APPENDIX A: ECOHYDRAULICS OF THE ORANGE RIVER

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ABBREVIATIONS AND ACRONYMS

ADP	Acoustic Doppler Profiler
EFR/s	Environmental Flow Requirement/s
FSL	Full Supply Level
Max.	Maximum
Meas.	Measured
Min.	Minimum
MS	Microsoft
NA	Not Applicable
PD	Present Day
prep.	preparation
REC	Recommended Ecological Category
Sc	Scenario
WL	Water level

ACKNOWLEDGEMENTS

The contributions to site selection and data collection by James Mackenzie (Mackenzie Ecological and Development Services), Ahmed Desai and Delana Louw (Rivers for Africa eFlows Consulting), Mark Rountree (Fluvius Environmental), Rob Palmer (Nepid Consultants) and Piet Kotze (Clean Stream Biological Services).

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OBJECTIVES

The objectives of the ecohydraulic component of this study are to provide geomorphologically and ecologically relevant hydraulic information (data collection, analysis and results) for assessing the Environmental Flow Requirements (EFRs) at six river sites: two sites along the Caledon River, one site along the Kraai River and three sites along the lower Orange River. A further site was located in the wetland downstream of the Molopo Eye.

A1 ECOHYDRAULIC INFORMATION FOR ENVIRONMENTAL WATER ASSESSMENT ALONG THE ORANGE RIVER

The application of holistic methods for ecological flow determination (refer to Tharme, 1996) requires environmental flow requirements to be expressed as discharge rates (including its 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 synthesized data (refer to Rowlston *et al.* (2000), Birkhead (1999), Jordanova *et al.* (2004), Hirschowitz *et al.* (2007) and Birkhead (in press) 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 A2.3).

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 Hirchowitz *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.

A1.1 DATA COLLECTION

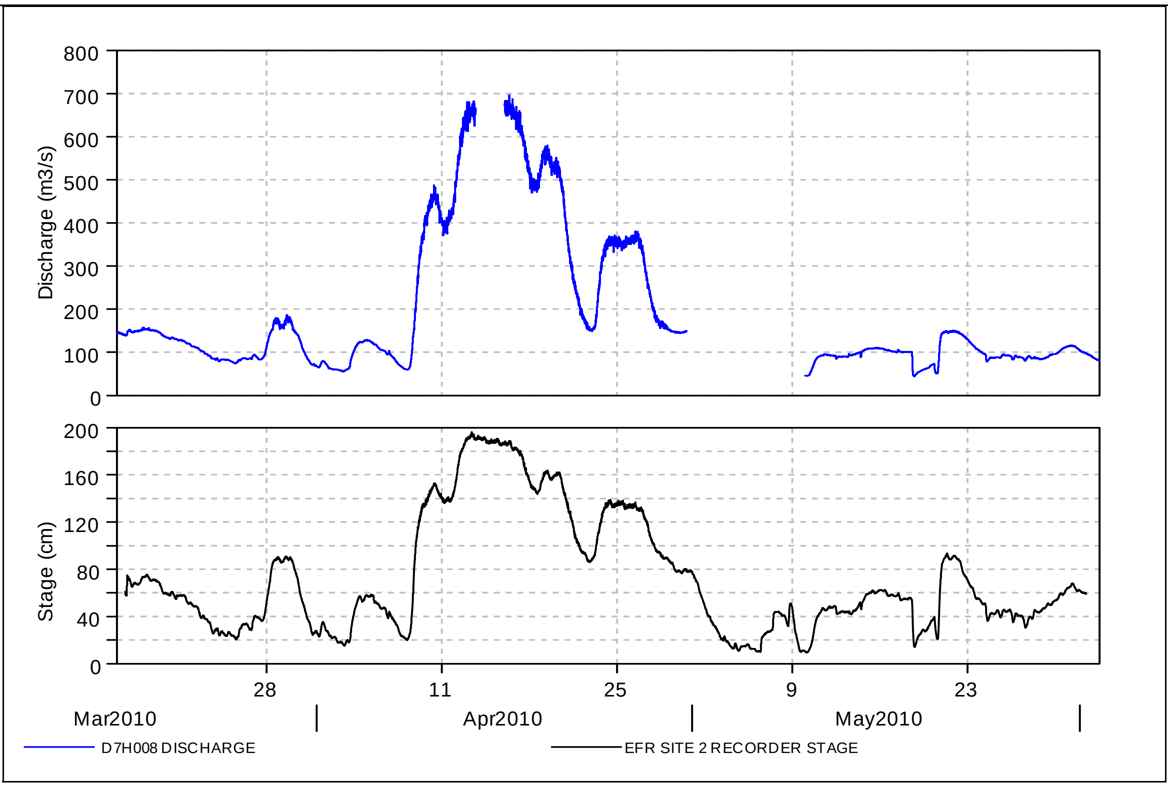
The measured discharge and flow depth data are provided in Table A1, together with the dates when the data were collected.

Table A1 Hydraulic data surveyed at EFR sites along the Orange River System

River	Site no.	Cross-section no.	Date	Discharge *Q* (m^3/s)	Max. flow depth *y* (m)	Stage AMSL *z* (m)
Orange	2	A	31/05/10	110 - 115[1]	3.57	NA
			01/06/10	99[1], 123[ADP]	3.51	NA
			16/03/10	139[1]	3.67	NA
	3	A	29/05/10	110[ADP]	3.60	NA
			17/03/10	252[2]	4.10	NA
	4	A	26/05/10	71[3], 79[ADP]	1.85	NA
			15/12/09	179[3]	2.39	NA
Caledon	5	A	22/06/10	0.24	0.35	NA
			08/02/10	2.0	0.54	NA
Caledon	6	A	23/06/10	7.7	1.22	NA
			10/02/10	60	1.98	NA
Kraai	7	A	24/06/10	4.7	0.59	NA
			10/07/10	3.1	0.55	NA
			04/08/10	2.3	0.50	NA
		B	24/06/10	4.7	0.36	NA
			10/07/10	3.1	0.30	NA
			04/08/10	2.3	0.28	NA
Molopo	8	A	21/04/10	0.15	0.64	NA
		B	21/04/10	0.15	0.56	NA
		C	20/04/10	0.15	1.57	NA
		D	20/04/10	0.15	2.25	NA

[1]D7H008 (Zeekoebaart)
[2]D7H014 (Neusberg)
[3]D8H003 (Vioolsdrif)
ADP - Acoustic Doppler Profiler
NA – Not Applicable (local datums used)

Automatic stage recorders were installed at EFR Sites 2, 3 and 4 along the lower Orange River to augment the rating data in Table A1. Stage measurements were correlated with discharges from local DWA gauges (refer to Table A1), and these data are plotted in Figures A1 to A3.



|Figure A1 Top: discharge gauged at D7H008 (Zeekoebaart), and bottom: stage recorded at EFR Site 2.

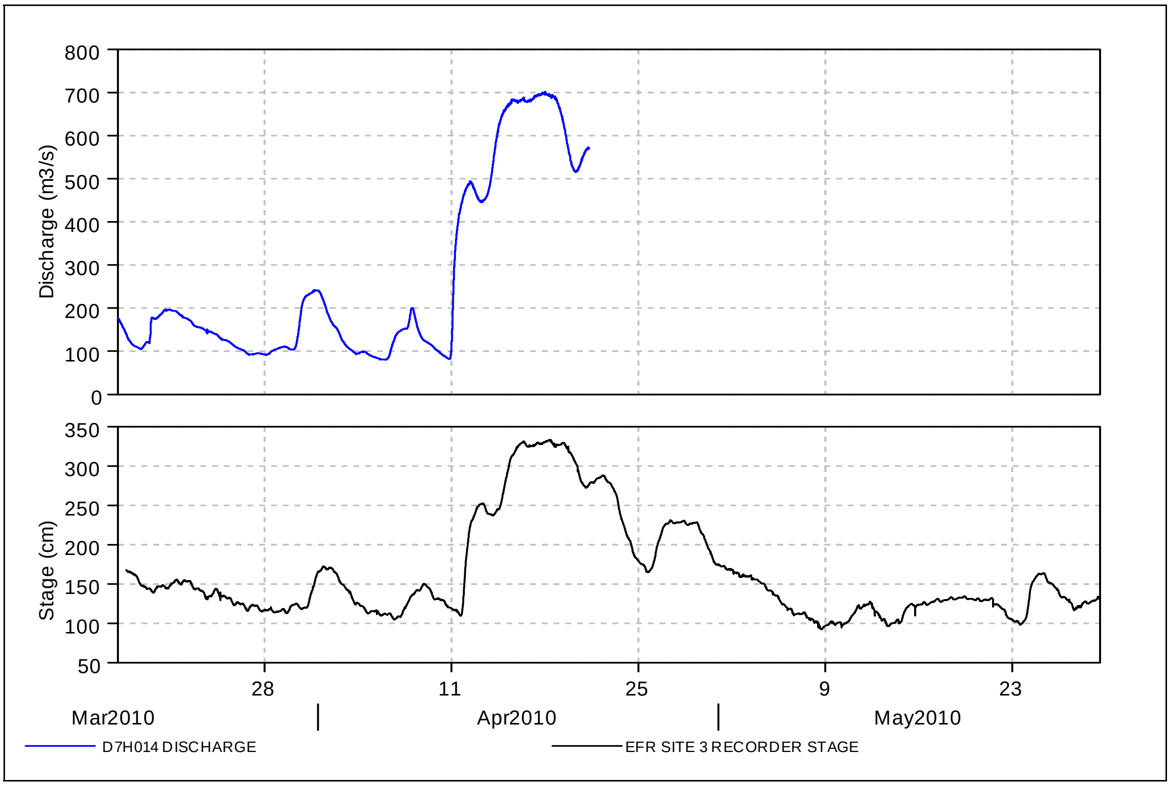


Figure A2 Top: discharge gauged at D7H014 (Neusberg), and bottom: stage recorded at EFR Site 3.

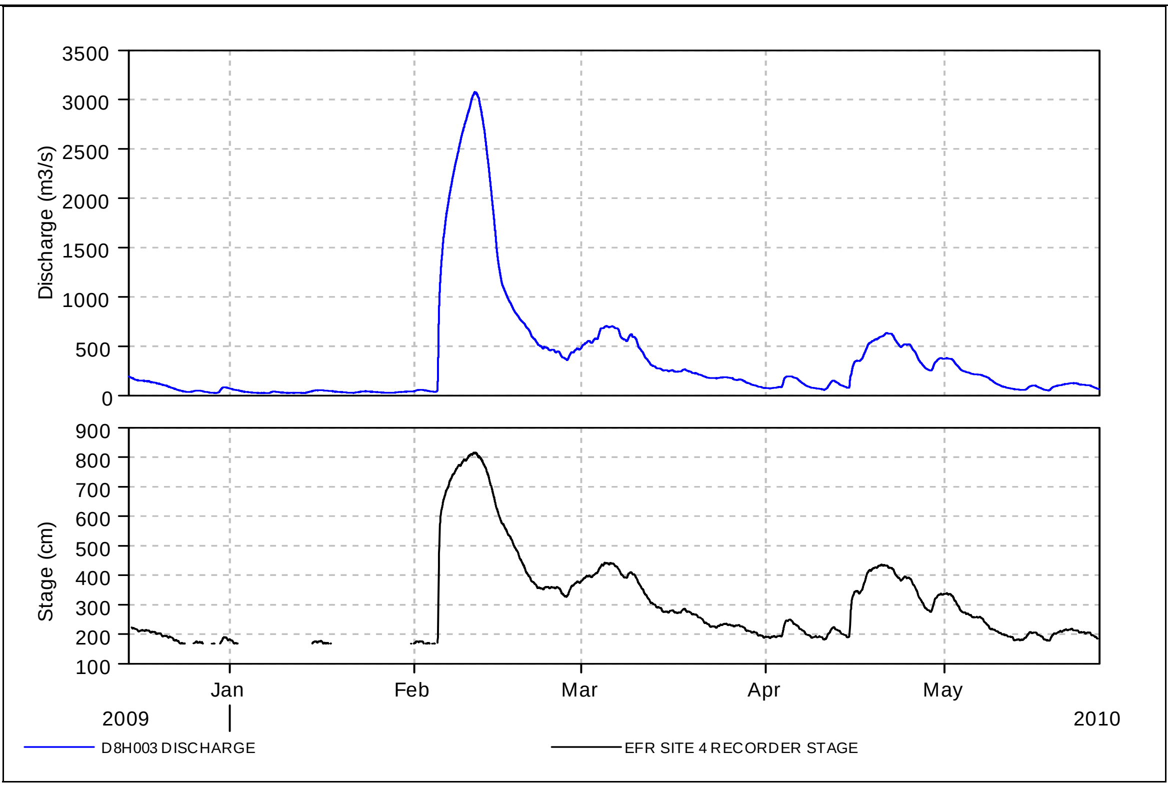


Figure A3 Top: discharge gauged at D8H003 (Vioolsdrif), and bottom: stage recorded at EFR Site 4.

A1.2 MODELLING

Predicted resistance coefficients, energy slopes and modelled rating relationships are archived electronically for the river sites (1 to 7) and included in the EFR ecohydraulics database (Birkhead *et al.*, in prep.).

A1.3 RESULTS

A1.3.1 Cross-sectional profiles

Refer to Figures A4 - A13.

A1.3.2 Lookup tables

Lookup tables (hydraulic variables and flow-classes) are archived electronically in MS Excel.

A1.3.3 Molopo Wetland

The section of the Molopo Wetland considered in this study extends approx. 1.66km from the diversion/gauging weirs (D4H014 & D4H030) to the second downstream road crossing. This (second) road crossing consists of an elevated roadway (approx. 2.5m) with eight 205mm diameter pipes positioned below the road surface. It therefore acts as a substantial impoundment, backing up the water level over an upstream distance of approx. 1.2km. Three (bank-to-bank) cross-sections (refer to Figures A5-A7) were surveyed in the section upstream of the impoundment at distances of approx. 500m (D), 800m (C) and 1200m (B). A further road crossing exists approx. 230m downstream of the gauging weir (i.e. 1.43km upstream of the second road crossing). A left bank cross-section (A) was surveyed between the weir and the first road crossing (dense reeds prevented a complete bank-to-bank survey). The first road crossing incorporates a rectangular culvert (width: 1.65m (upstream) to 0.61m (downstream)).

At the time of the survey, the discharge into the wetland (after the diversion to Mafekeng) was $0.15m^3/s$. The maximum measured flow depths at cross-sections A to D were 0.64m, 0.56m, 1.57m and 2.25m, respectively. In addition, the maximum depths in the wetland upstream and downstream of the first road crossing were 0.43m and 0.49m respectively. Consequently, the average depth at this discharge for unimpounded areas of the wetland is estimated at approx. 0.50m (the survey indicates that cross-sections C and D are within the backup area). The average depth at cross-section B at this flow was approx. 0.15m. This average depth at cross-section C (though currently backed-up), corresponds to a maximum depth of 0.43m - supporting the above approx. maximum depth value of 0.50m at $0.15m^3/s$. At average depths of 0.15m at cross-sections B and C (and $0.15m^3/s$), the average velocities range from approx. 0.02m/s to 0.09m/s.

Estimates of changes in discharge corresponding to (reasonably small) changes in depth can be made by assuming that average velocities remain invariant (a general characteristic of flow through dense reed stands). For a 0.1m increase and reduction in (maximum) depth, the corresponding discharges are approx. $0.28m^3/s$ and $0.070m^3/s$ (using the channel geometry for cross-sections B and C).

A number of hydraulically-related scenarios were devised for the Molopo Wetland: the first of these (Scenario 1) considers a reduction in water level of 1.2m at the (second) downstream road crossing such that the backup extends upstream to cross-section C; for the second scenario (2) the backup extends to cross-section D (a reduction by 2.2m); Scenario 3 assess no substantial backup from the road crossing; a reduction in the discharge to $0.075m^3/s$ is considered in Scenario 4 (increased abstractions to Mafekeng), with the existing impoundment remaining in place. For Scenarios 1 - 3, the flows in the wetland remain unchanged from present day conditions. Note that under present day conditions, the backup extends to approx. cross-section B. The confidence ratings in the hydraulic characterisations for these scenarios are provided in Table A.5 (provided separately for impounded and unimpounded areas of the wetland).

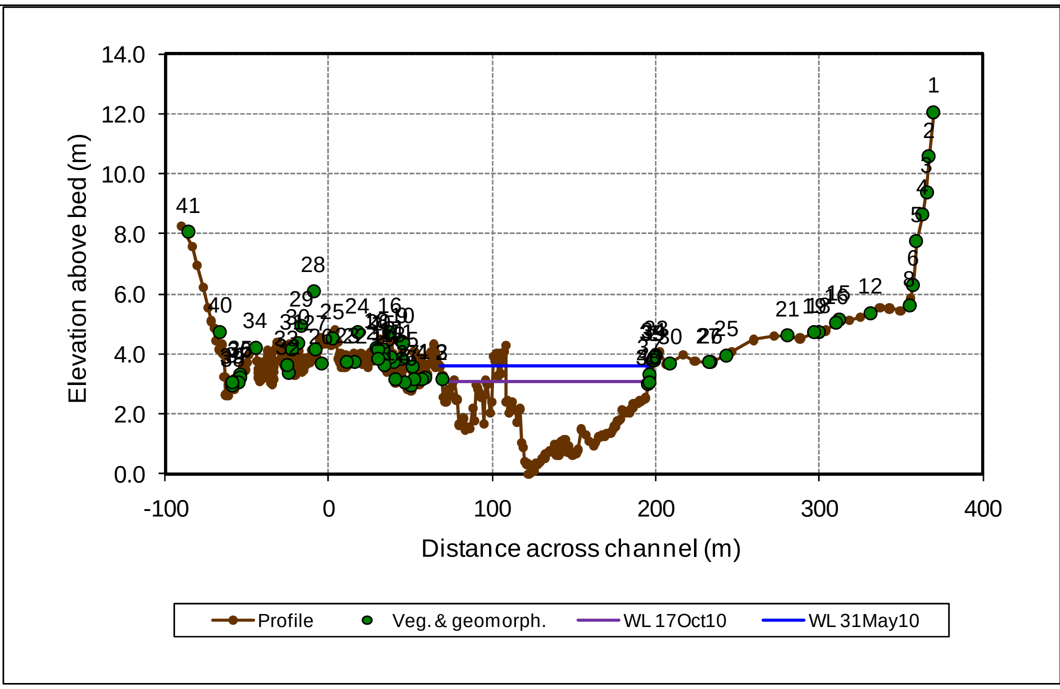


Figure A4 **Cross-sectional profile at Site EFR 2 on the lower Orange River, showing the water levels (WL) surveyed on 17 October and 31 May 2010, as well as the position of geomorphological and vegetation markers (numeric markers).**

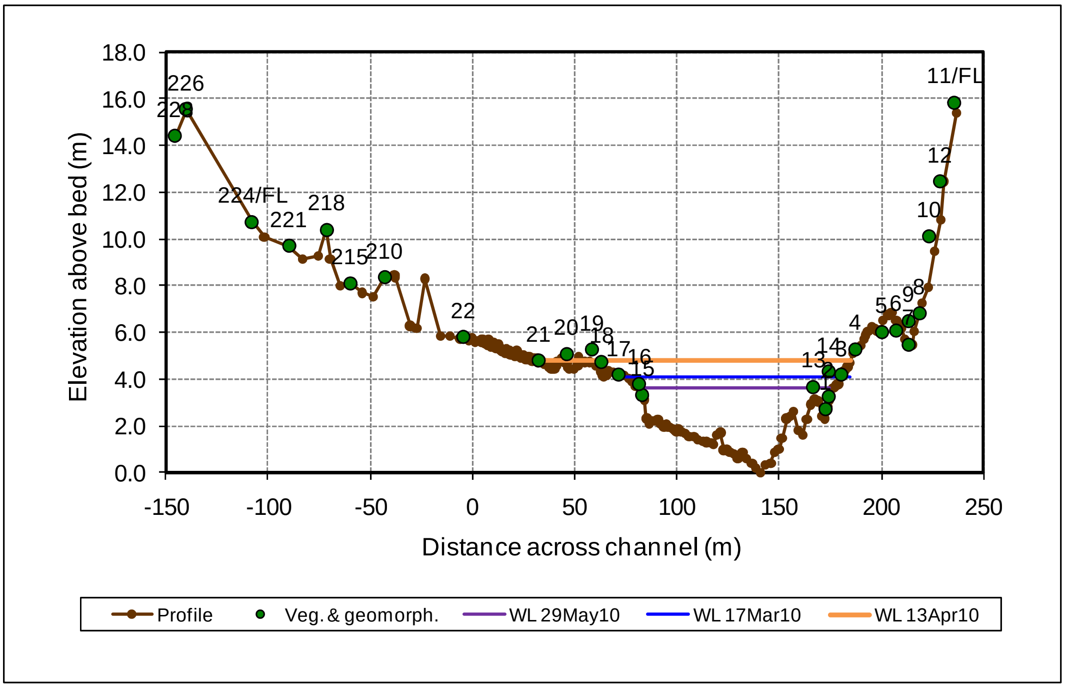


Figure A5 **Cross-sectional profile at Site EFR 3 on the lower Orange River, showing the water levels (WL) surveyed on 29 May, 17 March and 13 April 2010, as well as the position of geomorphological and vegetation markers (numeric markers). Water levels inferred from flood strand lines (FL) are also indicated (224/FL = February 2010).**

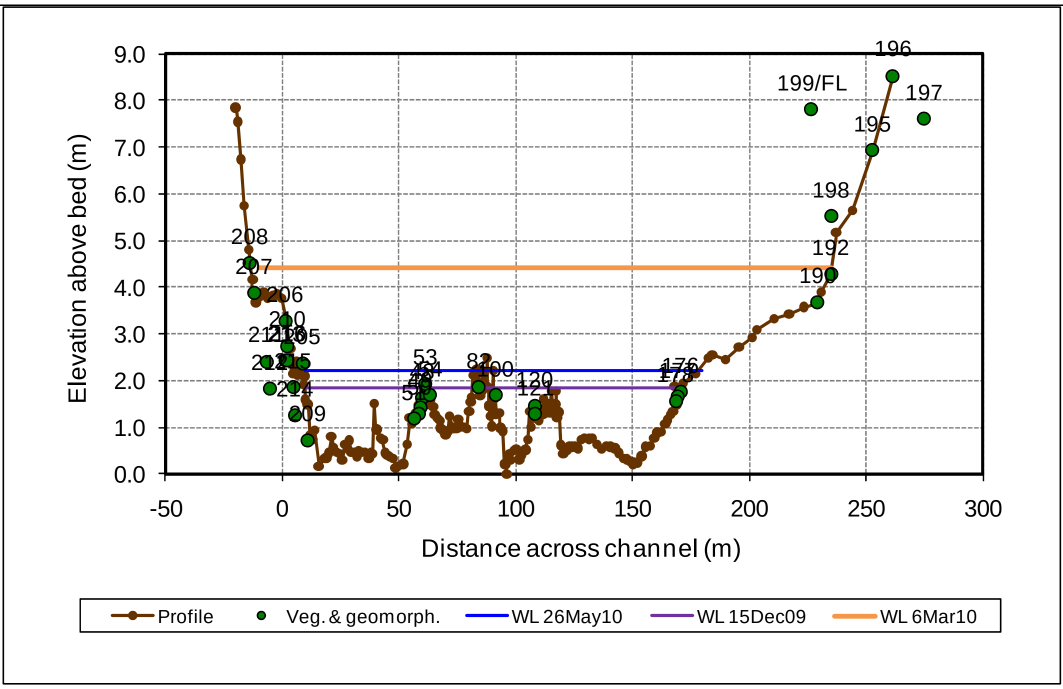


Figure A6 **Cross-sectional profile at Site EFR 4 on the lower Orange River, showing the water levels (WL) surveyed on 17 October and 31 May 2010, as well as the position of geomorphological and vegetation markers (numeric markers).**

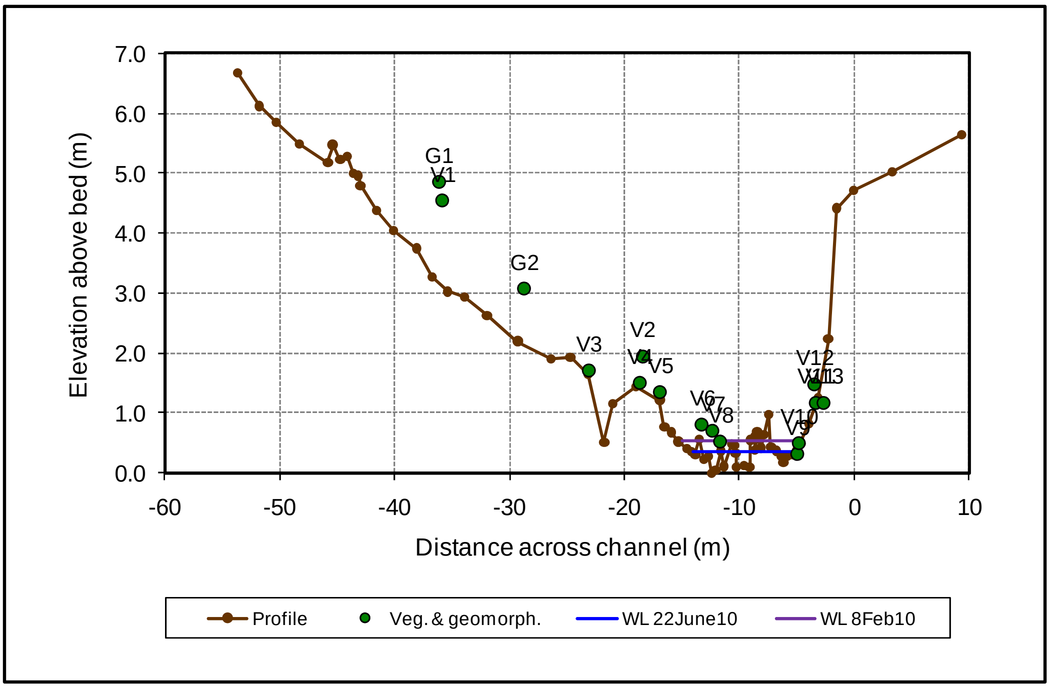


Figure A7 **Cross-sectional profile at Site EFR 5 on the upper Caledon River, showing the water levels (WL) surveyed on 22 June and 8 February 2010, as well as the position of geomorphological (G) and vegetation (V) markers.**

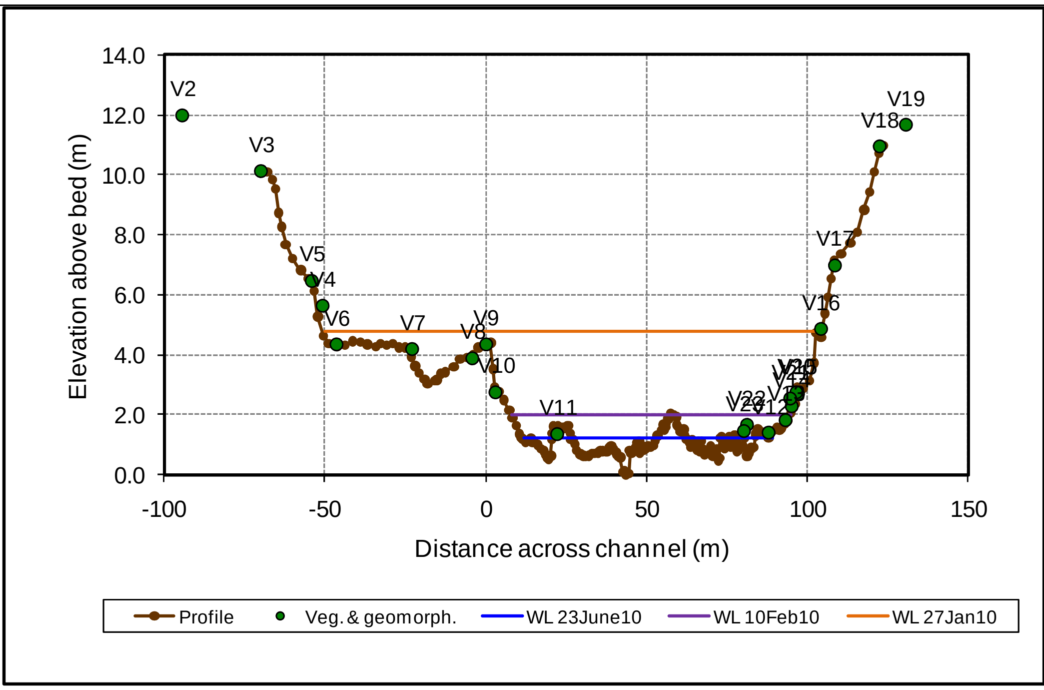


Figure A8 **Cross-sectional profile at Site EFR 6 on the lower Caledon River, showing the water levels (WL) surveyed on 23 June and 10 February, and inferred from the 27 January 2010 strand line. The position of vegetation (V) markers are also indicated.**

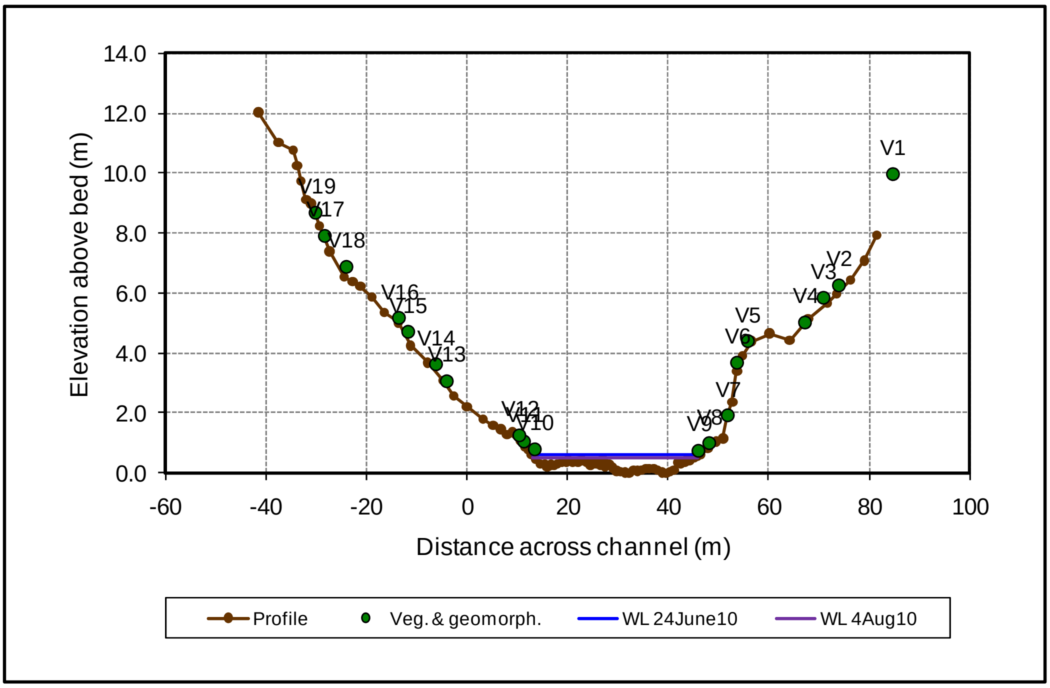


Figure A9 **Cross-sectional profile A at Site EFR 7 on the Kraai River, showing the water levels (WL) surveyed on 24 June and 4 August 2010, as well as the position of vegetation (V) markers.**

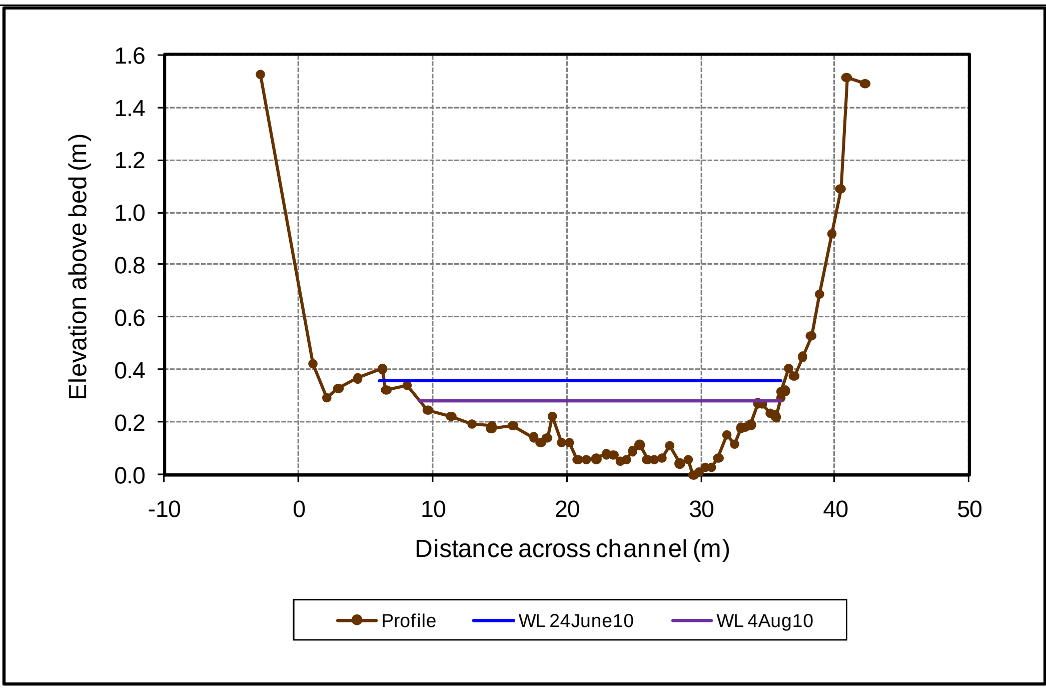


Figure A10 Cross-sectional profile B at Site EFR 7 on the Kraai River, showing the water levels (WL) surveyed on 24 June and 4 August 2010.

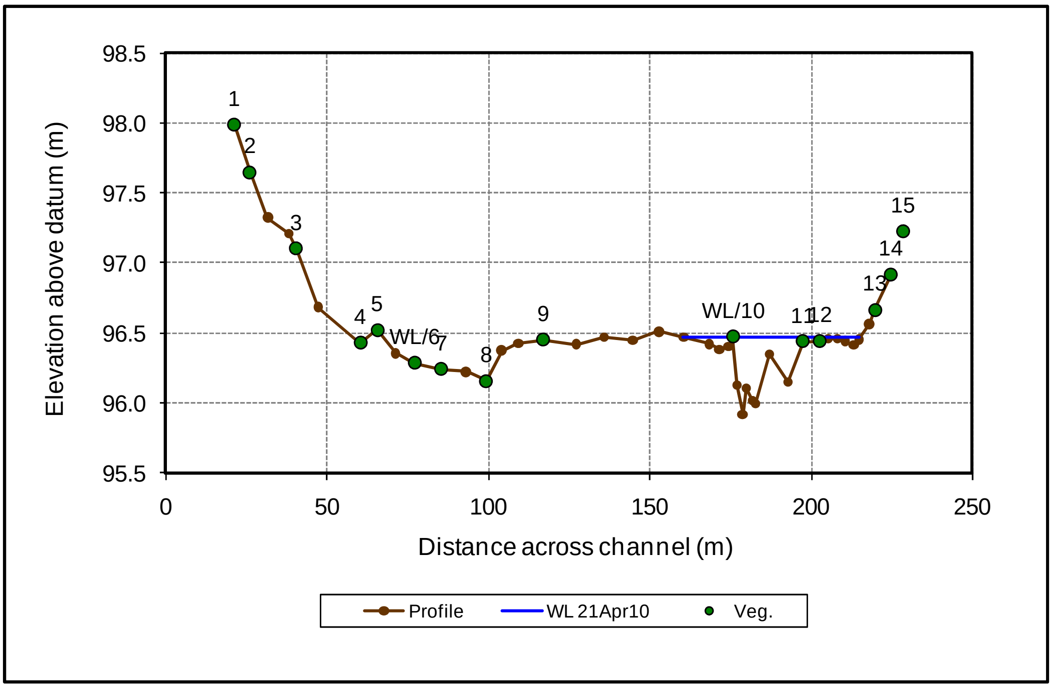


Figure A11 Cross-sectional profile B at Site EFR 8 on the Molopo Wetland, showing the water level (WL) surveyed on 21 April 2010, as well as the position of vegetation markers.

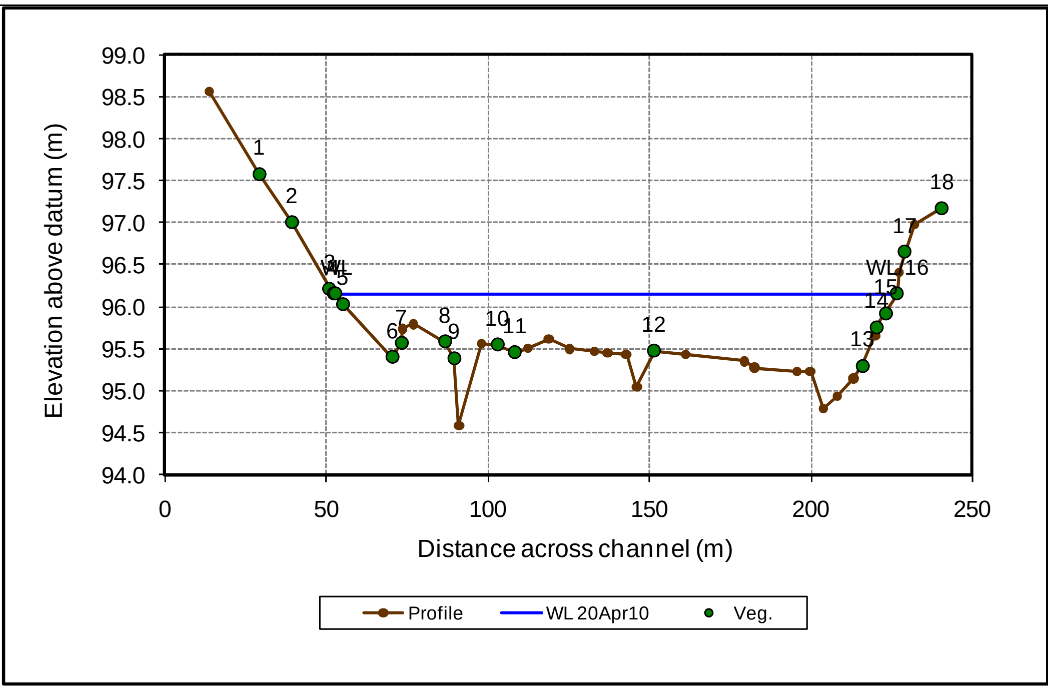


Figure A12 **Cross-sectional profile C at Site EFR 8 on the Molopo Wetland, showing the water level (WL) surveyed on 21 April 2010 (backup from the downstream impoundment), as well as the position of vegetation markers.**

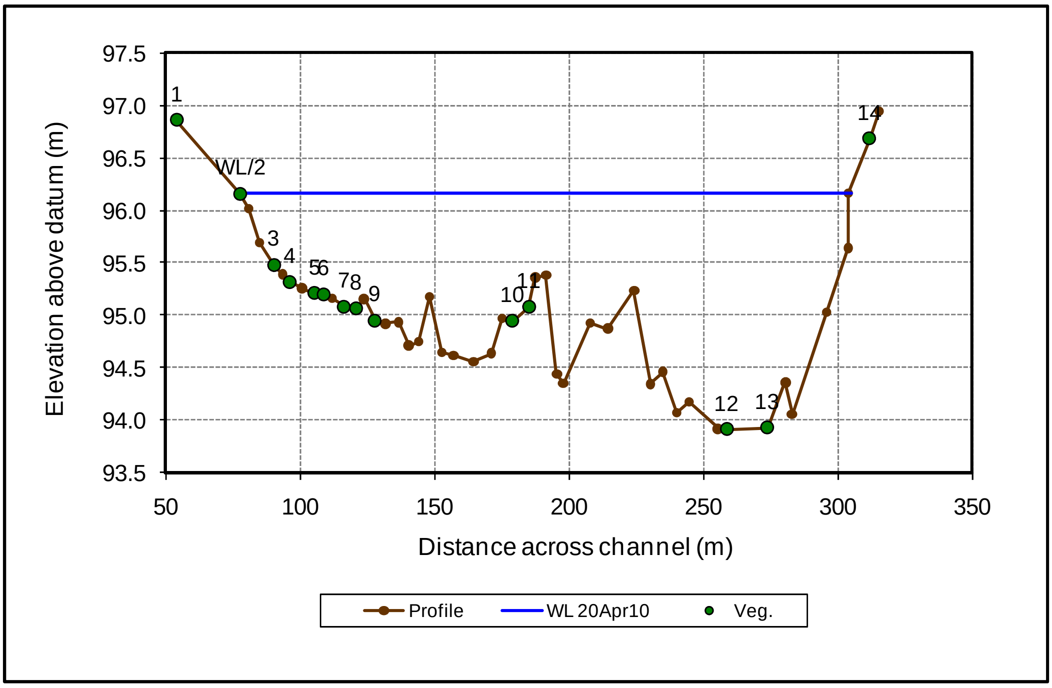


Figure A13 **Cross-sectional profile D at Site EFR 8 on the Molopo Wetland, showing the water level (WL) surveyed on 21 April 2010 (backup from the downstream impoundment), as well as the position of vegetation markers.**

A1.4 CONFIDENCE IN THE HYDRAULIC CHARACTERISATIONS

Table A2 Confidence ratings for the hydraulic characterisations

Site	REC	Season (dry/wet low & high flows)		Discharge, *Q* (m^3/s) Exceedance (%) 95[1]	40[2]	Meas. range or values	Rating (Confidence)	Comments
2	C	Low	Dry	10.2	29	60 - 660[12], 3650	2	Below min. meas. *Q.* Complex site. Uncertainty with flow class modelling. (Overall low flow confidence = 2).
			Wet	31	60		3	
		High		150-200, 300-400[5], 850-1000[7], 2000+[8]			5	Within meas. *Q* range.
3	B	Low	Dry	5.7	29	81 - 698[12], 2700	1	Below min. meas. *Q.* Modelled residual flow depth at the cessation of flow. (Overall low flow confidence = 2).
			Wet	29	108		3	
		High		150-200, 300-450[5], 650-780[7], 1200+[8]			5	Within meas. *Q* range.
4	B/C	Low	Dry	0.0	21	26 - 3042[12]	2	Below min. meas. *Q.* Complex site. Uncertainty with flow class modelling. (Overall low flow confidence = 3).
			Wet	14	56		3	
		High		60-70, 170, 340[5], 450-650[7], 1000+[8]			5	Within meas. *Q* range.
5	C/D	Low	Dry	0.08	0.17	0.24, 2.0	3	Mostly within meas. *Q* but complex site. Uncertainty with flow class modelling. (Overall low flow confidence = 3).
			Wet	0.27	2.23		4	
		High		3-5, 7-10, 15-20, 35-45[7]			3	Above meas. *Q*. Complex site.
6	D	Low	Dry	0.0	0.48	7.7, 60 (& 816)[3]	1	Below min. meas. *Q*. Possibility of backup from Gariep Dam when near FSL. Uncertainty with flow class modelling. (Overall low flow confidence = 2).
			Wet	1.6	35		3	
		High		50-70, 100-120, 200-400, 650+[7]			4	Substantial distance to upstream gauge (meas. 816 m^3/s).
7	C	Low	Dry	0.0	1.9	2.3 - 4.7 (& 700)[4]	3	Below min. meas. *Q*. (Overall low flow confidence = 3).
			Wet	0.14	5.1		3	
		High		14, 30-60, 100-150, 400-400[7], 500-650[7]			3	Single recent high *Q* meas. correlated with surveyed strand level.
8	PD	NA		0.1-0.2[11]		0.15	4[9]/3[10]	Backup extent to cross-section B.
	Sc1						4[9]/2[10]	Backup extent reduced to cross-section C.
	Sc2						4[9]/2[10]	Backup extent further reduced to cross-section D.
	Sc3						2[10]	No backup.
	Sc5			0.075			4[9]/2[10]	PD backup, discharge reduced by 50%.

Rating (confidence): 0:None 1:Low 2:Low/Medium 3:Medium 4:Medium/High 5:High

1: Drought conditions (refer to main report)
2: Maintenance conditions (refer to main report)
3: Gauge D2H033 (Welbedacht) - 27 January 2010
4: Gauge D1H011- 13 October 2009
5: 1:1
6: 1:2
7: 1:3
8: 1:5
9: Impounded areas
10: Unimpounded areas
11: Range applicable to confidence for unimpounded areas
12: Automatic stage recorders & gauge correlated discharges
Low: 'Base' flows
High flows: Daily averages unless otherwise noted

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