	0	41	9	0	0
0.25	97.3	0.12	0.4	53	53	0.06	0.23	0.004	38	12	0	0	38	12	0	0
0.3	97.4	0.15	0.73	60	60	0.08	0.28	0.004	35	14	1	0	35	14	1	0
0.35	97.4	0.18	1.2	69	69	0.1	0.36	0.004	30	17	3	0	30	17	3	0
0.4	97.5	0.21	2	77	78	0.13	0.44	0.004	26	19	5	0	26	19	5	0
0.45	97.5	0.23	3.2	88	88	0.16	0.56	0.004	22	20	7	1	22	20	7	1
0.5	97.6	0.27	4.7	93	93	0.19	0.65	0.0041	19	21	8	2	19	21	8	2
0.55	97.6	0.3	5.9	99	99	0.2	0.67	0.0041	18	21	9	2	18	21	9	2
0.6	97.7	0.33	7.3	104	104	0.21	0.71	0.0041	17	21	10	3	17	21	10	3
0.65	97.7	0.37	8.9	109	109	0.22	0.74	0.0041	16	21	11	3	16	21	11	3
0.7	97.8	0.39	11	115	116	0.24	0.79	0.0041	15	20	12	3	15	20	12	3
0.75	97.8	0.42	13	123	123	0.25	0.83	0.0041	14	19	13	4	14	19	13	4
0.8	97.9	0.44	15	133	133	0.26	0.87	0.0041	13	18	14	4	13	18	14	4
0.85	97.9	0.43	18	149	149	0.28	0.9	0.0041	13	18	15	4	13	18	15	4
0.9	98.0	0.43	21	168	168	0.29	0.92	0.0041	12	17	16	4	12	17	16	4

Max. depth (m)	***Stage (m)***	***Ave depth (m)***	***Discharge (m^3/s)***	***Width (m)***	***Perim (m)***	***Ave vel (m/s)***	***Max vel (m/s)***	***Slope (m/m)***	***Macro-invertebrate flow class (%)***							
									VSCS	***SCS***	***FCS***	***VFCS***	***VSFS***	***SFS***	***FFS***	***VFFS***
0.95	98.0	0.43	24	190	191	0.3	0.94	0.0041	12	17	17	5	12	17	17	5
1	98.1	0.47	28	193	194	0.31	0.98	0.0041	11	17	17	5	11	17	17	5
1.05	98.1	0.52	32	196	196	0.32	1	0.0041	11	16	18	6	11	16	18	6
1.1	98.2	0.56	36	198	198	0.33	1.05	0.0041	10	16	18	6	10	16	18	6
1.15	98.2	0.61	41	199	200	0.34	1.05	0.0041	10	15	18	7	10	15	18	7
1.2	98.3	0.65	46	201	201	0.35	1.11	0.0041	9	15	19	7	9	15	19	7
1.25	98.3	0.7	52	202	202	0.37	1.14	0.0041	8	14	19	8	8	14	19	8
1.3	98.4	0.74	58	203	203	0.39	1.18	0.0042	8	14	19	9	8	14	19	9
1.35	98.4	0.79	65	204	204	0.4	1.24	0.0042	7	13	19	11	7	13	19	11
1.4	98.5	0.81	72	211	211	0.42	1.25	0.0042	7	13	19	11	7	13	19	11
1.45	98.5	0.83	80	218	219	0.44	1.33	0.0042	7	12	19	13	7	12	19	13
1.5	98.6	0.84	88	229	230	0.46	1.36	0.0042	6	11	18	14	6	11	18	14
1.55	98.6	0.85	97	241	242	0.47	1.39	0.0042	6	11	18	15	6	11	18	15
1.6	98.7	0.89	107	244	245	0.49	1.43	0.0042	6	11	17	17	6	11	17	17
1.65	98.7	0.94	117	245	246	0.51	1.46	0.0042	5	10	17	17	5	10	17	17
1.7	98.8	0.98	128	246	247	0.53	1.52	0.0042	5	10	16	19	5	10	16	19
1.75	98.8	1.03	139	247	248	0.55	1.56	0.0042	5	9	16	20	5	9	16	20
1.8	98.9	1.07	151	249	249	0.57	1.58	0.0042	5	9	15	21	5	9	15	21
1.85	98.9	1.12	164	250	251	0.59	1.63	0.0042	4	9	15	22	4	9	15	22
1.9	99.0	1.16	178	251	252	0.61	1.68	0.0042	4	8	14	23	4	8	14	23
1.95	99.0	1.2	192	253	253	0.63	1.7	0.0042	4	8	14	24	4	8	14	24

Max. depth (m)	*Stage (m)*	*Ave depth (m)*	*Discharge (m^3/s)*	*Width (m)*	*Perim (m)*	*Ave vel (m/s)*	*Max vel (m/s)*	*Slope (m/m)*	*Macro-invertebrate flow class (%)*							
									VSCS	*SCS*	*FCS*	*VFCS*	*VSFS*	*SFS*	*FFS*	*VFFS*
2	99.1	1.25	207	254	255	0.65	1.77	0.0042	4	8	13	25	4	8	13	25
2.05	99.1	1.26	223	261	262	0.68	1.8	0.0044	4	7	12	27	4	7	12	27
2.1	99.2	1.19	240	287	288	0.7	1.82	0.0046	3	7	12	28	3	7	12	28
2.15	99.2	1.22	258	293	294	0.72	1.87	0.0047	3	7	12	29	3	7	12	29
2.2	99.3	1.27	277	294	295	0.74	1.89	0.0049	3	6	11	29	3	6	11	29
2.25	99.3	1.31	296	295	296	0.77	1.96	0.0051	3	6	11	30	3	6	11	30
2.3	99.4	1.36	317	296	297	0.79	1.99	0.0053	3	6	10	31	3	6	10	31
2.35	99.4	1.4	339	298	298	0.81	2.02	0.0054	3	6	10	32	3	6	10	32
2.4	99.5	1.45	361	299	299	0.84	2.05	0.0056	3	5	10	32	3	5	10	32
2.45	99.5	1.49	385	300	301	0.86	2.1	0.0058	3	5	9	33	3	5	9	33
2.5	99.6	1.53	409	301	302	0.89	2.08	0.0059	2	5	9	34	2	5	9	34
2.55	99.6	1.58	435	302	303	0.91	2.15	0.006	2	5	8	34	2	5	8	34
2.6	99.7	1.62	462	304	304	0.94	2.2	0.006	2	4	8	35	2	4	8	35
2.65	99.7	1.66	490	305	306	0.97	2.25	0.006	2	4	8	36	2	4	8	36
2.7	99.8	1.71	519	306	307	0.99	2.27	0.006	2	4	7	36	2	4	7	36
2.75	99.8	1.75	549	307	308	1.02	2.34	0.006	2	4	7	37	2	4	7	37

Table B4. Fish: Lookup table providing relevant hydraulic parameters and flow classes used for ecological interpretation using the Orange River EFR O5 cross-section

Max depth (m)	***Stage (m)***	***Ave depth (m)***	***Discharge (m^3/s)***	***Width (m)***	***Perim (m/m)***	***Ave vel (m/s)***	***Max vel (m/s)***	***Fish flow class (%)***						
								SVS	***SS***	***SD***	***FVS***	***FS***	***FI***	***FD***
0.05	0.03	0.003	2	2	0.06	0.22	0.0147	100	0	0	0	0	0	0
0.1	0.04	0.02	7	7	0.08	0.28	0.0147	97	1	0	2	0	0	0
0.15	0.07	0.08	9	9	0.13	0.43	0.0147	72	20	0	6	2	0	0
0.2	0.1	0.2	12	12	0.16	0.55	0.0147	37	48	0	6	8	0	0
0.25	0.13	0.37	15	15	0.2	0.65	0.0147	28	51	0	7	10	3	0
0.3	0.14	0.58	20	20	0.21	0.7	0.0147	29	47	0	9	7	8	0
0.35	0.17	0.95	22	22	0.25	0.83	0.0147	22	44	0	11	8	12	3
0.4	0.19	1.4	27	27	0.28	0.87	0.0147	16	47	0	9	10	7	10
0.45	0.22	2	30	30	0.31	1.03	0.0147	14	40	0	12	12	8	14
0.5	0.22	2.6	37	37	0.33	1.06	0.0147	14	38	0	13	10	10	15
0.55	0.25	3.7	40	41	0.37	1.18	0.0147	12	32	3	13	11	10	19
0.6	0.25	4.7	49	50	0.38	1.22	0.0147	12	28	5	14	12	8	21
0.65	0.28	6.3	54	54	0.42	1.34	0.0147	9	24	7	14	11	10	24
0.7	0.31	8.4	57	58	0.48	1.46	0.0147	5	24	8	8	15	10	31
0.75	0.34	11	60	61	0.53	1.67	0.0147	4	20	8	9	15	11	33
0.8	0.37	14	63	64	0.58	1.81	0.0147	3	18	9	7	10	14	40
0.85	0.4	17	67	68	0.64	1.95	0.0147	3	15	9	7	8	12	46

Max depth (m)	Stage (m)	Ave depth (m)	Discharge (m^3/s)	Width (m)	Perim (m/m)	Ave vel (m/s)	Max vel (m/s)	Fish flow class (%)						
								SVS	SS	SD	FVS	FS	FI	FD
0.9	0.42	21	73	74	0.69	2.08	0.0147	3	12	9	10	8	5	52
0.95	0.44	26	77	78	0.75	2.24	0.0147	3	11	9	9	8	6	55
1	0.48	31	79	81	0.81	2.36	0.0146	2	10	9	6	9	6	58
1.05	0.52	34	81	83	0.82	2.44	0.0143	1	8	11	6	8	7	59
1.1	0.55	39	84	86	0.83	2.45	0.014	1	8	12	4	6	9	61
1.15	0.58	43	86	89	0.85	2.54	0.0137	1	6	13	5	4	9	62
1.2	0.61	47	90	92	0.87	2.6	0.0134	1	6	13	6	5	4	65
1.25	0.63	52	94	96	0.88	2.59	0.0131	1	5	13	5	6	3	66
1.3	0.66	58	97	100	0.9	2.69	0.0129	1	5	13	6	7	4	65
1.35	0.69	63	100	103	0.91	2.71	0.0126	1	5	13	4	6	4	67
1.4	0.73	69	102	106	0.93	2.77	0.0123	1	4	13	5	4	6	67
1.45	0.76	75	105	108	0.94	2.76	0.012	1	4	13	4	5	6	67
1.5	0.79	81	107	111	0.96	2.73	0.0117	1	3	13	4	3	6	70
1.55	0.81	88	111	115	0.97	2.76	0.0114	1	3	12	6	2	5	71
1.6	0.79	94	122	126	0.99	2.81	0.0111	2	4	11	9	5	4	66
1.65	0.81	102	127	131	1	2.84	0.0108	2	3	11	11	4	4	66
1.7	0.83	109	130	135	1.01	2.81	0.0105	1	4	11	6	6	5	67
1.75	0.86	117	134	138	1.02	2.75	0.0102	0	4	12	1	10	7	67
1.8	0.89	125	137	141	1.03	2.82	0.01	1	4	11	4	7	5	69

Max depth (m)	***Stage (m)***	***Ave depth (m)***	***Discharge (m^3/s)***	***Width (m)***	***Perim (m/m)***	***Ave vel (m/s)***	***Max vel (m/s)***	***Fish flow class (%)***						
								SVS	***SS***	***SD***	***FVS***	***FS***	***FI***	***FD***
1.85	0.92	134	140	144	1.04	2.84	0.0097	1	3	11	4	5	7	70
1.9	0.95	143	143	147	1.05	2.8	0.0094	0	4	11	2	5	6	73
1.95	0.98	152	147	151	1.06	2.87	0.0091	1	3	10	3	3	6	74
2	1	161	150	155	1.07	2.83	0.0088	1	3	10	4	3	3	75
2.05	1.02	171	154	159	1.08	2.87	0.0085	1	3	10	4	4	4	75
2.1	1.05	181	159	163	1.09	2.89	0.0082	1	3	10	5	3	3	75
2.15	1.02	192	172	176	1.1	2.87	0.0079	1	3	10	7	5	4	71
2.2	1.01	202	181	186	1.11	2.86	0.0076	1	2	10	8	6	4	69
2.25	1.05	214	182	187	1.11	2.88	0.0074	1	2	10	7	6	4	70
2.3	1.09	225	184	189	1.12	2.88	0.0071	1	3	10	3	5	7	72
2.35	1.13	237	186	191	1.13	2.84	0.0068	0	3	10	1	4	8	75
2.4	1.15	249	191	196	1.13	2.94	0.0065	0	3	9	2	4	8	73
2.45	1	262	232	237	1.14	2.91	0.0062	1	3	8	10	8	5	64
2.5	0.97	275	249	254	1.13	2.95	0.0059	2	3	8	13	10	2	63
2.55	1	288	255	260	1.13	2.93	0.0056	2	3	8	14	10	1	62
2.6	1.03	302	261	266	1.13	2.93	0.0053	1	3	8	9	8	5	64
2.65	1.06	316	267	272	1.12	2.89	0.005	1	4	8	5	6	10	67
2.7	1.09	330	271	276	1.12	2.87	0.0048	1	4	8	4	5	11	68
2.75	1.12	345	275	280	1.12	2.85	0.0045	0	4	9	2	4	12	69

Max depth (m)	***Stage (m)***	***Ave depth (m)***	***Discharge (m^3/s)***	***Width (m)***	***Perim (m/m)***	***Ave vel (m/s)***	***Max vel (m/s)***	***Fish flow class (%)***						
								SVS	***SS***	***SD***	***FVS***	***FS***	***FI***	***FD***
2.8	1.15	360	280	285	1.12	2.87	0.0042	0	4	9	3	3	8	73
2.85	1.19	376	282	288	1.12	2.88	0.0039	0	3	9	3	3	3	78
2.9	1.23	392	285	290	1.12	2.87	0.0036	0	3	9	2	2	4	80
2.95	1.27	408	287	293	1.12	2.86	0.0033	0	3	10	2	2	3	81
3	1.3	425	291	297	1.12	2.88	0.003	0	3	10	1	1	4	81
3.05	1.34	442	295	301	1.12	2.83	0.0027	0	2	10	2	2	3	82
3.1	1.37	460	299	305	1.12	2.82	0.0024	0	1	11	2	2	2	81
3.15	1.4	478	302	308	1.13	2.85	0.0022	0	1	11	2	2	2	81
3.2	1.44	496	305	310	1.13	2.85	0.0019	0	1	11	2	2	1	83
3.25	1.48	515	307	313	1.13	2.85	0.0016	0	1	11	2	2	2	83
3.3	1.52	534	309	315	1.14	2.84	0.0013	0	1	11	1	1	2	83
3.35	1.56	554	312	318	1.14	2.84	0.001	0	1	11	2	2	2	83
3.4	1.59	574	314	320	1.14	2.82	0.001	0	1	11	1	1	2	84
3.45	1.63	594	317	323	1.15	2.88	0.001	0	1	11	2	2	2	83
3.5	1.67	615	319	325	1.15	2.87	0.001	0	1	11	1	1	2	83
3.55	1.7	636	322	328	1.16	2.89	0.001	0	1	11	1	1	1	84
3.6	1.74	658	324	331	1.16	2.88	0.001	0	1	11	1	1	1	85
3.65	1.78	680	327	333	1.17	2.87	0.001	0	1	11	1	1	1	85
3.7	1.81	702	329	336	1.17	2.91	0.001	0	1	10	1	1	2	84

Max depth (m)	***Stage (m)***	***Ave depth (m)***	***Discharge (m^3/s)***	***Width (m)***	***Perim (m/m)***	***Ave vel (m/s)***	***Max vel (m/s)***	***Fish flow class (%)***						
								SVS	***SS***	***SD***	***FVS***	***FS***	***FI***	***FD***
3.75	1.85	725	332	338	1.18	2.94	0.001	0	1	10	2	2	1	84
3.8	1.89	748	334	340	1.19	2.95	0.001	0	1	11	2	2	1	84
3.85	1.93	772	336	343	1.19	2.97	0.001	0	1	10	2	2	1	84
3.9	1.96	796	338	345	1.2	2.94	0.001	0	1	11	1	1	1	86
3.95	1.99	821	342	348	1.2	2.99	0.001	0	1	10	2	2	1	84
4	2.02	846	346	352	1.21	2.98	0.001	0	1	10	2	2	1	84
4.05	2.05	872	350	357	1.22	2.98	0.001	0	1	10	1	1	1	85
4.1	2.07	898	354	360	1.22	2.92	0.001	0	1	10	1	1	1	85
4.15	2.1	924	357	364	1.23	2.95	0.001	0	1	10	2	2	2	84
4.2	2.13	951	360	367	1.24	2.94	0.001	0	1	10	2	2	2	85
4.25	2.16	978	364	371	1.24	2.97	0.001	0	1	10	2	2	2	85
4.3	2.19	1006	369	375	1.25	2.99	0.001	0	1	10	2	2	2	84
4.35	2.19	1034	376	382	1.25	3.02	0.001	0	1	9	2	2	2	83
4.4	2.2	1063	383	390	1.26	3.03	0.001	0	1	9	2	2	2	82
4.45	2.16	1092	399	406	1.27	3.05	0.001	0	1	9	3	3	3	80
4.5	2.17	1121	406	413	1.27	3.05	0.001	0	1	9	3	3	3	80
4.55	2.19	1152	412	419	1.27	3.07	0.001	0	1	9	4	4	4	78
4.6	2.24	1182	413	419	1.28	3.05	0.001	0	1	9	3	3	3	80
4.65	2.29	1213	413	420	1.28	3.03	0.001	0	1	9	3	3	3	82

Max depth (m)	***Stage (m)***	***Ave depth (m)***	***Discharge (m^3/s)***	***Width (m)***	***Perim (m/m)***	***Ave vel (m/s)***	***Max vel (m/s)***	***Fish flow class (%)***						
								SVS	***SS***	***SD***	***FVS***	***FS***	***FI***	***FD***
4.7	2.34	1244	413	420	1.29	3.08	0.001	0	1	9	2	2	2	83
4.75	2.38	1276	415	422	1.29	3.05	0.001	0	1	9	1	1	1	87
4.8	2.42	1309	417	424	1.3	3.07	0.001	0	1	9	1	1	1	88
4.85	2.46	1342	418	425	1.31	3.08	0.001	0	1	9	0	0	0	89
4.9	2.5	1375	420	427	1.31	3.11	0.001	0	1	9	0	0	0	89
4.95	2.54	1409	420	427	1.32	3.14	0.001	0	1	9	1	1	1	89
5	2.59	1443	421	428	1.32	3.15	0.001	0	1	9	1	1	1	89
5.05	2.63	1478	422	429	1.33	3.16	0.001	0	0	9	0	0	0	90
5.1	2.68	1513	423	430	1.34	3.17	0.001	0	0	9	0	0	0	90
5.15	2.72	1549	424	431	1.34	3.19	0.001	0	0	9	0	0	0	90
5.2	2.77	1585	425	432	1.35	3.18	0.001	0	0	9	0	0	0	90
5.25	2.82	1622	425	432	1.36	3.16	0.001	0	0	9	0	0	0	91
5.3	2.86	1659	426	433	1.36	3.22	0.001	0	0	9	1	1	1	89
5.35	2.91	1697	426	433	1.37	3.22	0.001	0	0	9	1	1	1	89
5.4	2.96	1735	427	434	1.38	3.21	0.001	0	0	9	0	0	0	90
5.45	3	1773	427	434	1.38	3.24	0.001	0	0	9	0	0	0	90
5.5	3.05	1813	427	435	1.39	3.29	0.001	0	0	9	0	0	0	90
5.55	3.1	1852	428	435	1.4	3.31	0.001	0	0	9	0	0	0	90
5.6	3.14	1892	428	436	1.41	3.3	0.001	0	0	9	0	0	0	91

Max depth (m)	***Stage (m)***	***Ave depth (m)***	***Discharge (m^3/s)***	***Width (m)***	***Perim (m/m)***	***Ave vel (m/s)***	***Max vel (m/s)***	***Fish flow class (%)***						
								SVS	***SS***	***SD***	***FVS***	***FS***	***FI***	***FD***
5.65	3.19	1933	429	436	1.41	3.31	0.001	0	0	9	0	0	0	91
5.7	3.23	1974	429	437	1.42	3.36	0.001	0	0	9	0	0	0	90
5.75	3.28	2016	430	437	1.43	3.38	0.001	0	0	9	0	0	0	91
5.8	3.32	2058	431	439	1.44	3.37	0.001	0	0	9	0	0	0	91
5.85	3.36	2101	433	440	1.45	3.42	0.001	0	0	9	0	0	0	91
5.9	3.4	2144	434	441	1.45	3.41	0.001	0	0	8	0	0	0	91
5.95	3.44	2188	435	442	1.46	3.43	0.001	0	0	8	0	0	0	90
6	3.48	2232	436	444	1.47	3.46	0.001	0	0	8	0	0	0	90
0.05	0.03	0.003	2	2	0.06	0.22	0.0147	100	0	0	0	0	0	0
0.1	0.04	0.02	7	7	0.08	0.28	0.0147	97	1	0	2	0	0	0
0.15	0.07	0.08	9	9	0.13	0.43	0.0147	72	20	0	6	2	0	0
0.2	0.1	0.2	12	12	0.16	0.55	0.0147	37	48	0	6	8	0	0
0.25	0.13	0.37	15	15	0.2	0.65	0.0147	28	51	0	7	10	3	0

Table B5. Macro-invertebrates: Lookup table providing relevant hydraulic parameters and flow classes used for ecological interpretation using the Orange River EFR O5 cross-section

Max. depth (m)	***Stage (m)***	***Ave depth (m)***	***Discharge (m³/s)***	***Width (m)***	***Perim (m/m)***	***Ave vel (m/s)***	***Max vel (m/s)***	***Macro-invertebrate flow class (%)***							
								VSCS	***SCS***	***FCS***	***VFCS***	***VSFS***	***SFS***	***FFS***	***VFFS***
0.05	0.03	0.003	2	2	0.06	0.22	0.0147	40	10	0	0	16	4	0	0
0.1	0.04	0.02	7	7	0.08	0.28	0.0147	34	15	1	0	14	6	0	0
0.15	0.07	0.08	9	9	0.13	0.43	0.0147	24	22	4	0	10	9	2	0
0.2	0.1	0.2	12	12	0.16	0.55	0.0147	20	23	6	1	8	9	3	0
0.25	0.13	0.37	15	15	0.2	0.65	0.0147	17	22	9	2	7	9	3	1
0.3	0.14	0.58	20	20	0.21	0.7	0.0147	16	22	10	2	7	9	4	1
0.35	0.17	0.95	22	22	0.25	0.83	0.0147	14	19	13	3	6	8	5	1
0.4	0.19	1.4	27	27	0.28	0.87	0.0147	13	18	15	4	5	7	6	2
0.45	0.22	2	30	30	0.31	1.03	0.0147	11	16	17	6	4	6	7	2
0.5	0.22	2.6	37	37	0.33	1.06	0.0147	11	15	17	6	4	6	7	3
0.55	0.25	3.7	40	41	0.37	1.18	0.0147	9	14	18	9	4	6	7	3
0.6	0.25	4.7	49	50	0.38	1.22	0.0147	9	14	18	9	4	5	7	4
0.65	0.28	6.3	54	54	0.42	1.34	0.0147	8	12	18	12	3	5	7	5
0.7	0.31	8.4	57	58	0.48	1.46	0.0147	7	11	17	15	3	5	7	6
0.75	0.34	11	60	61	0.53	1.67	0.0147	6	10	15	19	2	4	6	8
0.8	0.37	14	63	64	0.58	1.81	0.0147	5	9	14	22	2	4	5	9
0.85	0.4	17	67	68	0.64	1.95	0.0147	5	9	12	24	2	3	5	10

Max. depth (m)	*Stage (m)*	*Ave depth (m)*	*Discharge (m^3/s)*	*Width (m)*	*Perim (m/m)*	*Ave vel (m/s)*	*Max vel (m/s)*	*Macro-invertebrate flow class (%)*							
								VSCS	*SCS*	*FCS*	*VFCS*	*VSFS*	*SFS*	*FFS*	*VFFS*
0.9	0.42	21	73	74	0.69	2.08	0.0147	4	8	11	26	2	3	5	10
0.95	0.44	26	77	78	0.75	2.24	0.0147	4	7	10	28	2	3	4	11
1	0.48	31	79	81	0.81	2.36	0.0146	4	7	10	30	1	3	4	12
1.05	0.52	34	81	83	0.82	2.44	0.0143	3	7	9	30	1	3	4	12
1.1	0.55	39	84	86	0.83	2.45	0.014	3	7	9	30	1	3	4	13
1.15	0.58	43	86	89	0.85	2.54	0.0137	3	7	9	31	1	3	4	13
1.2	0.61	47	90	92	0.87	2.6	0.0134	3	7	8	31	1	3	4	13
1.25	0.63	52	94	96	0.88	2.59	0.0131	3	7	8	31	1	3	4	13
1.3	0.66	58	97	100	0.9	2.69	0.0129	3	6	8	31	1	3	4	14
1.35	0.69	63	100	103	0.91	2.71	0.0126	3	6	8	32	1	3	4	14
1.4	0.73	69	102	106	0.93	2.77	0.0123	3	6	8	32	1	3	4	14
1.45	0.76	75	105	108	0.94	2.76	0.012	3	6	8	32	1	3	4	15
1.5	0.79	81	107	111	0.96	2.73	0.0117	3	6	8	32	1	3	4	15
1.55	0.81	88	111	115	0.97	2.76	0.0114	3	5	8	33	1	3	4	15
1.6	0.79	94	122	126	0.99	2.81	0.0111	3	5	7	33	1	3	4	16
1.65	0.81	102	127	131	1	2.84	0.0108	3	5	7	33	1	3	4	17
1.7	0.83	109	130	135	1.01	2.81	0.0105	3	5	7	33	1	3	4	17
1.75	0.86	117	134	138	1.02	2.75	0.0102	3	5	7	33	1	3	4	17
1.8	0.89	125	137	141	1.03	2.82	0.01	2	5	7	33	1	3	4	18

Max. depth (m)	***Stage (m)***	***Ave depth (m)***	***Discharge (m^3/s)***	***Width (m)***	***Perim (m/m)***	***Ave vel (m/s)***	***Max vel (m/s)***	***Macro-invertebrate flow class (%)***							
								VSCS	***SCS***	***FCS***	***VFCS***	***VSFS***	***SFS***	***FFS***	***VFFS***
1.85	0.92	134	140	144	1.04	2.84	0.0097	2	5	7	33	1	2	4	18
1.9	0.95	143	143	147	1.05	2.8	0.0094	2	5	7	33	1	2	4	18
1.95	0.98	152	147	151	1.06	2.87	0.0091	2	4	7	34	1	2	4	19
2	1	161	150	155	1.07	2.83	0.0088	2	4	7	34	1	2	4	19
2.05	1.02	171	154	159	1.08	2.87	0.0085	2	4	6	34	1	2	4	19
2.1	1.05	181	159	163	1.09	2.89	0.0082	2	4	6	34	1	2	4	20
2.15	1.02	192	172	176	1.1	2.87	0.0079	2	4	6	34	1	2	4	20
2.2	1.01	202	181	186	1.11	2.86	0.0076	2	4	6	33	1	3	4	21
2.25	1.05	214	182	187	1.11	2.88	0.0074	2	4	6	33	1	3	4	21
2.3	1.09	225	184	189	1.12	2.88	0.0071	2	4	6	34	1	2	4	21
2.35	1.13	237	186	191	1.13	2.84	0.0068	2	4	6	34	1	2	4	22
2.4	1.15	249	191	196	1.13	2.94	0.0065	2	4	6	34	1	2	4	22
2.45	1	262	232	237	1.14	2.91	0.0062	2	4	6	32	1	3	4	24
2.5	0.97	275	249	254	1.13	2.95	0.0059	2	4	6	32	1	3	5	26
2.55	1	288	255	260	1.13	2.93	0.0056	2	4	6	31	1	3	5	26
2.6	1.03	302	261	266	1.13	2.93	0.0053	2	4	6	31	2	3	5	26
2.65	1.06	316	267	272	1.12	2.89	0.005	2	4	6	31	2	3	5	27
2.7	1.09	330	271	276	1.12	2.87	0.0048	2	4	6	31	2	3	5	27
2.75	1.12	345	275	280	1.12	2.85	0.0045	2	4	6	31	2	3	5	27

Max. depth (m)	***Stage (m)***	***Ave depth (m)***	***Discharge (m^3/s)***	***Width (m)***	***Perim (m/m)***	***Ave vel (m/s)***	***Max vel (m/s)***	***Macro-invertebrate flow class (%)***							
								VSCS	***SCS***	***FCS***	***VFCS***	***VSFS***	***SFS***	***FFS***	***VFFS***
2.8	1.15	360	280	285	1.12	2.87	0.0042	2	4	5	31	2	3	5	28
2.85	1.19	376	282	288	1.12	2.88	0.0039	2	3	5	31	2	3	5	28
2.9	1.23	392	285	290	1.12	2.87	0.0036	2	3	5	31	2	3	5	28
2.95	1.27	408	287	293	1.12	2.86	0.0033	2	3	5	30	2	3	5	28
3	1.3	425	291	297	1.12	2.88	0.003	2	3	5	30	2	3	5	28
3.05	1.34	442	295	301	1.12	2.83	0.0027	2	3	5	30	2	3	5	29
3.1	1.37	460	299	305	1.12	2.82	0.0024	2	3	5	30	2	3	5	29
3.15	1.4	478	302	308	1.13	2.85	0.0022	2	3	5	30	2	3	5	29
3.2	1.44	496	305	310	1.13	2.85	0.0019	2	3	5	30	2	3	5	29
3.25	1.48	515	307	313	1.13	2.85	0.0016	2	3	5	30	2	3	5	30
3.3	1.52	534	309	315	1.14	2.84	0.0013	2	3	5	30	2	3	5	30
3.35	1.56	554	312	318	1.14	2.84	0.001	2	3	5	30	2	3	5	30
3.4	1.59	574	314	320	1.14	2.82	0.001	2	3	5	30	2	3	5	30
3.45	1.63	594	317	323	1.15	2.88	0.001	2	3	5	30	2	3	5	30
3.5	1.67	615	319	325	1.15	2.87	0.001	2	3	5	30	2	3	5	30
3.55	1.7	636	322	328	1.16	2.89	0.001	2	3	5	30	2	3	5	30
3.6	1.74	658	324	331	1.16	2.88	0.001	2	3	5	30	2	3	5	30
3.65	1.78	680	327	333	1.17	2.87	0.001	2	3	5	30	2	3	5	30
3.7	1.81	702	329	336	1.17	2.91	0.001	2	3	5	30	2	3	5	30

Max. depth (m)	***Stage (m)***	***Ave depth (m)***	***Discharge (m^3/s)***	***Width (m)***	***Perim (m/m)***	***Ave vel (m/s)***	***Max vel (m/s)***	***Macro-invertebrate flow class (%)***							
								VSCS	***SCS***	***FCS***	***VFCS***	***VSFS***	***SFS***	***FFS***	***VFFS***
3.75	1.85	725	332	338	1.18	2.94	0.001	2	3	5	31	2	3	5	31
3.8	1.89	748	334	340	1.19	2.95	0.001	2	3	5	31	2	3	5	31
3.85	1.93	772	336	343	1.19	2.97	0.001	1	3	5	31	1	3	5	31
3.9	1.96	796	338	345	1.2	2.94	0.001	1	3	5	31	1	3	5	31
3.95	1.99	821	342	348	1.2	2.99	0.001	1	3	5	31	1	3	5	31
4	2.02	846	346	352	1.21	2.98	0.001	1	3	5	31	1	3	5	31
4.05	2.05	872	350	357	1.22	2.98	0.001	1	3	5	31	1	3	5	31
4.1	2.07	898	354	360	1.22	2.92	0.001	1	3	5	31	1	3	5	31
4.15	2.1	924	357	364	1.23	2.95	0.001	1	3	5	31	1	3	5	31
4.2	2.13	951	360	367	1.24	2.94	0.001	1	3	5	31	1	3	5	31
4.25	2.16	978	364	371	1.24	2.97	0.001	1	3	5	31	1	3	5	31
4.3	2.19	1006	369	375	1.25	2.99	0.001	1	3	5	31	1	3	5	31
4.35	2.19	1034	376	382	1.25	3.02	0.001	1	3	5	31	1	3	5	31
4.4	2.2	1063	383	390	1.26	3.03	0.001	1	3	5	31	1	3	5	31
4.45	2.16	1092	399	406	1.27	3.05	0.001	1	3	4	31	1	3	4	31
4.5	2.17	1121	406	413	1.27	3.05	0.001	1	3	4	31	1	3	4	31
4.55	2.19	1152	412	419	1.27	3.07	0.001	1	3	4	32	1	3	4	32
4.6	2.24	1182	413	419	1.28	3.05	0.001	1	3	4	31	1	3	4	31
4.65	2.29	1213	413	420	1.28	3.03	0.001	1	3	4	31	1	3	4	31

Max. depth (m)	***Stage (m)***	***Ave depth (m)***	***Discharge (m^3/s)***	***Width (m)***	***Perim (m/m)***	***Ave vel (m/s)***	***Max vel (m/s)***	***Macro-invertebrate flow class (%)***							
								VSCS	***SCS***	***FCS***	***VFCS***	***VSFS***	***SFS***	***FFS***	***VFFS***
4.7	2.34	1244	413	420	1.29	3.08	0.001	1	3	4	32	1	3	4	32
4.75	2.38	1276	415	422	1.29	3.05	0.001	1	3	4	32	1	3	4	32
4.8	2.42	1309	417	424	1.3	3.07	0.001	1	3	4	32	1	3	4	32
4.85	2.46	1342	418	425	1.31	3.08	0.001	1	3	4	32	1	3	4	32
4.9	2.5	1375	420	427	1.31	3.11	0.001	1	3	4	32	1	3	4	32
4.95	2.54	1409	420	427	1.32	3.14	0.001	1	3	4	32	1	3	4	32
5	2.59	1443	421	428	1.32	3.15	0.001	1	3	4	32	1	3	4	32
5.05	2.63	1478	422	429	1.33	3.16	0.001	1	3	4	32	1	3	4	32
5.1	2.68	1513	423	430	1.34	3.17	0.001	1	3	4	32	1	3	4	32
5.15	2.72	1549	424	431	1.34	3.19	0.001	1	3	4	32	1	3	4	32
5.2	2.77	1585	425	432	1.35	3.18	0.001	1	3	4	32	1	3	4	32
5.25	2.82	1622	425	432	1.36	3.16	0.001	1	3	4	32	1	3	4	32
5.3	2.86	1659	426	433	1.36	3.22	0.001	1	2	4	32	1	2	4	32
5.35	2.91	1697	426	433	1.37	3.22	0.001	1	2	4	32	1	2	4	32
5.4	2.96	1735	427	434	1.38	3.21	0.001	1	2	4	32	1	2	4	32
5.45	3	1773	427	434	1.38	3.24	0.001	1	2	4	32	1	2	4	32
5.5	3.05	1813	427	435	1.39	3.29	0.001	1	2	4	32	1	2	4	32
5.55	3.1	1852	428	435	1.4	3.31	0.001	1	2	4	32	1	2	4	32
5.6	3.14	1892	428	436	1.41	3.3	0.001	1	2	4	32	1	2	4	32

Max. depth (m)	***Stage (m)***	***Ave depth (m)***	***Discharge (m^3/s)***	***Width (m)***	***Perim (m/m)***	***Ave vel (m/s)***	***Max vel (m/s)***	***Macro-invertebrate flow class (%)***							
								VSCS	***SCS***	***FCS***	***VFCS***	***VSFS***	***SFS***	***FFS***	***VFFS***
5.65	3.19	1933	429	436	1.41	3.31	0.001	1	2	4	32	1	2	4	32
5.7	3.23	1974	429	437	1.42	3.36	0.001	1	2	4	33	1	2	4	33
5.75	3.28	2016	430	437	1.43	3.38	0.001	1	2	4	33	1	2	4	33
5.8	3.32	2058	431	439	1.44	3.37	0.001	1	2	4	33	1	2	4	33
5.85	3.36	2101	433	440	1.45	3.42	0.001	1	2	4	33	1	2	4	33
5.9	3.4	2144	434	441	1.45	3.41	0.001	1	2	4	33	1	2	4	33
5.95	3.44	2188	435	442	1.46	3.43	0.001	1	2	4	33	1	2	4	33
6	3.48	2232	436	444	1.47	3.46	0.001	1	2	4	33	1	2	4	33
0.05	0.03	0.003	2	2	0.06	0.22	0.0147	40	10	0	0	16	4	0	0
0.1	0.04	0.02	7	7	0.08	0.28	0.0147	34	15	1	0	14	6	0	0
0.15	0.07	0.08	9	9	0.13	0.43	0.0147	24	22	4	0	10	9	2	0
0.2	0.1	0.2	12	12	0.16	0.55	0.0147	20	23	6	1	8	9	3	0
0.25	0.13	0.37	15	15	0.2	0.65	0.0147	17	22	9	2	7	9	3	1

Appendix C Hydrodynamic modelling of the Fish River

C.1 Objective

The purpose of the hydrodynamic modelling component of the hydrological study for the Fish River system is to be able to predict how flow events (artificial releases and spills) from the proposed Neckartal Dam will attenuate with distance downstream.

C.2 Model setup

The hydrodynamic modelling was setup for the 597 km reach of the mainstem Fish River, from Hardap Dam to the Ai-Ais gauge. EFR Fish 1 was selected upstream of Neckartal Dam to cater for possible scenarios such as the raising of Hardap Dam wall. Present day conditions (against which future scenarios are assessed) would be provided by routing events from the Hardap Dam as far as Ai-Ais gauge. The modelling therefore had to include the reach upstream of Neckartal Dam to Hardap Dam. It was decided during the scenario phase of the project that as all scenarios in the Fish River are routed from Neckartal Dam and that the hydrodynamic modelling was only relevant for the reach between Neckartal Dam and Ai-Ais gauge.

Hydrological data for use in the modelling became available as follows:

- November 2011 data were available for the Seeheim gauge (Station 0496M01) for the period 01/1961 to 05/2010 (from a previous study undertaken by Knight Piesold (Pty) Ltd, and obtained in turn from the Namibia Ministry of Water Affairs and Forestry (MAWF)).
- Sub-daily flows data were sought for the Seeheim and Ai-Ais gauges, as well as releases from the Hardap and Naute Dams. These data were received from the Namibia MAWF during September and October 2012.

The unsteady open-source hydraulic modelling software, HEC-RAS v4.1 (available at http://www.hec.usace.army.mil/) was used. Although more sophisticated hydraulic models are available, their transferability is limited to a handful of organisations and institutions (proprietary software). Furthermore, the available hydrological and topographical information for the Fish River system and resources available for this component of the study (which is in support of an environmental flow assessment) do not warrant the parameterisation of more complex models. A drawback of using HEC-RAS for the Fish River system is its inability to explicitly account for changes in pool storage during the cessation of surface flow, which is an important hydrological characteristic of the system. These, were, however, included in the HEC-RAS modelling using various other available hydraulic structures and storage systems (described below).

The intention was to make use of the SRTM (Shuttle Radar Topography Mission) 90 m DEM (Digital Elevation Model) to obtain approximate estimates of the macro-channel topography (and longitudinal gradient), into which approximate active-channel profiles were inserted. Such a topographical model was developed for the Fish River between Hardap Dam and Ai-Ais gauge, using profiles at 1 km intervals. Unfortunately, the use of the resulting highly variable topography and longitudinal gradient resulted in modelling computational instabilities when routing highly variable (unsteady) flood events. Consequently, simple trapezoidal cross-sectional channel profiles and uniform longitudinal gradients were used in conjunction with observed flow data from the gauges and dam releases to obtain a calibrated but computationally stable hydraulic routing model (refer to Section C3, following).

Figure C1 is a schematic diagram of the HEC-RAS model setup, showing the longitudinal location of:

- The existing Hardap and Naute Dams;
- the proposed Neckartal Dam;
- existing gauges;
- EFR Fish 1 and 2;
- incremental and cumulative flows from the hydrological modelling (catchment numbering used in the hydrological modelling (refer to the main report) is used for consistency); and
- discrete models accounting for losses to pool storage and evaporation.

River stations (RS) refer to the distances (in km) upstream of the Orange-Fish River confluence. (Catch. x = catchment number x used in the hydrological modelling - refer to the main sections of this report).

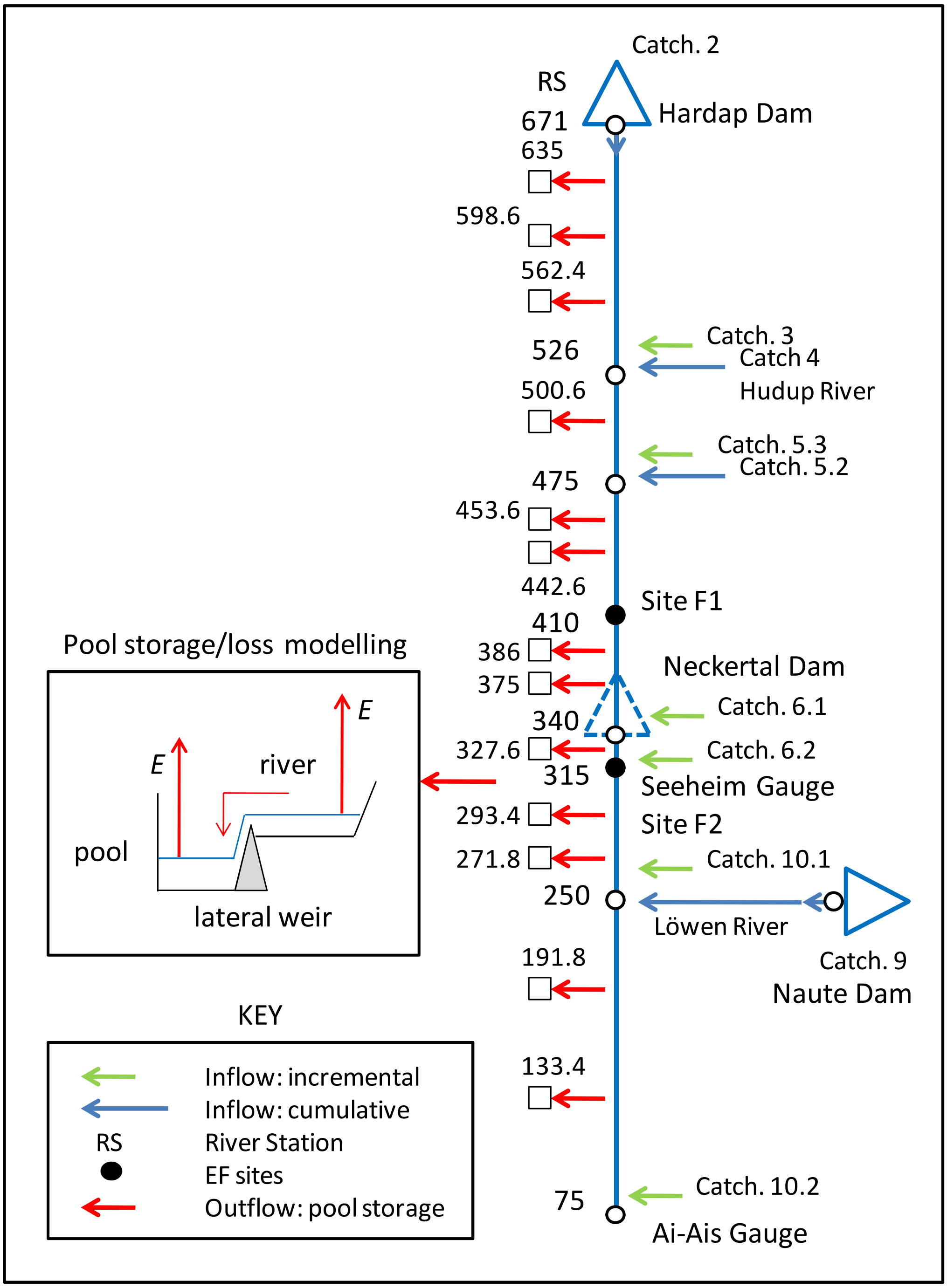


Figure C1. Schematic diagram showing the HEC-RAS model setup for routing flows from Hardap and the proposed Neckartal Dams, along 671 km of the Fish River as far as Ai-Ais gauge.

Pool storage is included in the hydraulic modelling by incorporating a number of discrete off-channel storage elements. These structures are connected to surface flow in the river channel using lateral weirs (refer to Figure C1, inset). The weir crest elevations are specified slightly above river bed elevations to maintain a minimum flow in the channel (a necessary HEC-RAS modelling construct). Linear routing is used to compute flow over the lateral weirs (the most stable of the available lateral-weir routing methods), and evaporation from both off-channel (representing pool) and in-channel (river) storage is approximated using average annual values. In this way, pool storage systematically reduces flow in the river as an event progresses downstream and dead storage is filled-up. In the model, evaporation from pool storage continues after river stages have fallen below weir-crest elevations, simulating recessional pool stages into the dry season. To be consistent with the hydrological modelling, the hydraulic routing model uses similar dead-storage values for the river reaches.

Given the length of the river, two separate models were set up: the upstream reach from Hardap Dam to the Seeheim gauge, and the downstream reach from the proposed Neckartal Dam to the gauge at /Ai-/Ais Hot Springs Resort (called the Ai-Ais gauge).

C.3 Model assessment using historical flows

The accuracy of the routing models was assessed using historical flow data. For the Hardap Dam to Seeheim reach the period 1962 to 2012 was used, and for the proposed Neckartal Dam to the Ai-Ais gauge reach the period 1976[1] to 2012 was used. With the exception of the Löwen River at Naute Dam the intervening tributaries are ungauged. The approach, therefore, was to route flows from Hardap (and Naute) Dams for the above periods, and to assess model accuracy for events where releases do not appear to have coincided with (substantial) rainfall in the catchments downstream of Hardap Dam. Releases from Hardap Dam are only made when it reaches 70% of full supply level, and it appears, however, that these generally coincide with reasonably widespread rainfall. In the absence of daily rainfall-runoff modelling[2], the above approach is deemed to be reasonable for broadly assessing the accuracy of the routing models.

Historical release and spill data from the Hardap and Naute Dams were provided in various formats (and time intervals) in EXCEL spread sheet format. These were reformatted for the periods 1962 to 2012 and 1970 to 2012, respectively, using three-hourly time intervals, and imported into the HEC DSS-Vue.[3]

It was envisaged that the unsteady hydraulic model would be capable of routing dam releases for extended hydrological periods, including extreme flood events characteristic of the Fish River system (e.g. rise to 3 500 m^3/s over 15 hours on 16 March 1972). Computational stability was achieved by adopting simple characteristic (but nonetheless physically meaningful) model parameterisation, including: a uniform longitudinal gradient; a uniform trapezoidal channel cross-section with bed width of 120 m and 1:1 bank slope; and a constant Manning flow resistance coefficient of 0.035.

1 Although release data from Naute Dam are available from 1971 (when it was constructed), the data for Ai-Ais gauge commences in 1976.

2 Beyond the resources of the broader EFR assessment study.

3 The visual utility data storage system used by HEC-RAS.

Figure C2 provides discharge time-series plots of releases from Hardap Dam, and both measured and routed flows (daily average) at the Seeheim Gauge, for the period February to April 1977. The routing model simulates the attenuation of peak releases satisfactorily: a peak release of 1,000 m^3/s is attenuated to 460 m^3/s and modelled at 440 m^3/s; a lower peak release of 200 m^3/s is attenuated to 57 m^3/s and modelled at 38 m^3/s. Similarly acceptable accuracy may be noted from the plots in Figure C3 for February and March 2009, where a peak release of 600 m^3/s (10 March 2009) results in measured and modelled (average daily) peaks of 241 m^3/s and 285 m^3/s, respectively.

The adequacy of the routing model for the river reach between the proposed Neckartal Dam and Ai-Ais gauge was assessed by routing measured flows from the Seeheim Gauge to Ai-Ais gauge, and including inflows from the Löwen River as measured at Naute Dam. Figure C4 and Figure C5 provide example discharge time-series plots for February 1989 and the period January to March 1994, respectively: measured peak flows of 1,070 m^3/s (average daily) at the Seeheim Gauge and 800 m^3/s (three-hourly) at Naute Dam result in measured and routed peak flows (average daily) at the Ai-Ais gauge of 1,300 m^3/s and 1,540 m^3/s, respectively (Figure C4); measured peak flows of 40 m^3/s (average daily) at the Seeheim Gauge and 200 m^3/s (three-hourly) at Naute Dam result in measured and routed peak flows (average daily) at Ai-Ais gauge of 126 m^3/s and 110 m^3/s, respectively (Figure C5).

Although some of the differences between measured and modelled behaviour can be attributed to the simulation capabilities of the hydraulic routing model, the accuracy of measured flows (dam releases and spills, and at river gauges) as well as flows from ungauged tributaries, also contribute.

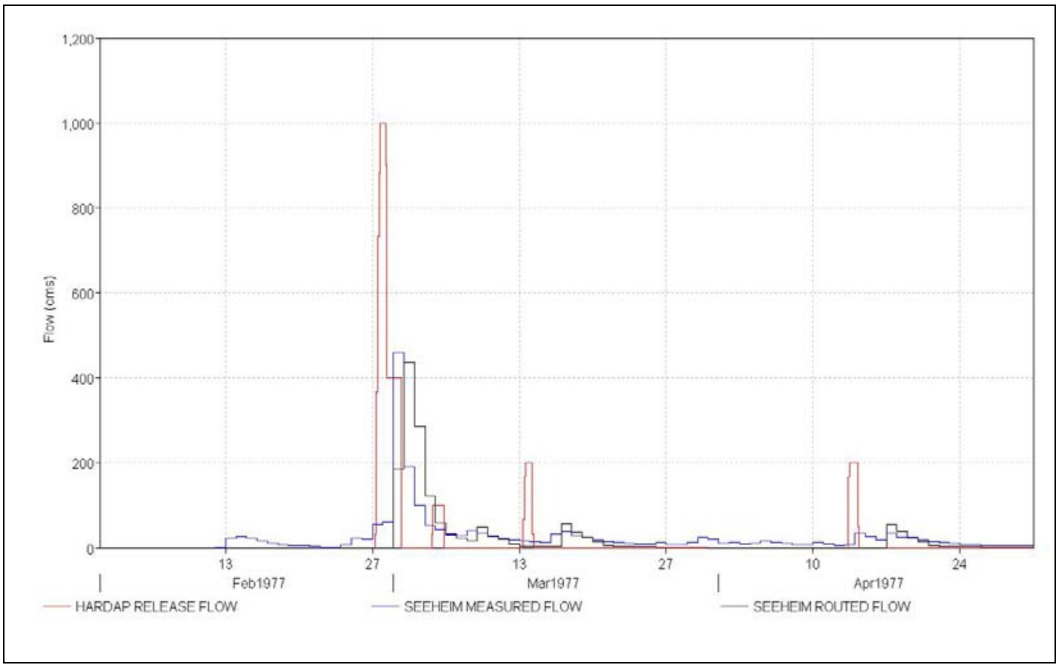


Figure C2. Discharge time-series plots of releases from Hardap Dam, measured and routed flows (daily average) at the Seeheim gauge, for the period February to April 1977 (cms = m³/s)

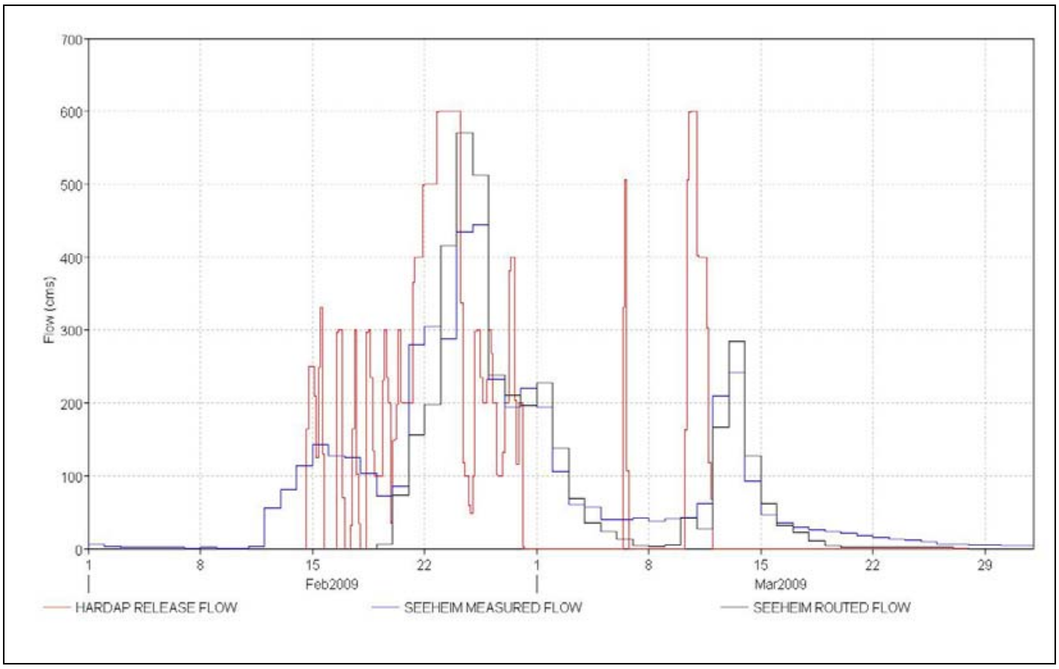


Figure C3. Discharge time-series plots of releases (3-hourly) from Hardap Dam, measured and routed flows (daily average) at the Seeheim gauge, for the period February to March 2009 (cms = m³/s)

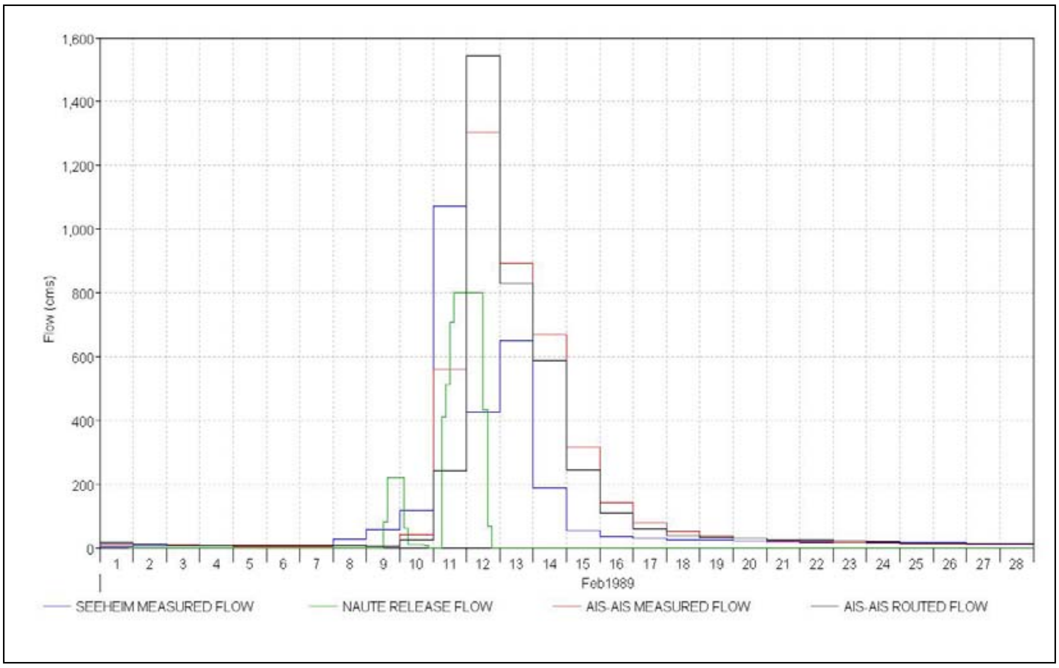


Figure C4. Discharge time-series plots of flows at the Seeheim gauge, and measured and routed flows (daily average) at the Ai-Ais gauge, for February 1989 (cms = m³/s)

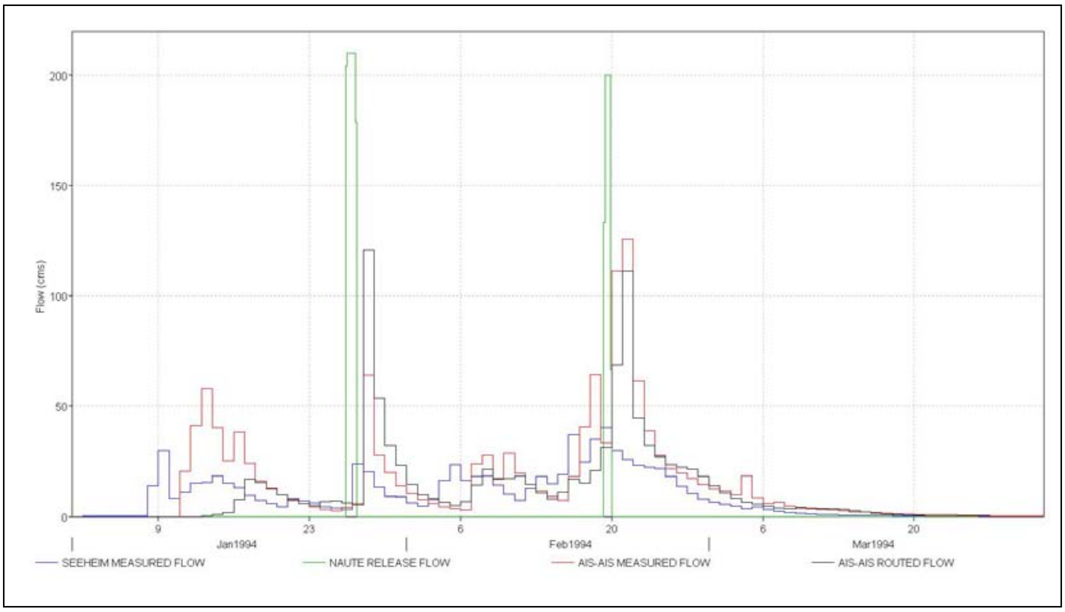


Figure C5. Discharge timeseries plots of flows at the Seeheim gauge, and measured and routed flows (daily average) at the Ai-Ais gauge, for the period January to March 1994 (cms = m³/s)

Discrete storage areas (refer to Figure C1) are used to characterise total pool storage along reaches of the Fish River. Dead-storage volumes and pool depths (used to derive them) are as applied in the hydrological modelling (refer to the main sections of this report). Storage areas with rectangular profiles have been used, which allows a constant (average annual) evaporation rate to be applied - resulting in a concomitant constant rate of stage recession (as required for a constant rate of evaporation). Figure C6 shows stage time-series plots for the pool storage areas representing the 32 km reach downstream of the Seeheim Gauge, and the 88 km reach upstream of Ai-Ais gauge. The time series represent historical conditions, based on the routing of measured flows at the Seeheim Gauge and measured releases from Naute Dam. Negative stages infer no surface flow. For the 43-year hydrological period, the results indicate that pool storage within these two reaches has been depleted (for extended periods greater than one month) approximately 3 and 4 times, respectively. The 1993 period, however, coincides with missing data at the Seeheim gauge.[4]

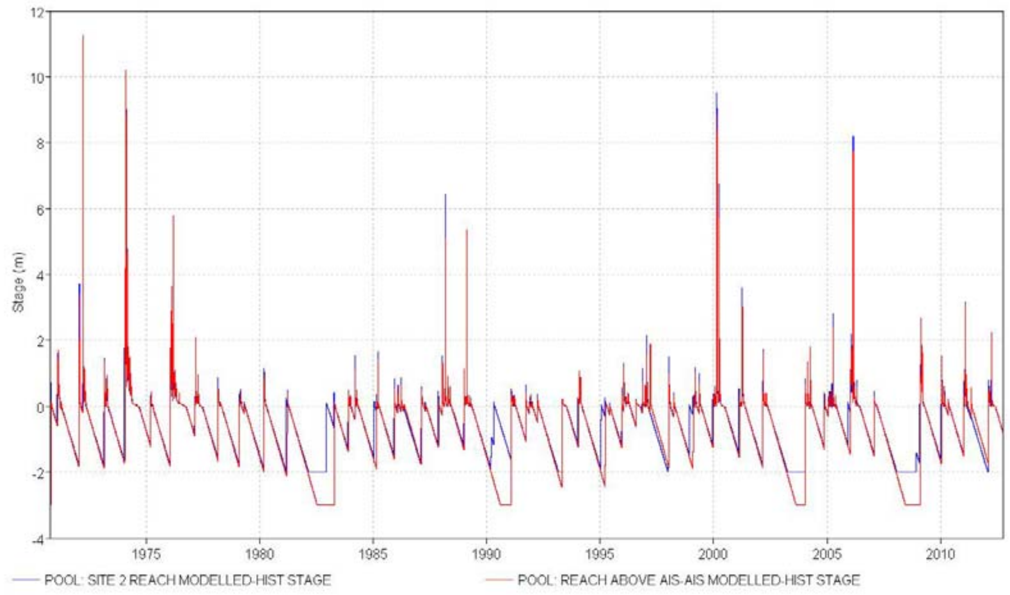


Figure C6. Stage time-series plots from October 1970 to September 2012 of modelled water levels (stages) in the discrete pool storage areas below Seeheim gauge (EFR Fish 2 location) and upstream of Ai-Ais gauge.

C.4 Model application using characteristic hydrographs

The monthly hydrological modelling[5] and disaggregation of monthly flow volumes into characteristic events is discussed in the main section of this report. The purpose of the hydrodynamic modelling is to route these characteristic events along the main stem Fish River between the Hardap Dam and Ai-Ais gauge. Hydrologically simulated events used in the routing analyses include (refer to Figure C1) cumulative flows (i.e. including all upstream catchment contributions) from catchments 2 (i.e. releases and spills from Hardap Dam), 4 (i.e. the Hudup

4 and implied zero flows which may be incorrect.

5 This includes for naturalised conditions (main report) and for PD and future scenarios (main report).

River), 5.2, and 9 (i.e. the Löwen River); and incremental flows for catchments 3, 5.3, 6.1, 6.2, 10.1 and 10.2.

Hydrodynamic simulations have been done for so-called PD hydrology conditions and for various Neckartal Dam release scenarios.

Present day conditions

Present day conditions refer to the hydrological situation with all PD water resource developments (i.e. current operation of Hardap and Naute Dams and associated water use to support domestic, agricultural and industrial requirements), and provides the base-line against which operation of proposed water resource developments (operation of Neckartal Dam) are assessed.

Figure C7 is an example discharge time series (average daily) of PD releases from Hardap Dam and routed flows at the Ai-Ais gauge, for the 1956/57 hydrological years. The routed flows include all catchment contributions between Hardap Dam and the Ai-Ais gauge, which are substantially higher in 1956 than 1957 (for similar releases from Hardap Dam).

Figure C8 shows historical and PD stage time-series plots for the pool storage areas representing the 32 km reach downstream of the Seeheim gauge (EFR Fish 2 location). Negative stages infer no surface flow. With the exception of the extended period of depleted pool storage in 1982 (for the historical simulation), both time series display similar behaviour: i.e., for pool-storage depths of 2 m, dead storage is generally replenished during wet seasons. When comparing modelled historical and PD pool storage, it needs to be re-emphasised that the historical simulations do not include tributary contributions[6], and furthermore, PD simulations neglect alluvial and pool storage in the tributaries. These are likely to contribute to the comparative over- and under-estimation of dead-storage replenishment in pools for historical and PD conditions, respectively (as indicated in Figure C8).

6 Except for the Löwen River at Naute Dam.

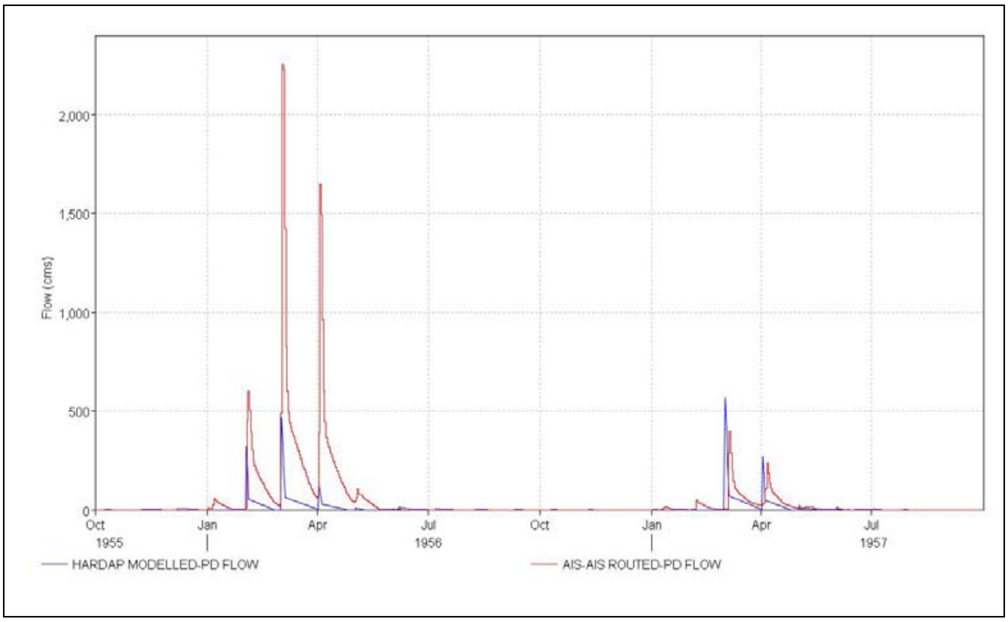


Figure C7. Discharge time-series plots of characteristic PD releases from Hardap Dam and the routed flows (daily average) at Ai-Ais gauge for the period October 1955 to September 1957 (cms = m³/s)

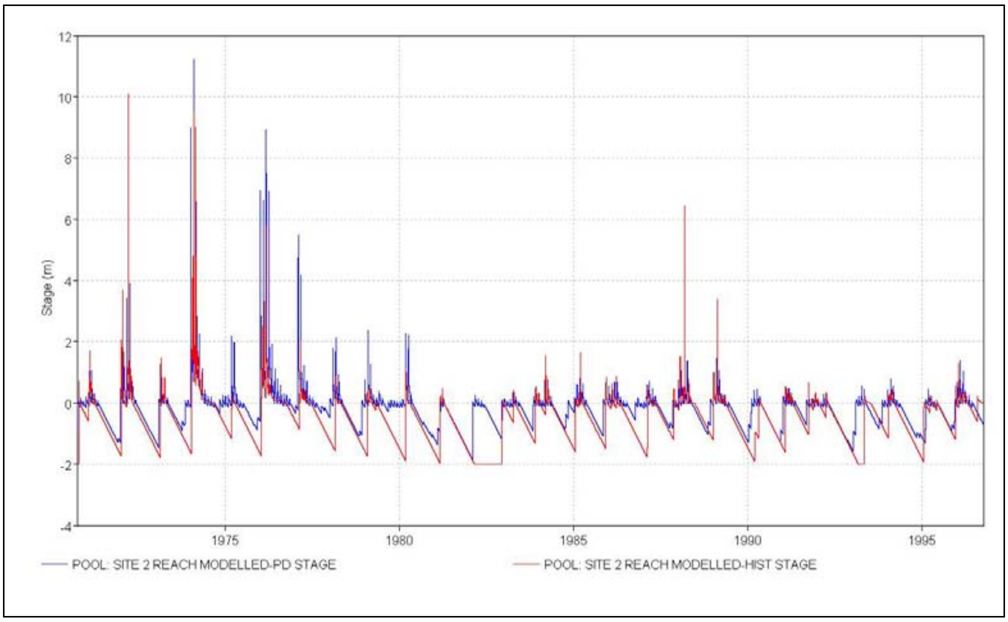


Figure C8. Stage time-series plots from October 1970 to September 1996 of modelled historical and PD water levels (stages) Seeheim gauge

Release options from Neckartal Dam

The hydrological yield modelling (main report) provided monthly flow volumes for various or release scenarios from the proposed Neckartal Dam. These were, in turn, disaggregated into characteristic events (as for PD conditions - refer to Section C4.1) and routed along the main-stem Fish River as far as the Ai-Ais gauge. Six different release options were routed, including: no release (RO 0%), RO 20%, RO 30%, RO 40%, RO 50% and RO Opt, where percentages refer to dam release/inflow proportions.[7] The RO Opt refers to a combination of RO 30% and RO 40%, depending on storage in the reservoir.

The PD time series were the routed flows (and associated pool stages) from the position of the proposed Neckartal Dam, and not from Hardap Dam. The reason for this is that all disaggregated monthly volumes (for all catchments) provide events commencing at the beginning of the month (refer to the main report). Therefore, PD routed (i.e. lagged) flows from Hardap Dam are not synchronous with cumulative releases/spills from the proposed Neckartal Dam, which are used in the scenario simulations.

The hydrodynamic modelling provided the following results for further statistical analyses (refer to the main report) and subsequent ecological interpretation; flow time series (average daily) for EFR Fish 2 located immediately downstream of Seeheim gauge (for which detailed hydraulic information is available - refer to Chapter 6) and at the Ai-Ais gauge; and stage time series (average daily) for the pool dead-storage areas representing the 32 km reach downstream of the Seeheim gauge, and the 88 km reach upstream of the Ai-Ais gauge.

Figure C9 is an example plot of the discharge time series (average daily) for the period October 1937 to October 1939, showing comparative modelled events for PD conditions, no release and the 30% release scenario. Comparative stage time series (average daily) plots for the pool storage along the 32 km reach downstream of the Seeheim gauge, are illustrated in Figure C10 where negative stages infer no surface flow. As expected, the no-release scenario results in extended periods of depleted pool storage (with up to 4 successive years of no surface flow), which are mitigated to different extents by the positive release scenarios (i.e., RO 20% to RO 50%).

[7] Note, all release scenarios were limited by the capacity (100 m^3/s) of the outlet works, as provided.

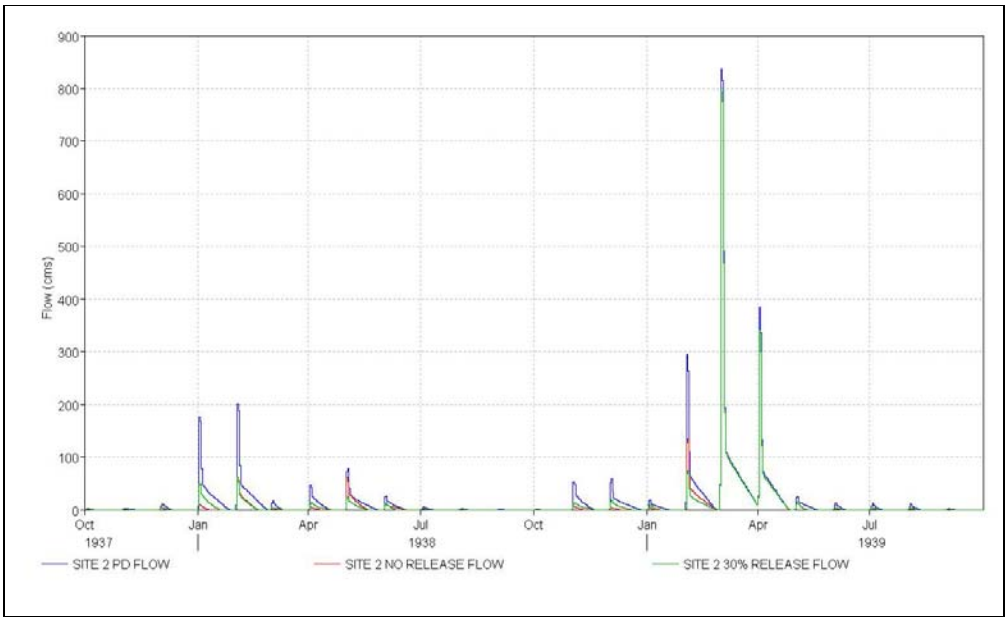


Figure C9. Discharge time series plot using characteristic events for PD, no release and RO 30% for the proposed Neckartal Dam, from October 1937 to September 1939 (cms = m³/s)

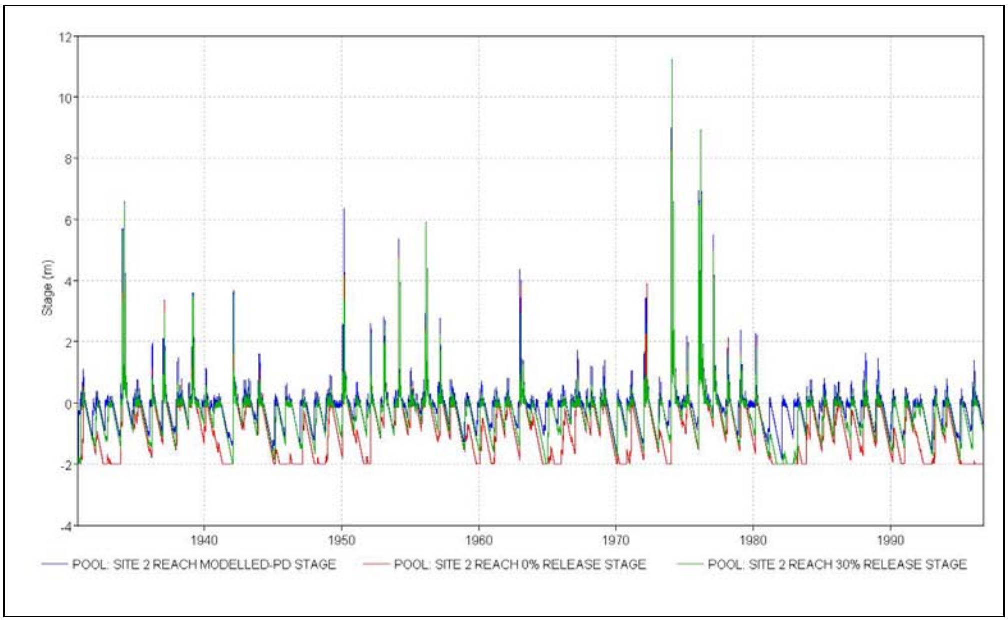


Figure C10. Stage time series in the discrete pool-storage areas for the 32 km reach below Seeheim gauge for modelled PD, RO 0% and RO 30, from October 1930 to September 1996

Appendix D Fish River hydrogeology: Hydrogeological review of interaction between aquifers and river

D.1 Background

Due to the ephemeral nature of the Fish River, the linkage between ground and surface water is an important aspect in EFR studies. Some of the aspects that were considered in this groundwater study were the following:

- Does leakage from groundwater and aquifers contribute to flow within the Fish River?
- Do flow and flood events in the Fish River contribute to recharge to groundwater resources and aquifers in the vicinity of the river?
- Will the construction of the Neckartal Dam have an impact on groundwater resources and the utilization thereof downstream of the dam site?
- Can environmental flow releases mitigate the impact?

D.2 Methods and approach

The hydrogeology study was based on available data and site observations only.

Data from Namwater production schemes and from the Groundwater Information System (GROWAS) from the Ministry of Agriculture, Water and Forestry (MAWF - Department of Geohydrology)) was consulted. In addition, a field trip to locate boreholes and measure water levels in and around Seeheim was undertaken. Collected data was presented on small maps and profiles created using SRTM worldwide elevation data. D Sarma (Namib Hydrosearch) is acknowledged for the processing of maps and profiles using SRTM data.

Annual scheme assessments from Namwater have been analysed and combined with daily river flow data as recorded by the Hydrology Department of the MAWF.

D.3 Constraints, limitations and data availability

Considering the large area covered, and the lack of recorded data with respect to ground water levels in close proximity of the Fish River basin, detailed assessments could only be attempted at a few locations. These locations focussed on areas where water supply schemes are operated by the Namibia Water Corporation (Namwater), and for which localities' detailed abstraction figures are recorded alongside regular water level measurements. River flow data, groundwater abstraction and resultant groundwater levels were only available at the /Ai-/Ais Hot Springs Resort.

A comprehensive groundwater study would therefore be necessary to understand the recharge and discharge mechanism of groundwater in the basin. The first and most important step will be to increase the rather poor monitoring network. Without recorded data such an assessment cannot be attempted. Reference to the lack of monitoring data has been made in a report by this author (Bockmühl, 2009) for the Desert Research Foundation (DRFN) of Namibia.

D.4 Geology and hydrogeology overview

The Fish River Basin covers an extensive area of southern Namibia, draining an area of approximately 120,000 km^2.

The basin includes rocks formed during all the major rock-forming periods known from Namibia. The landforms of the basin reflect the wide variety of lithologies found as well as the long geomorphological history of the area. Consequently the variety of rock types, fossils and mineral deposits that can be found in the basin is enormous. Similarly the landforms of the basin reflect the wide variety of lithologies found as well as the long geomorphological history of the area. Geology has influenced the location, quantity and quality of groundwater resources in the basin.

In a region with low and erratic rainfall, recharge to the aquifers is similarly low and erratic. With predominantly shallow groundwater tables in the basin and very limited overburden, recharge to groundwater happens very fast after rainfall events. In the vicinity of the Fish River, recharge to groundwater is controlled by flooding, which can be as a result of precipitation far from the point of recharge.

Most of the groundwater resources in the Fish River Basin are of good quality, suitable for both domestic and livestock watering. The water quality is mostly also suitable for irrigation purposes.

In general, boreholes have a low yield, and care should always be taken when high and constant abstraction is planned. Scientific data regarding the character and behaviour of the groundwater in the area is limited. However, there is quite clear correlation between recharge events and the reaction of water levels recorded. This is specifically of importance for aquifers in the Fish River, where indications are clear that these aquifers are primarily dependent on regular and continued floods within the river.

D.5 Surface-groundwater interaction

Geological descriptions have been adopted from *The Fish River Basin: An earth science review for the Ephemeral River Basins Project* (Swart, 2008). The focus is on the Nama Group and the Karoo sequence in terms of surface-groundwater interaction in the Fish River.

Nama Basin

The Nama Basin developed as a broad, gentle foreland basin in response to orogenies which were developing to the north and west. The Nama Group has been sub-divided into three formations – a basal Kuibis Subgroup, middle Schwarzrand Subgroup and an upper Fish River Subgroup. In

Figure D1, these are indicated as yellow (Kuibis), green (Schwarzrand) and orange (Fish River Subgroup). Two sub-basins are also recognised, the northern Zaris Basin separated from the southern Witputs Basin by the Osis Ridge. In the deepest parts of the sub-basins thicknesses are around 2-3 km thinning to less than 1km towards the Osis Ridge (Grotzinger, 2000).

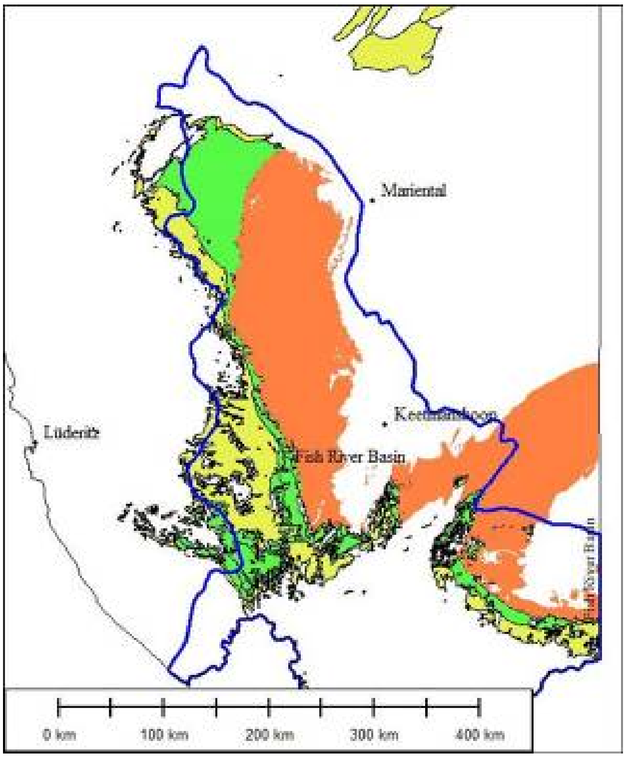


Figure D1. Distribution and type areas of the Nama Group in Namibia (source: Swart, 2008)

Towns like Aroab, Maltahöhe, Kalkrand (via a pipeline), Gibeon (partly only), Berseba and Bethanie are all supplied with groundwater pumped from rocks belonging to the Nama Group. Due to the nature of its predominantly horizontal bedding rocks, the Nama Group tends to weather and erode in layers, resulting in flat plains, with major drainages resulting in canyon and canyon-like incisions. Rivers in these areas also tend to accumulate limited thicknesses of alluvium, which can also be ascribed to the fact that erosion takes place in layers.

Inherently, rocks belonging to the Nama Group, are impermeable, i.e. with little or no primary porosity and very low permeability. Groundwater is hosted in faults and joints (in sedimentary rocks of clastic origin, like quartzitic sandstone, quartzite and shale) and in secondary solution features in limestones and dolomites. Faults occur in the western parts of the Fish River Basin and trend N-S to NW-SE and are generally normal faults although some strike slip movement has been observed. Some of these faults have remained active to the present and may reflect the edge of a new proto-continent. These faults are prime targets for the exploration for groundwater, however represent difficult drilling targets especially in the quartzitic lithologies, as severe collapse can occur during drilling.

In the Hardap and Karas Regions, water levels are generally shallow in the east, close to the course of the Fish River, but progressively become deeper towards the escarp in the west, where water levels deeper than 200 m are recorded. A typical water level profile has been measured in the area around Seeheim. Figure D2 gives an overview of water level profiles discussed, while Figure D3 indicates detailed profile locations around Seeheim.

Profile B-B' on Figure D4 is significant in that a clear gradient from west (Naiams) towards the Fish River indicates groundwater flow towards the river. However, from the river in an easterly direction, the gradient is essentially flat: The reason for this drastic change can be twofold:

- the influence of recharge from the Fish River to the groundwater;
- a result of lithology changes. At Seeheim, the course of the river follows the surface contact zone between Nama Group sediments (predominantly sandstone and quartzite) with overlying Dwyka Formation (shale and tillite);
- a combination of the two obvious reasons will probably be the most likely explanation.

What is important here however, is the fact that groundwater does not contribute to river flow in this locality, and that a periodic contribution of water from the river to the groundwater is likely.

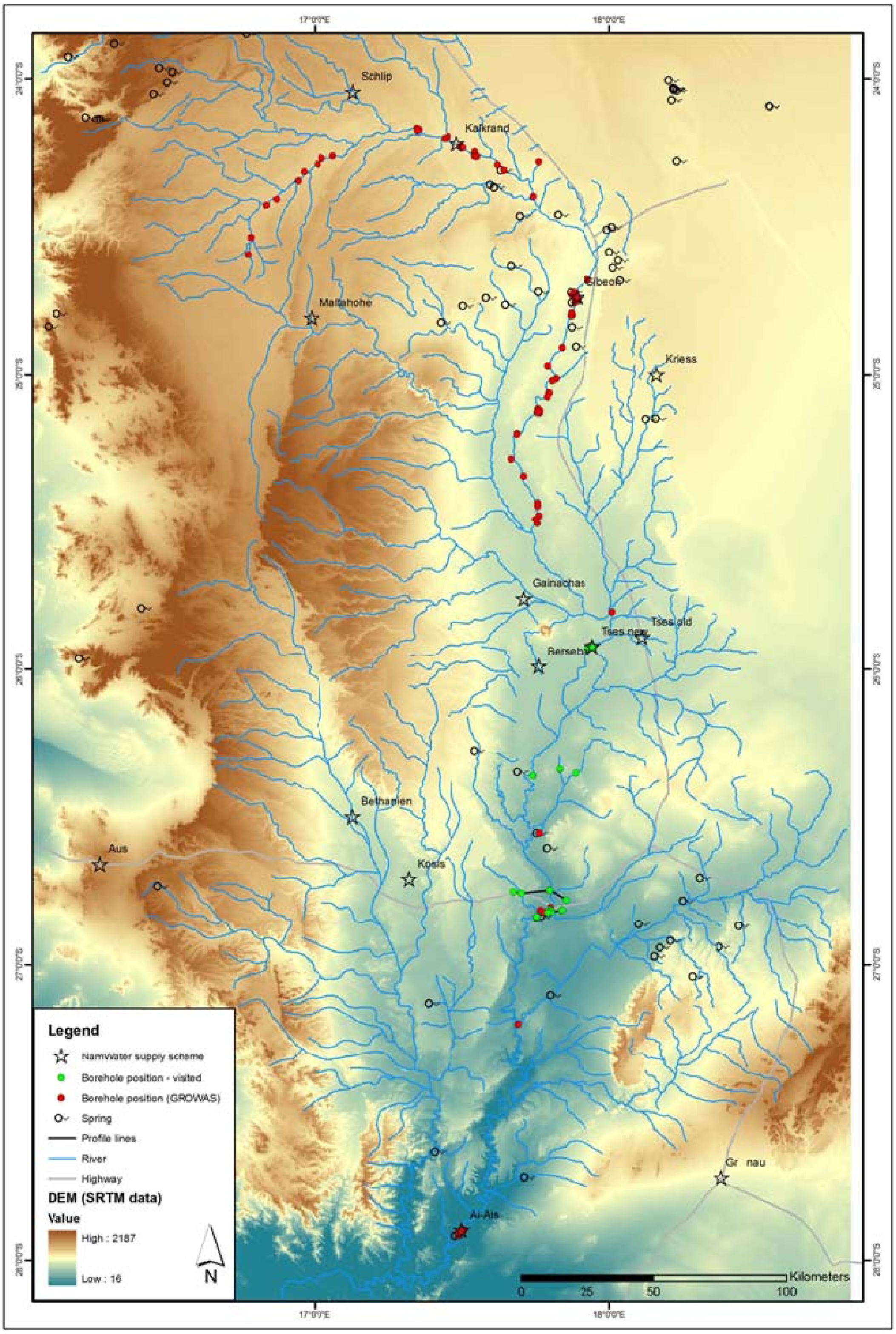


Figure D2. Map indicating relative positions of Water level profiles at Seeheim and Tses

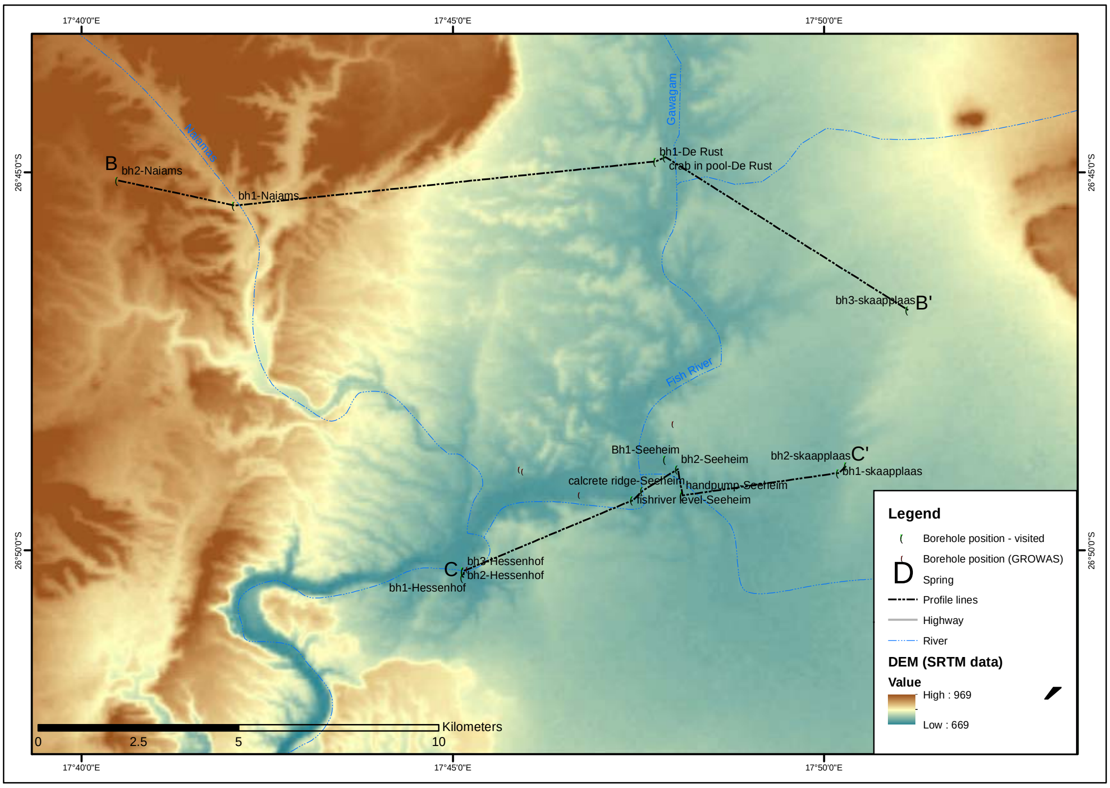


Figure D3. Detailed location of Seeheim area profiles

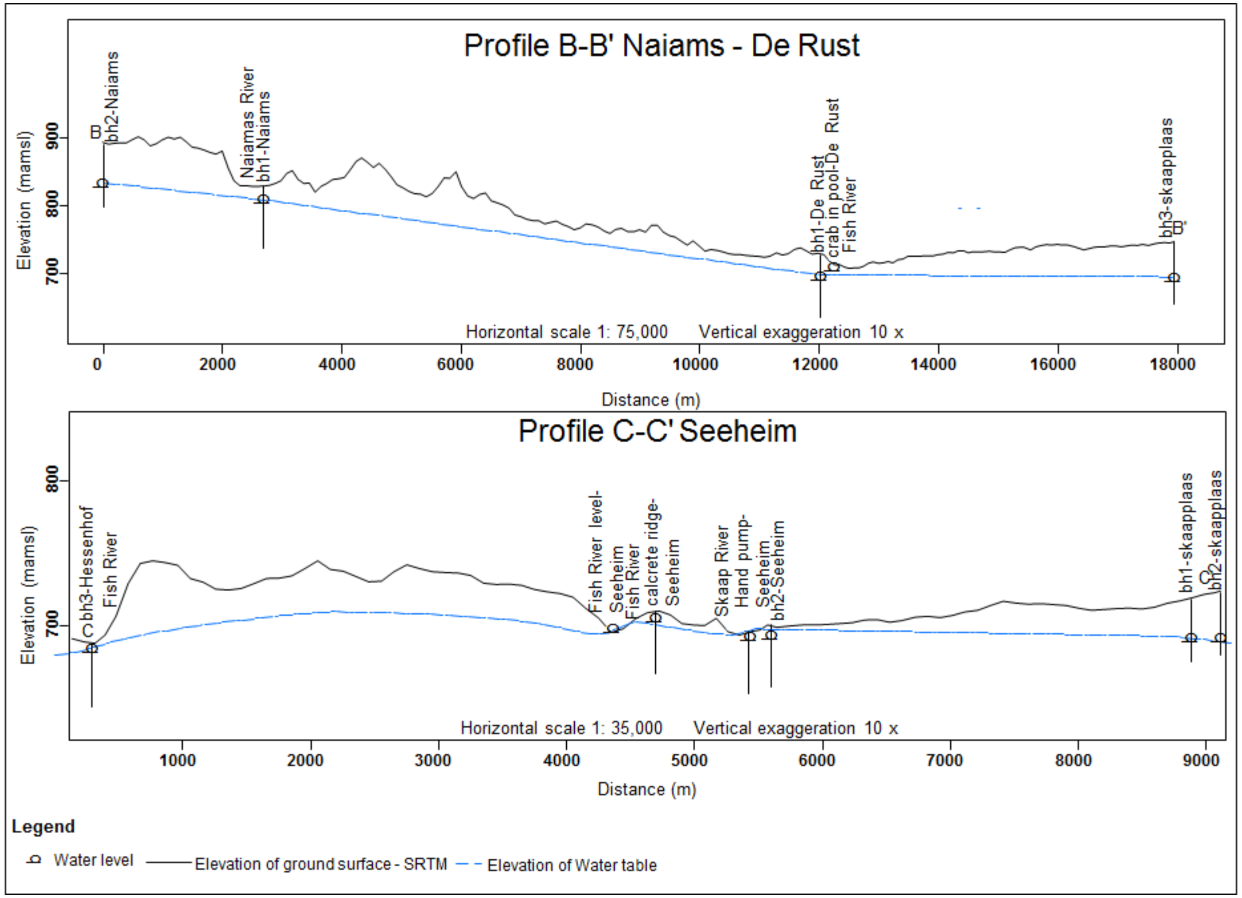


Figure D4. Profiles B-B' and C-C' in the Seeheim area

At the /Ai-/Ais Hot Springs Resort, several boreholes are operated to produce water to maintain the tourist camp of the Ministry of Environment and Tourism. WW32668 is one of the more important of these boreholes. The ground water abstractions show clear seasonal fluctuations, potentially linked to river flow (Figure D5). REST WL refers to water levels during times of no pumping.

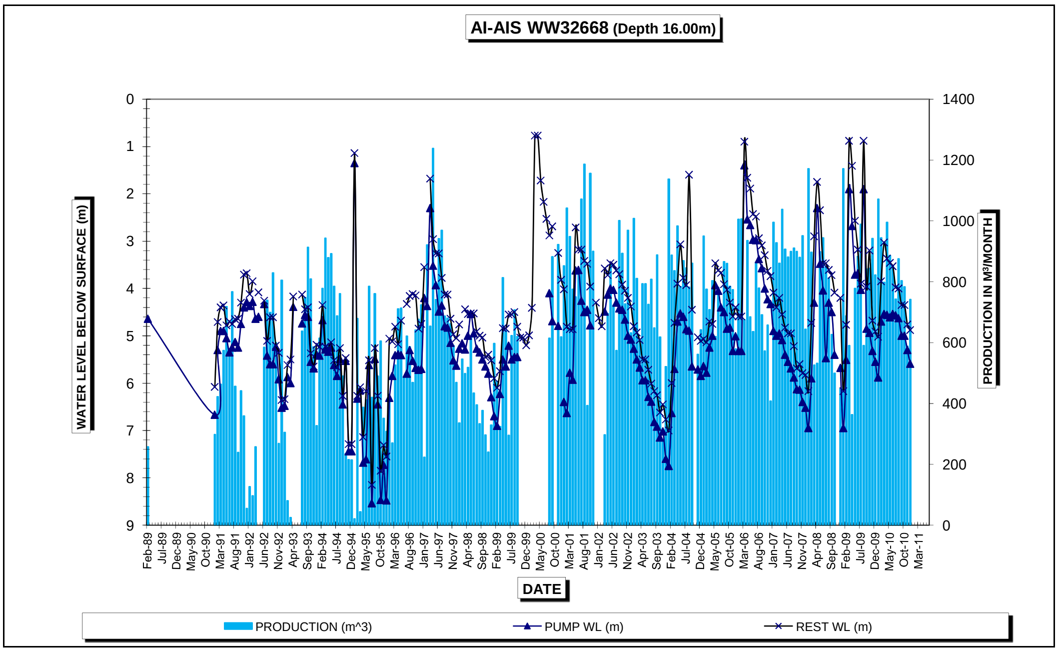


Figure D5. Water level Data WW32668, Ai-Ais

Karoo Sequence

Sedimentary and volcanic rocks of the Carboniferous to Jurassic Karoo Sequence occur in the Aranos Basin on the north-eastern edge of the Fish River Basin as well as the Gamkab Basin in the far south (Figure D6). In the Fish River Basin, the Karoo Sequence is mostly represented by the final phase of Karoo crustal evolution: the eruption of 360 m of basaltic lavas make up the Kalkrand Formation in the Late Triassic-Early Jurassic around 178 Ma (Marsh, et al., 1997). Extensive dolerite sills and dyke swarms (Figure D6) of this age intrude the Karoo Group rocks.

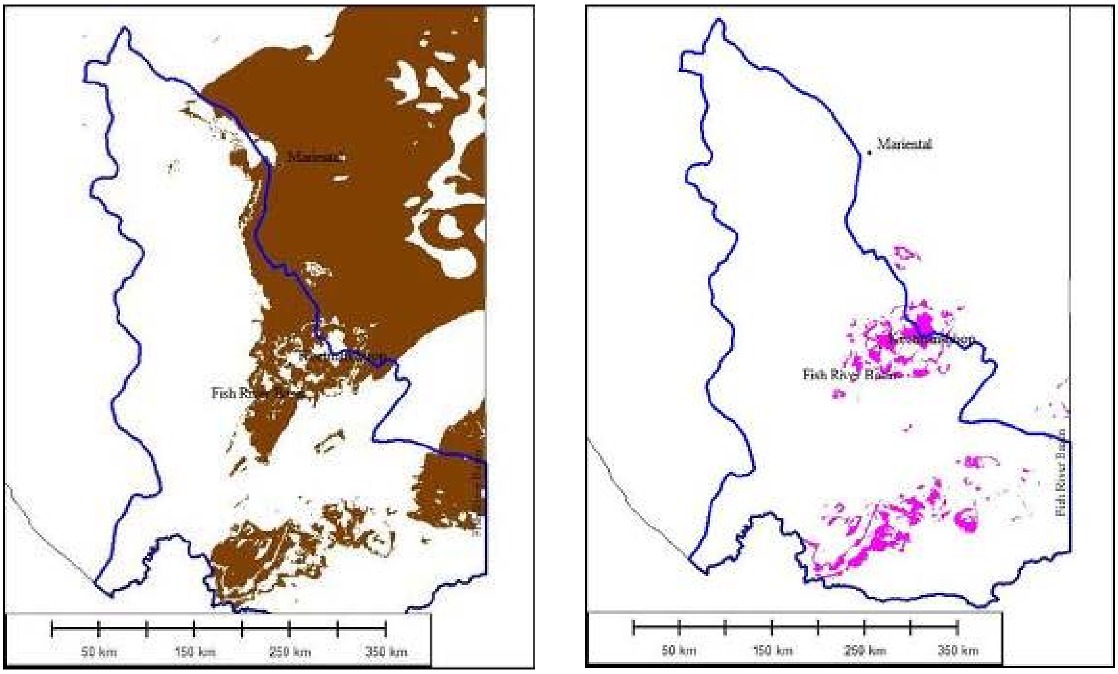


Figure D6. Distribution of Karoo Group sedimentary rocks (left) and Karoo dolerites (right) in southern Namibia

The village of Tses is dependent on groundwater. The Namibia Water Corporation operates a small borehole scheme consisting of 7 boreholes spread out along the Tses River. Two of these boreholes are located on a fault close to the Fish River (Figure D6). WW35899 has been drilled immediately on the banks of the Fish River, with WW35908 some 50 m further away from the river, and on higher ground. Both boreholes are on the same fault and water levels within this fault indicate a clear gradient towards the river (Figure D6). These water levels (recorded in the Namwater Production data) do not show seasonal fluctuations (Figure D7 and D8).

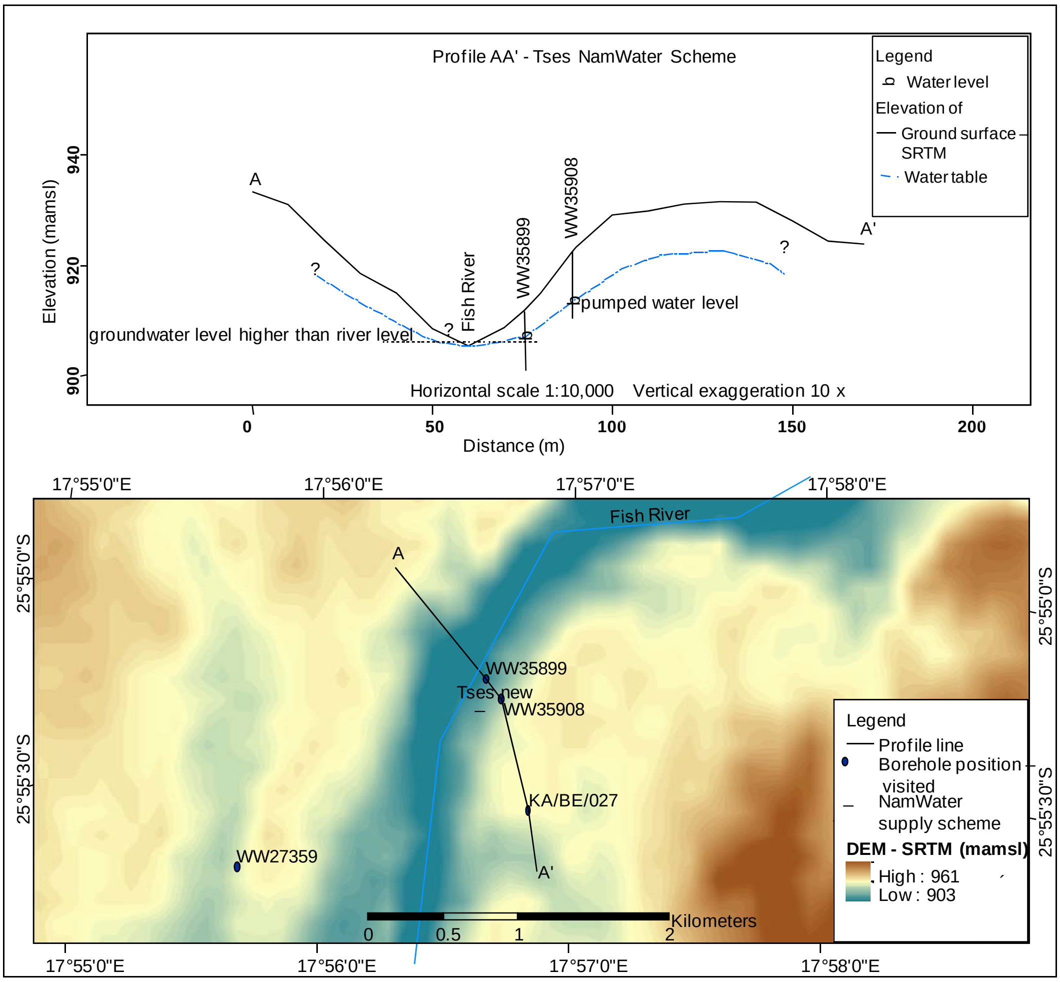


Figure D7. Water Level Profile WW35899 (Tses Water Supply) at Fish River

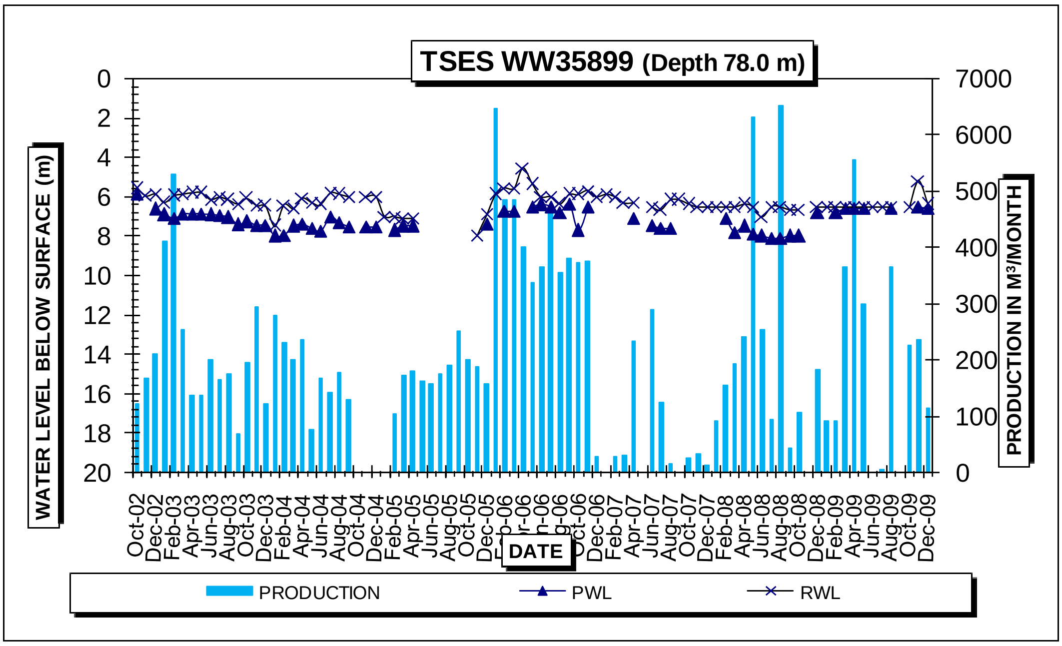


Figure D8. Water Level Data WW35899

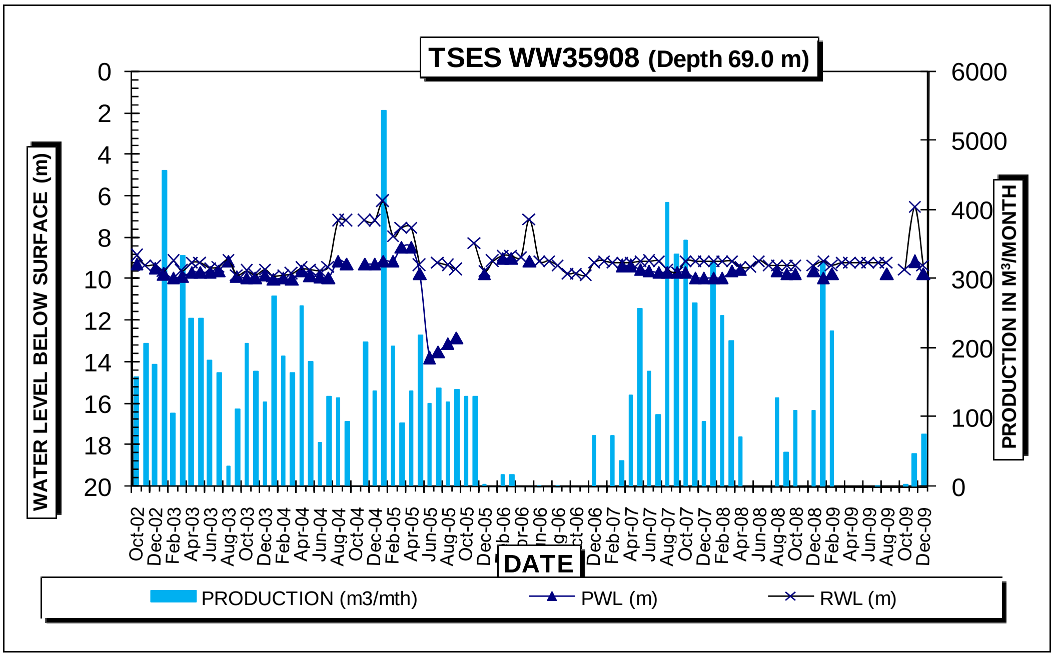


Figure D9. Water Level Data WW35908

Along the Tses Tributary itself, a different seasonal reaction of the water levels in production boreholes is recorded. Boreholes in this environment typically reflect annual recharge events. Borehole WW 24550 has been operative since February 1987. The water levels in these boreholes clearly follow the expected seasonal trend. Figure D9 for WW24550 is representative of these aquifers.

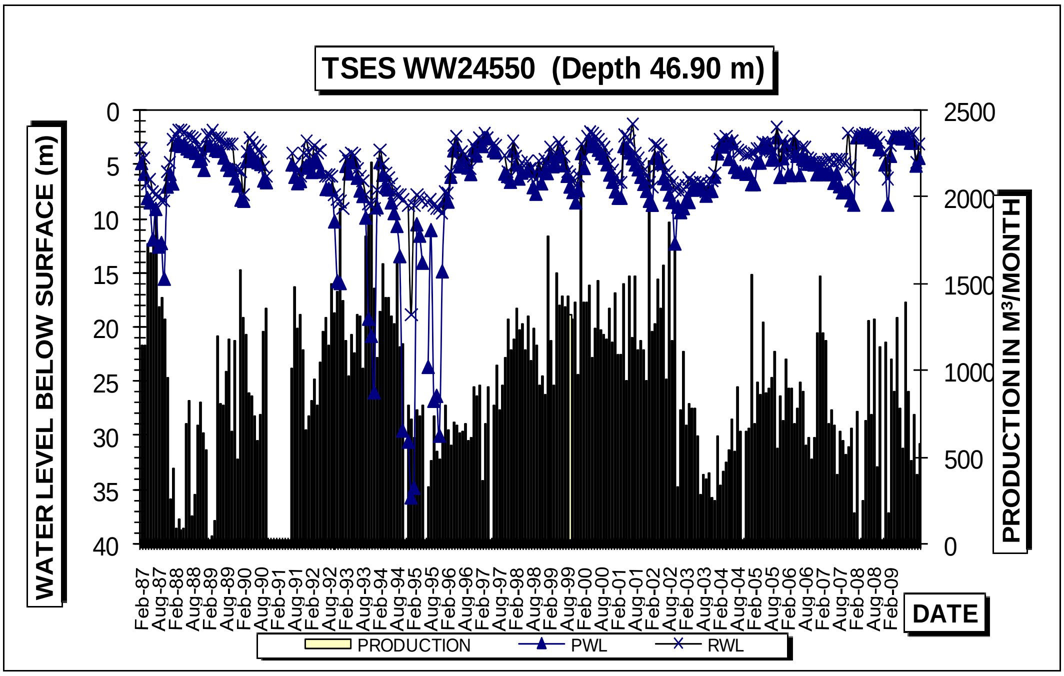


Figure D10. Production history WW 24550, Tses (source Namwater, processed F. Bockmühl)

Figure D9 clearly indicates the seasonal recovery of water levels in borehole WW24550. This picture is repeated in all the other production boreholes along the Tses River.

In conclusion, the Tses River has a significant influence on the recharge to these boreholes. A seasonal fluctuation is clearly recognizable. Flood events in the summer rainfall areas is predicted to be spread between the months of November and April, and in Figure D10 the recharge events clearly follow this trend.

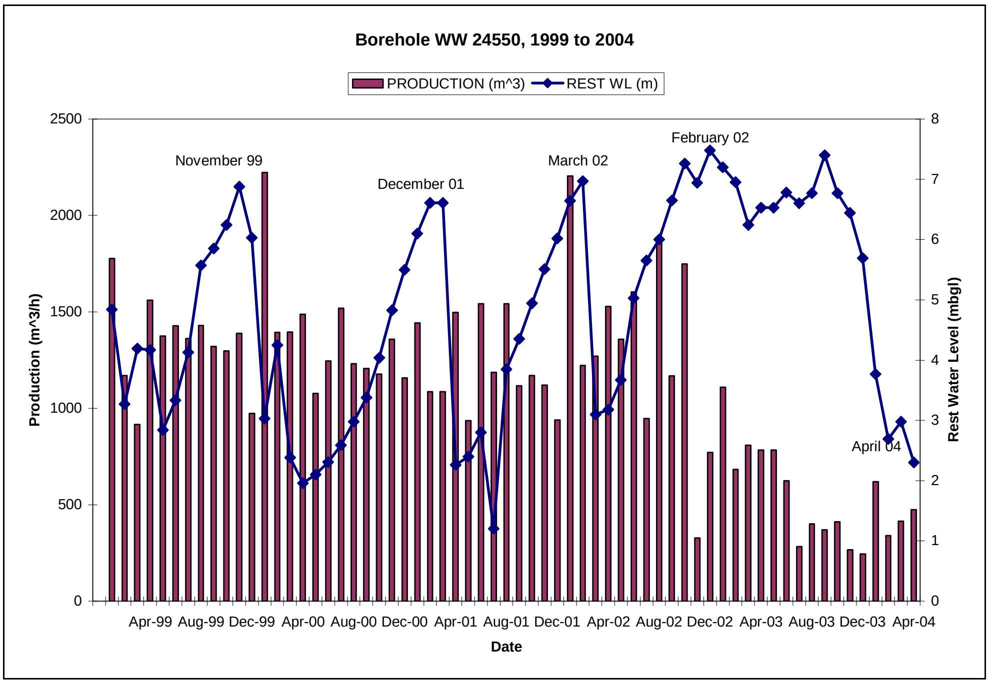


Figure D11. Chart indicating influence of flood events on groundwater recharge, Tses (source Namwater, processed F. Bockmühl)

D.6 Pool recharge in the Fish River

Tses (Dwyka)

At Tses two situations are clearly indicative of the dependence of groundwater reliability on regular recharge events like flooding in dryer rivers (e.g. the Tses River), or on permanent pools in the Fish River.

In both cases, boreholes are drilled in faults and fractures in Dwyka formation rocks. Figures D9 and D10 (on the Tses River) show that groundwater reserves decline during periods with no floods, and that relative significant recovery occurs during times of periodic flooding.

In contrast, boreholes drilled in the closer to the Fish River with a more permanent recharge source (perennial pools) shows a lack of seasonality in the water levels that could indicate permanent leakage from the surface source into the groundwater (Figures D7 and D8). Therefore, one can argue that in the event that the pools in the Fish River dry up (or fewer perennial pools are present), the character of the water level curve would be similar to that indicated in Figures D9 and D10 (only periodic floods recorded, with no significant flood in 2004).

Groundwater is not considered to contribute towards river flow.

Seeheim (Dwyka and Fish River Group)

With water levels within several hundreds of meters from the active channel of the Fish River at a deeper level than the surface water of the river, no contribution of groundwater to the river flow is expected (Figure D4, profile B-B').

However, it can be interpreted, that river water contributes towards the recharge of groundwater in this area to the east of the river.

/Ai-/Ais Hot Springs Resort (Fish River Group and Namaqua Metamorphic Complex)

At /Ai-/Ais Hot Springs Resort, the flow of the river contributes to the recharge (Figure D11) and thus the availability of groundwater for the maintenance of a significant tourism industry.

An analysis of the hydrology from the Ai-Ais gauge linked to ground water levels show the following (Figure D11):

- between September and October 1991 eleven days of flooding was recorded. Flow was more than 2 m^3/s with a maximum of 34,7 m^3/s recorded;
- during November 1991 12 days of flooding (minimum 2, maximum 37,1 m^3/s) were recorded;
- the combined effect of these floods on the ground water resource was a recovery of water levels to approximately 4 m below surface or below ground level (mgbl);
- resultant reserves were not very large, as is indicated by the rapid decline of the water levels (and thus available reserves) to levels of 6 mgbl.

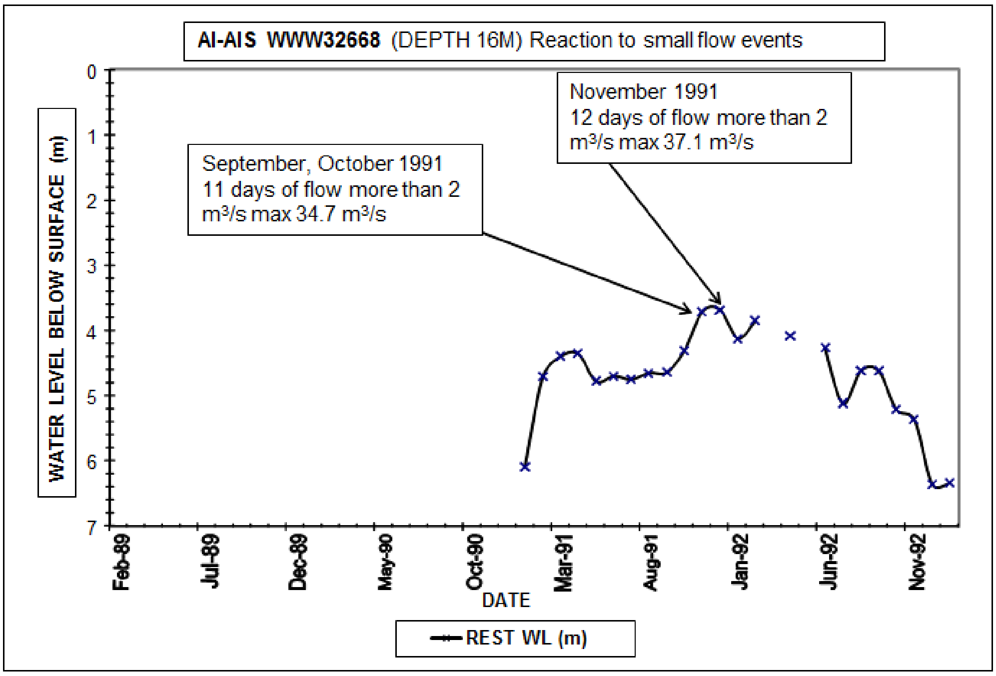


Figure D12. WW32668 water levels reaction to small flood events

Analysis of a different time period shows that (Figure D12):

- during January to March 2000 a total of 20 days of floods exceeding 200 m^3/s (maximum 3351 m^3/s) were recorded. This resulted in a recharge to the resource represented by high water levels of less than 1 mgbl;
- during April/May 2001 again major floods were recorded. Twelve days of flows between 100 m^3/s and 613 m^3/s resulted in water levels in the aquifer of above 3e mgbl;
- during March to May 2002, 29 days of flow between 10 m^3/s and 423 m^3/s resulted in water levels of approximately 3,5 mgbl.

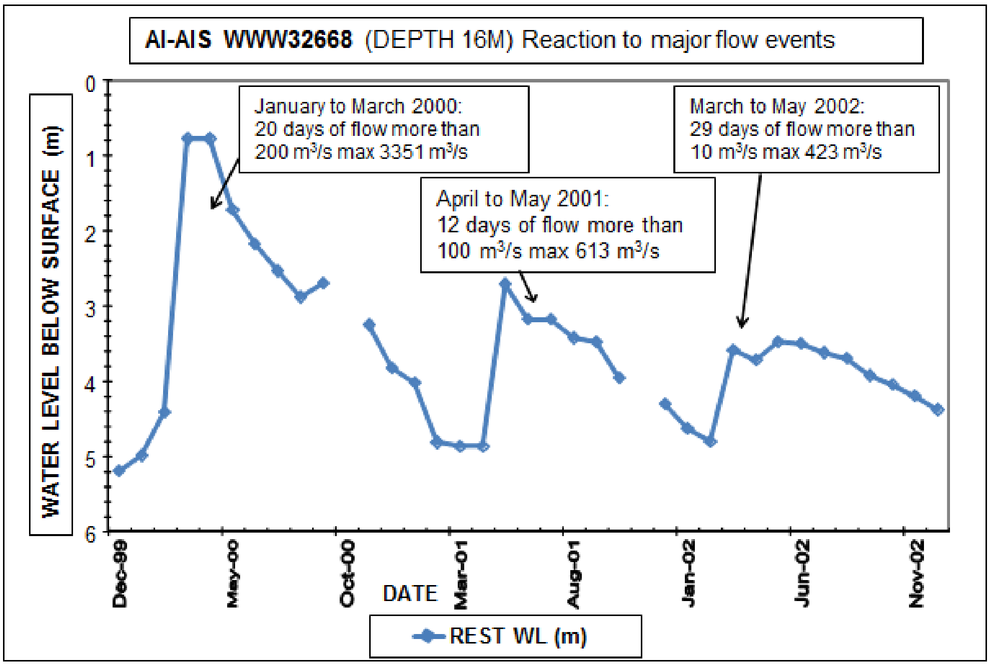


Figure D13. WW32668 water level reaction to major floods

Both Figures D11 and D12 indicate a dependence of groundwater resource recharge to regular flood events. This relationship is dependent on both flood magnitude and duration. This means that recharge to the groundwater takes time, but is also dependent on the volume flowing across the aquifer.

A further analysis was undertaken when a period of no flow was recorded followed by floods. Figure D13 illustrates the following:

- between 9 July 2002 and 18 January 2004 no flow was recorded at the Ai-Ais gauge;
- continuous production of groundwater from WW32668 resulted in a drop of the water level (and thus the volume of the reserves) from approximately 3,2 mgbl to 7 mgbl;
- floods exceeding 100 m^3/s for only four days between January and March 2004 resulted in a recovery of the resource to levels recorded before the no-flow period.

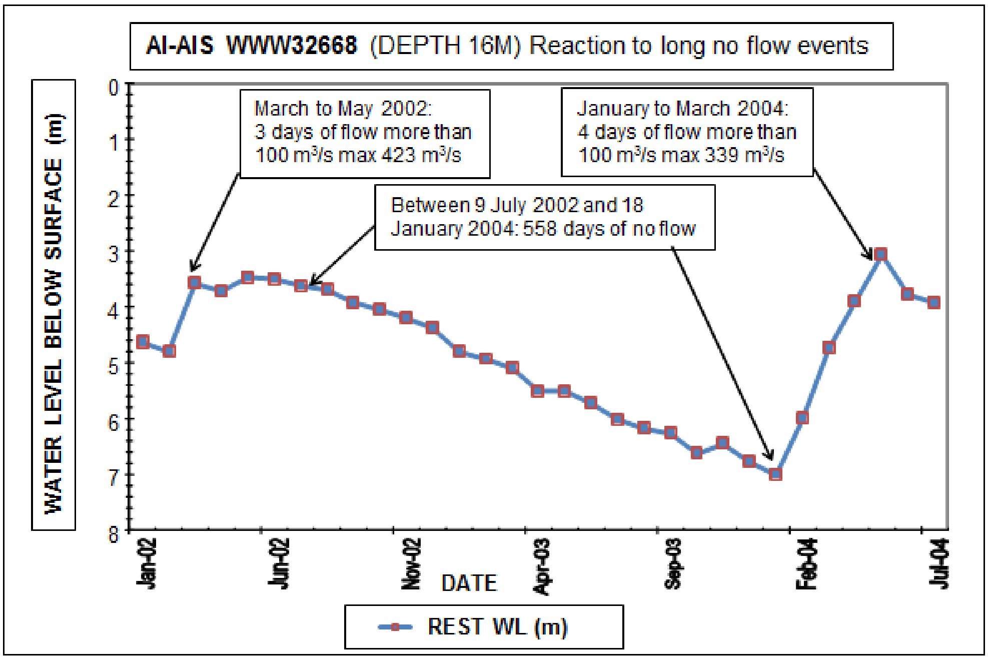


Figure D14. WW32668 reaction to extended no-flow cycle

In order to illustrate the significance of extended floods more clearly, the data are presented in scatter diagrams. In Figure D14, the number of days of flow exceeding 20 m^3/s is plotted against the resultant ground water levels measured. Each data point on the scatter diagram indicates:

- the number of flow days per relative season;
- the resultant water level at the end of the season;
- that low water levels do not seem to indicate any correlation;
- that only high water levels seem to correlate to increased number of days;
- significantly, the aquifer recovers to levels above 3 mgbl only when flows exceeding 20 m^3/s continue for more than 15 days per season.

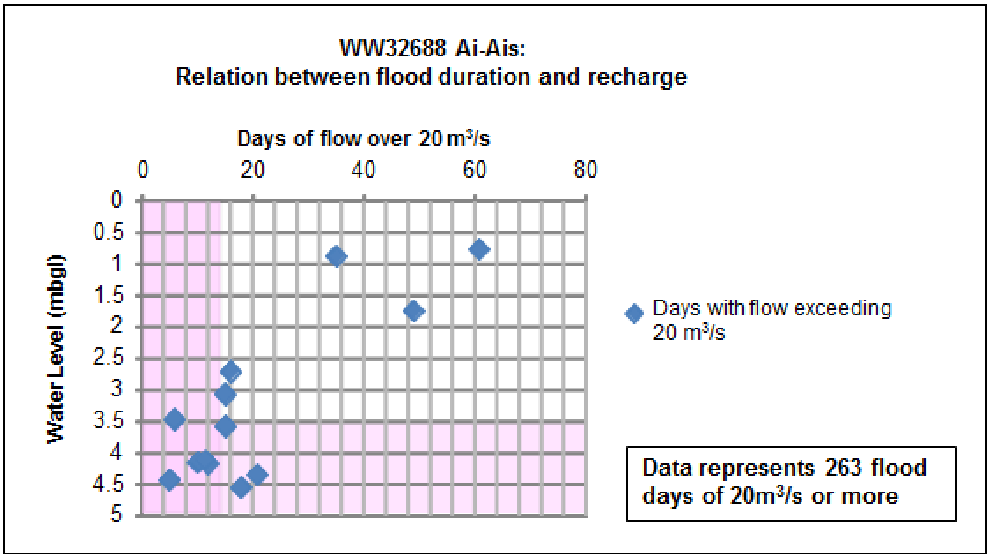


Figure D15. WW32688 relation between flood frequency and recharge (flows over 20 m³/s)

Figures D15 and D16 illustrate the situation for floods in excess of 50 and 100 m³/s and the following observations can be made:

- there is a slightly better correlation between water levels and shorter duration flood events;
- the resultant water level at the end of the season;
- that low water levels do not seem to indicate any correlation;
- that only high water levels seem to correlate to increased number of days;
- the aquifer recovers to levels above 3 mbgl only when flows exceeding 20 m³/s continue for more than 15 days per season;
- the aquifer recovers to levels above 3 mbgl only when flows exceeding 50 m³/s continue for six to eight days per season;
- the aquifer recovers to levels above 3 mbgl only when flows exceeding 100 m³/s continue for four to five days per season.

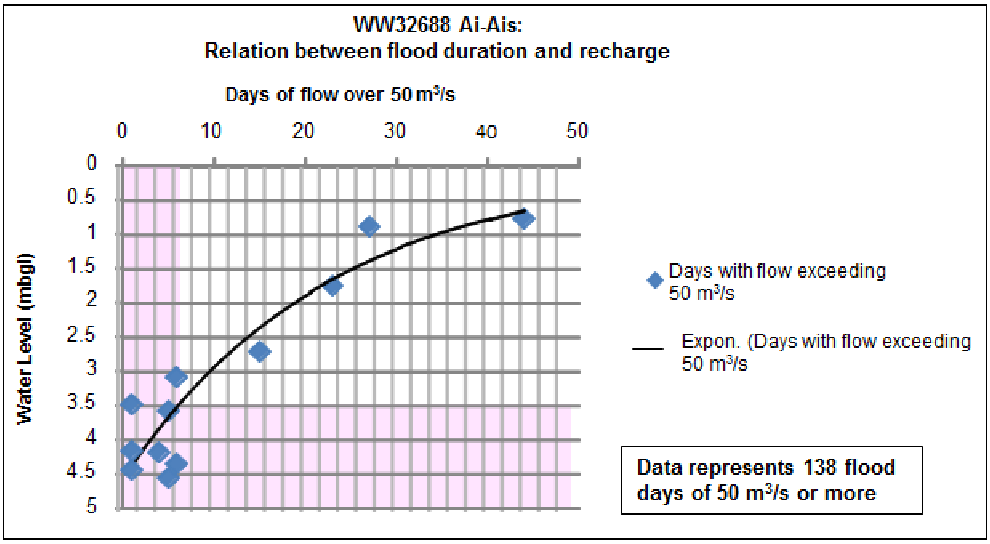


Figure D16. WW32668 relation between flood frequency and recharge (flows over 50 m³/s)

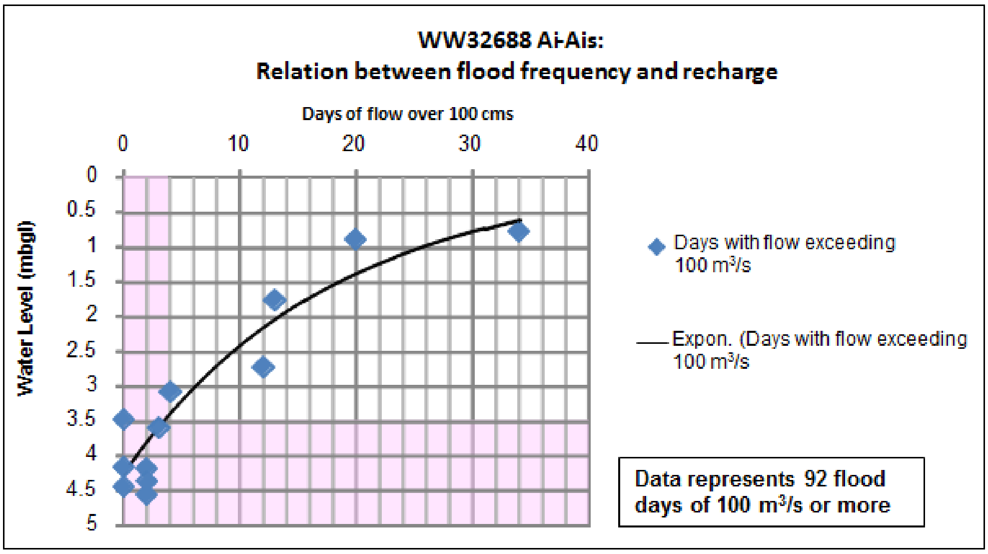


Figure D17. WW32668 relation between flood frequency and recharge (flows over 100 m³/s)

An analysis was undertaken to illustrate how the different release scenarios (described in Chapter 4) from Neckartal Dam will change the discharge and potential recharge to groundwater from the present situation (Table D1) and indicates the following:

- modelling of present day situation indicates that flow events of 50 m³/s for more than eight days occurred 53 times during the simulation period of 1930 to 1995. Under RO 50%, this flow event will occur 28% of the time;
- 100 m³/s events of more than 4 days duration occurred 67 times. Under RO 50%, this flow event will occur 48 % of the time.

Table D1. Changes in flood events from present day and with Neckartal Dam with different release options in place

	Present day	**RO 0 %**	**RO 20 %**	**RO 30 %**	**RO 40 %**	**RO 50 %**
50 for 8 days	53	32	29	29	29	28
100 for 4 days	67	42	42	46	45	48

It must be noted that the analysis to show the link between ground and surface water could only be undertaken at /Ai-/Ais Hot Springs Resort from 1993 as water levels were only measured from 1993. This period includes some very wet years. The increased water demand (expansion after 2000) of the tourist resort has been satisfied due to adequate recharge that occurred after 2000. There are however concerns that sufficient groundwater will not be available even under present conditions during the drier or drought periods such as occurred pre 2000. This situation can be aggravated with Neckartal Dam in place and the potential for decreased recharge to the aquifer.

D.7 Summary

Analysis of records of groundwater levels and flood data has resulted in the following findings:

- groundwater does not contribute significantly to maintaining the pools in the Fish River. Locally, certain isolated fountains may however feed into certain pools;
- river flow contributes the majority of recharge water to aquifers adjacent to the river bed. Certain State Water Schemes operated by the Namibian Water Corporation depend on such regular and continued recharge, and thus on regular flow in the Fish River;
- the impact of the construction of the Neckartal Dam can be significant on aquifers downstream of the dam;
- water Supply to /Ai-/Ais Hot Springs Resort is dependent on regular flooding in the Fish River in order to be sustainable;
- groundwater levels in boreholes at /Ai-/Ais Hot Springs Resort have to recover to levels higher than 3 mgbl at least every second year to be able to maintain present abstraction rates. To achieve this, on a bi-annual basis flows exceeding 50 m^3/s for a minimum of eight days have to be guaranteed by releases from the Neckartal Dam.