# VOLUME 1

# HYDRAULICS

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Given the importance of reliable information for the river hydraulic characterisations that are necessary to undertake instream flow requirement assessments, the success of the hydraulics component of this study is a reflection of the efforts of those that assisted both in the field and with the procurement of streamflow records.

# GLOSSARY OF TERMS, SYMBOLS AND ACRONYMS

| | |
|---|---|
| $a$, $b$, $c$ | Regression coefficients in the rating relationships |
| Area | Cross-sectional flow area ($m^2$) |
| Average flow depth | Cross-sectional flow area divided by the width of the water surface (m) |
| Discharge | Volumetric flow rate ($m^3/s$) |
| Flow depth | Maximum flow depth measured from lowest bed elevation (m) |
| IFR | Instream flow requirement |
| Longitudinal | Along the length of the river |
| $n$ | Manning's resistance coefficient |
| Resistance | Overall resistance to flow imposed by the river channel, including all resistance components, eg. bed roughness, vegetation, channel plan form, etc. |
| Shear stress | Shear force per unit plan area of bed ($N/m^2$) |
| Stage/water level | Elevation of the water surface relative to local datum (m) |
| Uniform flow | Invariant flow conditions in a longitudinal direction |
| Velocity | Speed at which water moves per unit time past a fixed point in a given direction (m/s) |
| Wetted perimeter | Amount of channel in contact with flow, measured along the cross-section (m) |

# TABLE OF CONTENTS

# LIST OF TABLES AND FIGURES

## TABLES

# PART 1: INTRODUCTION

## 1 INTRODUCTION

The flow of water in a river channel and the physical structure of the channel are intimately related in a cycle of cause and effect, temporally and spatially. Depending on the susceptibility of the channel to flow-related change, its morphology is determined by the geology as well as by the sediment and flow regimes, whilst local hydraulic conditions are determined by the geometry and flow resistance of the channel. Local hydraulic and channel morphology are the primary determinants of the availability of physical habitat that, in turn, influences ecosystem functioning. A quantitative understanding of the flow regime of a river, its physical structure, and its depth/velocity regime, derived jointly and severally from hydrological, geomorphological and hydraulic analyses, is therefore a prerequisite for deriving quantitative information about its ecological functioning.

When evaluating the ecological flow requirements for rivers, scientists tend to quantify the needs of the various biotic components in terms of parameters such as flow depth, flow velocity, wetted perimeter and water surface width. They also add time as a parameter by referring to the frequency of occurrence of a particular flow rate, or the duration of inundation resulting from a particular flooding event. Hydrologists, water engineers and water resource planners, on the other hand, are more comfortable when dealing with the water needs of humankind, and habitually express these needs in terms of volume and time. This quantification can range from an instantaneous flow rate in cubic metres per second ($m^3/s$), to long-term requirements in millions of cubic metres per annum ($Mm^3/a$).

Both approaches are completely valid in their own context, but the application of an holistic instream flow requirement (IFR) assessment requires an interface between them: this interface is found in the hydraulic analysis of flow in natural open channels. The results of hydraulic analysis and modelling therefore form the essential link between the way in which the hydrologist, engineer and water resource manager express the flow of water in the river, and the ways in which the river scientists express the water requirements for the river system itself.

# PART 2: METHODOLOGY

## 2 METHODOLOGY

The product of the hydraulics work comprises a series of relationships between flow rate and, amongst others, flow depth, flow velocity, wetted perimeter and shear stress. These relationships are determined for cross-sections or transects that are surveyed at the IFR sites. In order to satisfactorily characterise the hydraulic relationships for an IFR study, extensive use is made of field data, with discharge and stage being recorded at each of the cross-sections for a range of flows observed over the hydrological season. The hydraulic modelling component of the study involves using the measured cross-sectional and flow data to develop rating relationships (discharge against flow depth) and the biologically useful parameters (wetted perimeter and flow velocity) for the entire range of flows of interest. These relationships are presented graphically and also using lookup tables.

## 3 DATA COLLECTION

### 3.1 Location and survey of profiles at IFR sites

The hydraulic complexity of the IFR sites, and positioning of cross-sections through important and critical habitats have a profound influence on the ways in which hydraulic data are collected and analysed. Proportions of observed and modelled data required for the development of reliable hydraulic relationships useful for the IFR process are highly site-dependent. As a general rule: the more hydraulically complex the site, the greater the reliance on observed data for reliable results from the hydraulic analysis. Although hydraulic considerations cannot be expected to enjoy pre-eminence in the IFR site selection process, it is essential that the selected sites are hydraulically tractable within the limits of available resources.

Eight IFR sites along the Matsoku (IFR Site 1), Malibamatso (IFR Site 2), Senqu (IFR Sites 3 to 6), and Senqunyane Rivers (IFR Sites 7 and 8) were pre-selected (refer to Inception Report No. 648-01 and Task 1 Report No. 648-02) for instream flow assessment and hence the hydraulic characteristics of the sites had been determined *a priori*. The most suitable location (in respect of hydraulic, geomorphological and biotic considerations) and the number of cross-sections (or transects) positioned at each of the sites was undertaken by the study team during the initial data collection exercise in April 1999. During the initial site visit, bench marks were installed and the river cross-sectional and longitudinal bed profiles were surveyed. Additionally, when possible, flow velocity data were collected using a Marsh-McBirney model 2000 Flo-Mate electromagnetic flow meter and an OTT C31 Universal current meter.

### 3.2 Stage and discharge measurements

The river stages at each of the cross-sections were surveyed during the initial site visit and during subsequent data collection trips throughout the hydrological season (The survey dates are given in Section 5, Tables 5.#.3, where # is the site no.).

Local gauging stations, including both physical structures and rated cross-sections, have been used, where they are located in the vicinity of the sites, to provide measurements of discharge. This not only facilitated the hydraulic data collection, but also ensures that the discharge applied at the sites are directly linked to the gauging stations that will ultimately be used to assess the flow regulation within the river systems. Manual flow gauging using the velocity-area method (BS 3680) was undertaken at sites not located in the vicinity of gauging stations (*viz*. IFR Site 4 (Sehonghong) and IFR Site 8 (Lower Senqunyane)).

# PART 3: HYDRAULIC MODELLING

## 4 HYDRAULIC MODELLING

Using the measured cross-sectional and flow data, rating and the biologically useful hydraulic relationships for the entire range of flows of interest are developed. Synthesis of a rating relationship essentially involves interpolation between sparse data points, but with more difficulty, extrapolation beyond the limit of recorded data. Rating data may be synthesised using a resistance equation (e.g., Manning, Chezy or Darcy-Weisbach) provided the applicable resistance coefficient and uniform energy gradient may be estimated. A backwater computation is necessary where flow conditions are non-uniform (i.e. change with distance along the river), but also require an estimate of the flow resistance and the characterisation (hydraulically and geometrically) of hydraulic controls. A steady-state backwater model, Channel Flow Profile (CFP), has been used in this study for non-uniform flow profile computations at the IFR sites.

### 4.1 Analysis of rating data

Flow resistance in natural channels is generally a function of stage (Broadhurst *et al*., 1997; Birkhead *et al*., 1997), particularly at low stages where the flow depth is of the same order of magnitude as the size of the roughness elements constituting the bed. With increased discharge, the local hydraulic controls become inundated and drowned-out, resulting in a tendency towards uniform water surface gradients and asymptotic resistance coefficient values (Birkhead *et al*., in press). The resistance coefficient and energy (or water surface for uniform flow conditions) gradient may therefore be estimated with a higher degree of confidence at high rather than low flows.

A reasonable range of rating data have been collected at the sites, particularly for low-flow conditions, and extrapolated regression functions are used to model the stage-discharge relationship below the range of observed data. The backwater model, CFP, has been used to calibrate the Manning's resistance coefficient between cross-sections based on the observed rating data. The calibrated variations in the flow resistance values (tabulated for each site), together with data from the literature (Barnes, 1967; Hicks and Mason, 1991; Broadhurst *et al*., 1997) have been used to derive an estimate of the Manning's resistance values at high flows (100 and 400 m$^3$/s for IFR Site 1, and 200 and 800 m$^3$/s for the remaining sites). The water surface gradient for the highest recorded discharge has been applied in the backwaters computations, together with the high flow estimate of the resistance coefficient to compute the stage and hence flood rating data for each of the cross-sections.

The local water surface gradients (at the sites) at the highest observed discharges are compared with the regional bed slope measured from topographical maps in Table 4.1. The longitudinal distances over which the regional slopes were determined are also indicated. Generally, the local and regional slopes compare reasonably well, with the differences attributed to non-uniform flow at the sites and local (site-related scale) changes in the water surface gradient that can not be represented using regional values. The sensitivity of the synthesised rating data to gradient is discussed in Section 5.9.

### 4.2 Characterising the rating relationships

#### 4.2.1 Standard cross-sections

General depth-discharge power relationship for open channel flow (Birkhead and James, 1998) is given as:

$$y = aQ^b + c \qquad 4.1$$

where $y$ is the maximum flow depth (m), $Q$ is the discharge rate (m$^3$/s), and $a$, $b$ and $c$ are regression coefficients. Equation 4.1 was fitted to the measured and synthesised rating data for each of the cross-sections using least squares regression. Where single rating functions can not adequately describe the trend in observed and modelled data over the flow range of interest, two equations have been fitted to the point data.

The resulting coefficients and discharge ranges for each function are given in Section 5 (Tables 5.#.5, where # is the site no.) and Section 9.1 for each of the cross-sections. Using these coefficients and equation 4.1, ecologically significant hydraulic parameters at any cross-section can be determined for given water depth or flow. The goodness of fit of the power relationships is discussed in Section 5.9, with an average absolute deviation in flow depth of 0.01-0.02 m.

Table 4.1 Measured water surface and regional bed gradients

| IFR Site | Local | | Regional | |
|---|---|---|---|---|
| | Water surface gradient | Discharge $Q$ (m$^3$/s) | Bed gradient | Longitudinal distance (km) |
| 1 | 1:147 | 12.6 | 1:130 | 18 |
| 2 | 1:525 | 9.1 | 1:300 | 31 |
| 3 | 1:270 | 23.0 | 1:300 | 31 |
| 4 | 1:1000 | 34.9 | 1:525 | 61 |
| 5 | 1:1666 | 151.6 | 1:715 | 74 |
| 6 | 1:1000 | 366.4 | 1:830 | 56 |
| 7 | 1:625 | 16.9 | 1:165 | 17 |
| 8 | 1:830 | 31.6 | 1:300 | 37 |

### 4.2.2 Special cases of transversely sloped water surface profiles or multiple active channels

At certain sites, it was considered necessary to locate transects through the river where the water surface along the cross-sections is not horizontal, or where more than one active channel exists, and these are flowing at different water levels. Non-horizontal water surfaces profoundly complicate the hydraulic analysis, and rating functions need to be derived for each active channel or, in the case of a non-horizontal water surface within a single active channel, for the left and right banks. Observed data covering a range of discharges are necessary if the cross-sectional rating relationships are to be reliably determined. For multiple channel cross-sections, a lower discharge limit may exist for some of the channels, that being the discharge at which flow in the channel ceases. The rating relationships have been extrapolated for flood discharges by assuming that, under flood conditions, the hydraulic controls (resulting in the non-horizontal water surfaces) are drowned out and that a horizontal water surface exists with a single rating relationship for the cross-section. The discharge at which this occurs is given by the intersection of the rating curves for the individual channels, or right and left bank relationships for the case of transversely sloped water surfaces. In the absence of observed stage data for seasonal and ephemeral channels, a horizontal water surface is assumed.

### 4.3 Determination of hydraulic parameters for use in the IFR process

The relationships between discharge and other hydraulic determinants (e.g., average flow depth (*yav*), cross-sectional flow area (*A*), surface width (*W*), wetted perimeter (*P*), and average velocity (*v*)) are readily computed based on the rating functions (*Q* vs. *y*) and cross-sectional geometry. Plots of the cross-sectional geometry; rating relationships (log discharge scale); and plots of discharge (normal scale) against flow depth, average flow depth; wetted perimeter; and average velocity are provided in Section 9.1. These data have been tabulated in Section 9.2 to facilitate the evaluation of the required parameter values. Frequency distributions of point flow depths across the transects have been computed for discharges of 0.5, 1, 2 and 5 m$^3$/s, based on the geometry of the cross-sectional profiles, and can be provided at the IFR Workshop for other discharges. The depths across the channel have been computed at equal intervals to prevent the bias of data (depths) at survey points. Frequency distributions of depth averaged velocity measurements have also been prepared where velocity has been measured on transects. These data are presented as bar charts in Section 9.1. In addition, it is necessary to compute the bed shear stress for sediment transport considerations. The shear stress has been calculated as follows:

$$\tau = \gamma RS \qquad 4.2$$

where

$\tau$ is the bed shear stress (N/m$^2$)
$\gamma$ is the unit weight of water (9810 N/m$^3$)
$R$ is the hydraulic radius, $A/P$ (m)
$S$ is the energy gradient

Measured water surface slopes have been used for the energy gradient in expression 4.2 (this assumes uniform flow conditions), with flood values taken equal to those recorded at the highest observed discharge. Linear interpolations have been applied for gradients between measured/modelled discharges, with values below and above the range of measured/modelled data approximated by the lowest and highest recorded gradient, respectively. The bed shear stresses are tabulated as a function of flow depth in Section 9.2.

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## 5 TABULATED MEASURED AND MODELLED DATA

According to conventional practise, the left and right river banks are labelled looking downstream (in the direction of flow), and cross-sections are labelled alphabetically, from upstream (A) to downstream (B, C, etc.).

### 5.1 IFR SITE 1 - MATSOKU

Table 5.1.1 Bed elevations for IFR Site 1, Matsoku, relative to a local datum

| Cross-section | Bed elevation, *z* (m) |
|---|---|
| A | 95.81 |
| B | 95.98 |
| C | 94.81 |

Table 5.1.2 Longitudinal distances between cross-sections for IFR Site 1, Matsoku

| Cross-section | Longitudinal distance (m) |
|---|---|
| A - B | 25.6 |
| B - C | 182.7 |

Table 5.1.3 Rating data for IFR Site 1, Matsoku

| Survey date | Discharge $Q$ (m$^3$/s) | Cross-section | | | |
|---|---|---|---|---|---|
| | | A | B | | C |
| | | | Left bank | Right bank | |

| | | **Stage z (m)** | **Flow depth y (m)** | **Stage z (m)** | **Flow depth y (m)** | **Stage z (m)** | **Flow depth y (m)** | **Stage z (m)** | **Flow depth y (m)** |
|---|---|---|---|---|---|---|---|---|---|
| 15/7/98 | 0.31 | 96.39 | 0.58 | 96.28 | 0.30 | | 0.00 | 94.97 | 0.16 |
| 12/4/98 | 1.5 | 96.57 | 0.76 | 96.31 | 0.33 | 96.46 | 0.48 | 95.13 | 0.32 |
| 5/1/98 | 1.8 | 96.59 | 0.78 | 96.43 | 0.45 | 96.55 | 0.57 | 95.12 | 0.31 |
| 2/12/98 | 12.6 | 96.96 | 1.15 | 96.54 | 0.56 | 96.89 | 0.91 | 95.55 | 0.73 |
| | | | | | | | | | |
| | 100 | *97.68* | *1.87* | *97.62* | *1.64* | *97.62* | *1.64* | *96.41* | *1.60* |
| | 400 | *99.34* | *3.53* | *99.16* | *3.18* | *99.16* | *3.18* | *97.99* | *3.18* |

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Table 5.1.4 Resistance data for IFR Site1, Matsoku

| **Discharge $Q$ (m³/s)** | **Manning's *n* between cross-sections** | | |
|---|---|---|---|
| | A - B | B - C | A - C |
| 0.31 | 0.45 | 0.23 | 0.33 |
| 1.5 | 0.26 | 0.11 | 0.20 |
| 1.8 | 0.20 | 0.16 | 0.18 |
| 12.6 | 0.12 | 0.060 | 0.093 |
| 100 | *0.035* | *0.035* | |
| 400 | *0.035* | *0.035* | |

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Table 5.1.5 Rating relationship coefficients for IFR Site 1, Matsoku

| **Cross-section** | **Discharge range $Q$ (m³/s)** | **Regression coefficients in equation 4.1** | | |
|---|---|---|---|---|
| | | *a* | *b* | *c* |
| A | $Q < 9.8$ | 0.464 | 0.266 | 0.240 |
| | $9.8 < Q$ | 0.038 | 0.709 | 0.900 |
| B – Left bank | $Q < 11$ | 0.360 | 0.175 | 0.000 |
| | $11 < Q$ | 0.169 | 0.490 | 0.000 |
| B – Right bank | $1.5 < Q < 13.8$ | 0.458 | 0.272 | 0.000 |
| | $13.8 < Q < 135$ | 0.037 | 0.704 | 0.700 |
| C | $Q < 14$ | 0.242 | 0.426 | 0.015 |
| | $14 < Q$ | 0.072 | 0.610 | 0.400 |

## 5.2 IFR SITE 2 - KATSE

Table 5.2.1 Bed elevations for IFR Site 2, Katse, relative to a local datum

| **Cross-section** | **Bed elevation, *z* (m)** |
|---|---|
| A | 94.08 |
| B | 94.71 |
| C | 94.11 |

Table 5.2.2 Longitudinal distances between cross-sections for IFR Site 2, Katse

| **Cross-section** | **Longitudinal distance (m)** |
|---|---|
| A - B | 189.4 |
| B - C | 218.3 |

Table 5.2.3 Rating data for IFR Site 2, Katse

| **Survey date** | **Discharge** **$Q$ (m³/s)** | **Cross-section** | | | | | |
|---|---|---|---|---|---|---|---|
| | | A | | B | | C | |
| | | **Stage** **$z$ (m)** | **Flow depth** **$y$ (m)** | **Stage** **$z$ (m)** | **Flow depth** **$y$ (m)** | **Stage** **$z$ (m)** | **Flow depth** **$y$ (m)** |
| 14/7/98 | 0.75 | 95.18 | 1.10 | 95.10 | 0.39 | 94.44 | 0.33 |
| 4/1/99 | 1.9 | 95.33 | 1.25 | 95.18 | 0.47 | 94.61 | 0.50 |
| 11/4/98 | 9.1 | 95.71 | 1.27 | 95.33 | 0.62 | 94.99 | 0.88 |
| | 200 | *97.39* | *3.31* | *98.02* | *2.28* | *96.61* | *2.50* |
| | 800 | *99.33* | *5.25* | *99.03* | *4.32* | *98.56* | *4.45* |

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Table 5.2.4 Resistance data for IFR Site 2, Katse

| **Discharge** **$Q$ (m³/s)** | **Manning's *n* between cross-sections** | | |
|---|---|---|---|
| | A - B | B - C | A - C |
| 0.75 | 0.15 | 0.093 | 0.13 |
| 1.9 | 0.13 | 0.072 | 0.10 |
| 9.1 | 0.12 | 0.026 | 0.084 |
| 200 | *0.030* | *0.030* | |
| 800 | *0.030* | *0.030* | |

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Table 5.2.5 Rating relationship coefficients for IFR Site 2, Katse

| **Cross-section** | **Discharge range** **$Q$ (m³/s)** | **Regression coefficients in equation 4.1** | | |
|---|---|---|---|---|
| | | *a* | *b* | *c* |
| A | $Q < 164.5$ | 0.632 | 0.281 | 0.508 |
| | $164.5 < Q$ | 0.251 | 0.424 | 0.975 |
| B | $Q < 15$ | 0.414 | 0.183 | 0.000 |
| | $15 < Q$ | 0.198 | 0.461 | 0.000 |
| C | $Q < 180$ | 0.399 | 0.349 | 0.000 |
| | $180 < Q$ | 0.220 | 0.441 | 0.246 |

## 5.3 IFR SITE 3 - PARAY

Table 5.3.1 Bed elevations for IFR Site 3, Paray, relative to a local datum

| **Cross-section** | **Bed elevation, $z$ (m)** |
|---|---|
| A | 96.04 |
| B | 94.38 |
| C | 94.06 |
| D | 93.88 |
| E | 93.12 |
| F | 90.74 |

Table 5.3.2 Longitudinal distances between cross-sections for IFR Site 3, Paray

| **Cross-section** | **Longitudinal distance (m)** |
|---|---|
| A - B | 268.8 |
| B - C | 170.1 |
| C - D | 105.9 |
| D - E | 254.5 |
| E - F | 147.8 |

Table 5.3.3a Rating data for cross-sections A, C & D at IFR Site 3, Paray

| **Survey date** | **Discharge *Q* (m³/s)** | **Cross-section** | | | | | |
|---|---|---|---|---|---|---|---|
| | | A | | C | | D | |
| | | **Stage *z* (m)** | **Flow depth *y* (m)** | **Stage *z* (m)** | **Flow depth *y* (m)** | **Stage *z* (m)** | **Flow depth *y* (m)** |
| 13/7/98 | 0.81 | 96.50 | 0.46 | 94.45 | 0.39 | 94.38 | 0.50 |
| 7/1/99 | 3.5 | 96.64 | 0.61 | 94.62 | 0.56 | 94.60 | 0.72 |
| 8/4/98 | 18.0 | | | 94.98 | 0.92 | 94.96 | 1.08 |
| 3/12/98 | 23.0 | 96.91 | 0.87 | 95.06 | 1.00 | 95.01 | 1.13 |
| | 200 | *97.70* | *1.66* | *96.42* | *2.36* | *95.99* | *2.11* |
| | 800 | *99.06* | *3.02* | *98.21* | *4.15* | *97.52* | *3.64* |

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Table 5.3.3b Rating data for cross-sections E & F at IFR Site 3, Paray

| **Survey date** | **Discharge *Q* (m³/s)** | **Cross-section** | | | |
|---|---|---|---|---|---|
| | | E | | F | |
| | | **Stage *z* (m)** | **Flow depth *y* (m)** | **Stage *z* (m)** | **Flow depth *y* (m)** |
| 13/7/98 | 0.81 | 93.48 | 0.36 | | |
| 7/1/99 | 3.5 | 93.67 | 0.55 | 91.72 | 0.98 |
| 8/4/98 | 18.0 | 93.90 | 0.78 | 92.24 | 1.50 |
| 3/12/98 | 23.0 | 93.95 | 0.83 | 92.26 | 1.52 |
| | 200 | *94.78* | *1.66* | *93.75* | *3.01* |
| | 800 | *96.24* | *3.10* | *95.54* | *4.80* |

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Table 5.3.4 Resistance data for IFR Site 3, Paray

| **Discharge $Q$ (m³/s)** | **Manning's *n* between cross-sections** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | A - B | B - C | C - D | D - E | E - F | A - E | B - F | A - F |
| 0.81 | 0.36 | 0.17 | 0.099 | 0.18 | | 0.36 | | |
| 3.5 | 0.15 | 0.033 | 0.033 | 0.11 | 0. 48 | | | 0.15 |
| 18.0 | | 0.044 | 0.021 | 0.081 | 0.17 | | 0.045 | |
| 23.0 | 0.062 | 0.045 | 0.027 | 0.072 | 0.15 | | | 0.062 |
| 200 | *0.039* | *0.039* | *0.039* | *0.039* | *0.039* | | | |
| 800 | *0.033* | *0.033* | *0.033* | *0.033* | *0.033* | | | |

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Table 5.3.5 Rating relationship coefficients for IFR Site 3, Paray

| **Cross-section** | **Discharge range $Q$ (m³/s)** | **Regression coefficients in equation 4.1** | | |
|---|---|---|---|---|
| | | *a* | *b* | *c* |
| A | $Q < 37.5$ | 0.372 | 0.228 | 0.109 |
| | $37.5 < Q$ | 0.063 | 0.551 | 0.495 |
| C | | 0.205 | 0.443 | 0.195 |
| D | $Q < 64$ | 0.529 | 0.244 | 0.000 |
| | $64 < Q$ | 0.091 | 0.521 | 0.665 |
| E | $Q < 16.7$ | 0.393 | 0.239 | 0.000 |
| | $16.7 < Q$ | 0.054 | 0.580 | 0.494 |
| F | | 0.341 | 0.382 | 0.433 |

## 5.4 IFR SITE 4 - SEHONGHONG

Table 5.4.1 Bed elevations for IFR Site 4, Sehonghong relative to a local datum

| **Cross-section** | **Bed elevation, *z* (m)** |
|---|---|
| A | 93.83 |
| B | 93.71 |
| C | 92.20 |

Table 5.4.2 Longitudinal distances between cross-sections for IFR Site 4, Sehonghong

| **Cross-section** | **Longitudinal distance (m)** |
|---|---|
| A - B | 195.7 |
| B - C | 47.4 |

Table 5.4.3 Rating data for IFR Site 4, Sehonghong

| Survey date | Discharge $Q$ (m$^3$/s) | Cross-section | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | A | | B | | C | | | |
| | | | | | | Left bank | | Right bank | |
| | | Stage $z$ (m) | Flow depth $y$ (m) | Stage $z$ (m) | Flow depth $y$ (m) | Stage $z$ (m) | Flow depth $y$ (m) | Stage $z$ (m) | Flow depth $y$ (m) |
| 12/7/98 | 2.2 | 94.38 | 0.55 | 94.33 | 0.62 | 93.21 | 1.01 | 94.36 | 2.16 |
| 6/1/99 | 11.9 | 94.58 | 0.75 | 94.55 | 0.84 | 93.50 | 1.30 | 94.53 | 2.33 |
| 9/4/98 | 34.9 | 94.85 | 1.02 | 94.68 | 0.97 | 94.11 | 1.91 | 94.66 | 2.46 |
| | 800 | *97.58* | *3.75* | *97.41* | *3.70* | *97.35* | *5.15* | *97.35* | *5.15* |

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Table 5.4.4 Resistance data for IFR Site 4, Sehonghong

| Discharge $Q$ (m$^3$/s) | Manning's $n$ between cross-sections | | |
|---|---|---|---|
| | A - B | B - C | A - C |
| 2.2 | 0.099 | 1.14 | 0.17 |
| 11.9 | 0.029 | 0.37 | 0.068 |
| 34.9 | 0.036 | 0.15 | 0.047 |
| 800 | *0.030* | *0.030* | |

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Table 5.4.5 Rating relationship coefficients for IFR Site 4, Sehonghong

| Cross-section | Discharge range $Q$ (m$^3$/s) | Regression coefficients in equation 4.1 | | |
|---|---|---|---|---|
| | | $a$ | $b$ | $c$ |
| A | | 0.087 | 0.546 | 0.416 |
| B | $Q < 33.5$ | 0.554 | 0.160 | 0.000 |
| | $33.5 < Q$ | 0.019 | 0.758 | 0.700 |
| C – Left bank | $Q < 12.4$ | 0.100 | 0.675 | 0.800 |
| | $12.4 < Q$ | 0.599 | 0.322 | 0.000 |
| C – Right bank | $0.15 < Q < 35$ | 1.194 | 0.077 | 0.888 |
| | $35 < Q < 132$ | 0.010 | 0.842 | 2.250 |

## 5.5 IFR SITE 5 - WHITEHILL

Table 5.5.1 Bed elevations for IFR Site 5, Whitehill, relative to a local datum

| Cross-section | Bed elevation, $z$ (m) |
|---|---|
| A | 89.82 |
| B | 90.93 |
| C | 88.99 |

Table 5.5.2 Longitudinal distances between cross-sections for IFR Site 5, Whitehill

| **Cross-section** | **Longitudinal distance (m)** |
|---|---|
| A - B | 81.3 |
| B - C | 64.1 |

Table 5.5.3 Rating data for IFR Site 5, Whitehill

| **Survey date** | **Discharge $Q$ (m$^3$/s)** | **Cross-section** | | | | | |
|---|---|---|---|---|---|---|---|
| | | A | | B | | C | |
| | | **Stage $z$ (m)** | **Flow depth $y$ (m)** | **Stage $z$ (m)** | **Flow depth $y$ (m)** | **Stage $z$ (m)** | **Flow depth $y$ (m)** |
| 9/7/98 | 3.7 | 91.69 | 1.87 | 91.65 | 0.72 | 90.55 | 1.56 |
| 7/1/99 | 19.0 | 91.98 | 2.16 | 91.96 | 1.03 | 91.20 | 2.21 |
| 13/4/98 | 41.4 | 92.20 | 2.38 | 92.18 | 1.25 | 91.69 | 2.70 |
| 30/11/98 | 151.6 | 93.23 | 3.41 | 93.20 | 2.27 | 93.14 | 4.15 |
| | 800 | *95.68* | *5.86* | *95.64* | *4.72* | *95.59* | *6.60* |

*italic* - modelled

Table 5.5.4 Resistance data for IFR Site 5, Whitehill

| **Discharge $Q$ (m$^3$/s)** | **Manning's $n$ between cross-sections** | | |
|---|---|---|---|
| | A - B | B - C | A - C |
| 3.7 | 0.20 | 0.66 | 0.34 |
| 19.0 | 0.054 | 0.29 | 0.14 |
| 41.4 | 0.036 | 0.17 | 0.095 |
| 151.6 | | | 0.042 |
| 800 | *0.030* | *0.030* | |

*italic* - modelled

Table 5.5.5 Rating relationship coefficients for IFR Site 5, Whitehill

| **Cross-section** | **Discharge range $Q$ (m$^3$/s)** | **Regression coefficients in equation 4.1** | | |
|---|---|---|---|---|
| | | $a$ | $b$ | $c$ |
| A | $Q < 43.5$ | 0.154 | 0.436 | 1.600 |
| | $43.5 < Q$ | 0.286 | 0.424 | 1.000 |
| B | $Q < 37.3$ | 0.529 | 0.229 | 0.000 |
| | $37.3 < Q$ | 0.242 | 0.445 | 0.000 |
| C | $Q < 40.3$ | 0.461 | 0.380 | 0.800 |
| | $40.3 < Q$ | 2.209 | 0.203 | -2.000 |

## 5.6 IFR SITE 6 - SEAKA

Table 5.6.1 Bed elevations for IFR Site 6, Seaka, relative to a local datum

| **Cross-section** | **Bed elevation, $z$ (m)** |
|---|---|
| A | 84.583 |
| B | 84.518 |

Table 5.6.2 Longitudinal distances between cross-sections for IFR Site 6, Seaka

| **Cross-section** | **Longitudinal distance (m)** |
|---|---|
| A - B | 466.3 |

Table 5.6.3 Rating data for IFR Site 6, Seaka

| **Survey date** | **Discharge** **$Q$ (m³/s)** | **Cross-section** | | | |
|---|---|---|---|---|---|
| | | A | | B | |
| | | **Stage** **$z$ (m)** | **Flow depth** **$y$ (m)** | **Stage** **$z$ (m)** | **Flow depth** **$y$ (m)** |
| 6/10/98 | 2.4 | 96.07 | 1.22 | 95.74 | 1.22 |
| 7/7/98 | 9.8 | 96.21 | 1.36 | 95.84 | 1.32 |
| 8/1/99 | 110 | 97.09 | 2.24 | 96.65 | 2.13 |
| 11/4/98 | 117 | | | 96.84 | 2.27 |
| 28/11/98 | 366 | 98.29 | 3.44 | 97.84 | 3.32 |
| | 800 | *99.26* | *4.41* | *98.80* | *4.28* |

*italic* - modelled

Table 5.6.4 Resistance data for IFR Site 6, Seaka

| **Discharge** **$Q$ (m³/s)** | **Manning's *n* between cross-section A - B** |
|---|---|
| 2.4 | 0.10 |
| 9.8 | 0.039 |
| 110 | 0.019 |
| 366 | 0.026 |
| 800 | *0.025* |

*italic* - modelled

Table 5.6.5 Rating relationship coefficients for IFR Site 6, Seaka

| **Cross-section** | **Discharge range** **$Q$ (m³/s)** | **Regression coefficients in equation 4.1** | | |
|---|---|---|---|---|
| | | *a* | *b* | *c* |
| A | $Q < 106$ | 0.067 | 0.604 | 1.101 |
| | $106 < Q$ | 0.965 | 0.258 | -1.000 |
| B | $Q < 81$ | 0.012 | 0.939 | 1.205 |
| | $81 < Q$ | 1.063 | 0.245 | -1.191 |

## 5.7 IFR SITE 7 - MARAKABEI

Table 5.7.1 Bed elevations for IFR Site 7, Marakabei, relative to a local datum

| **Cross-section** | **Bed elevation, $z$ (m)** |
|---|---|
| A | 93.32 |
| B | 92.58 |
| C | 92.50 |
| D | 92.24 |

Table 5.7.2 Longitudinal distances between cross-sections For IFR Site 7, Marakabei

| Cross-section | Longitudinal distance (m) |
|---|---|
| A – B | 159.3 |
| B – C | 381.2 |
| C – D | 38.4 |

Table 5.7.3a Rating data for cross-sections A & B at IFR Site 7, Marakabei

| Survey date | Discharge $Q$ (m$^3$/s) | Cross-section | | | | | |
|---|---|---|---|---|---|---|---|
| | | A | | | | B | |
| | | Left bank | | Right bank | | | |
| | | **Stage $z$ (m)** | **Flow depth $y$ (m)** | **Stage $z$ (m)** | **Flow depth $y$ (m)** | **Stage $z$ (m)** | **Flow depth $y$ (m)** |
| 7/10/98 | 0.41 | 94.27 | 0.95 | 93.65 | 0.33 | 93.67 | 1.09 |
| 16/7/98 | 0.59 | 94.33 | 1.01 | 93.73 | 0.41 | 93.73 | 1.14 |
| 4/12/98 | 5.6 | | | | 0.75 | 94.04 | 1.46 |
| 10/4/98 | 5.9 | 94.50 | 1.18 | 94.08 | 0.76 | 94.02 | 1.44 |
| 8/1/99 | 16.9 | 94.78 | 1.46 | 94.38 | 1.06 | 94.38 | 1.80 |
| | 200 | *95.94* | *2.62* | *95.94* | *2.62* | *95.53* | *2.95* |
| | 800 | *97.84* | *4.52* | *97.84* | *4.52* | *97.30* | *4.72* |

*italic* - modelled

Table 5.7.3b Rating data for cross-sections C & D at IFR Site 7, Marakabei

| Survey date | Discharge $Q$ (m$^3$/s) | Cross-section | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | C | | | | D | | | |
| | | Left bank | | Right bank | | | | | |
| | | **Stage $z$ (m)** | **Flow depth $y$ (m)** | **Stage $z$ (m)** | **Flow depth $y$ (m)** | **Stage $z$ (m)** | **Flow depth $y$ (m)** | **Stage $z$ (m)** | **Flow depth $y$ (m)** |
| 7/10/98 | 0.41 | 92.53 | 0.02 | 93.22 | 0.72 | 92.45 | 0.21 | 93.13 | 0.89 |
| 16/7/98 | 0.59 | 92.26 | 0.06 | 93.26 | 0.76 | 92.50 | 0.26 | 93.14 | 0.90 |
| 4/12/98 | 5.6 | 92.85 | 0.35 | 93.49 | 0.99 | 92.74 | 0.50 | 93.21 | 0.97 |
| 10/4/98 | 5.9 | 92.85 | 0.35 | 93.49 | 0.99 | 92.74 | 0.50 | 93.23 | 0.99 |
| 8/1/99 | 16.9 | 93.21 | 0.71 | 93.68 | 1.18 | 93.09 | 0.85 | 93.47 | 1.23 |
| | 200 | *95.05* | *2.55* | *95.05* | *2.55* | *95.04* | *2.80* | *95.04* | *2.80* |
| | 800 | *96.92* | *4.42* | *96.92* | *4.42* | *96.94* | *4.70* | *96.94* | *4.70* |

*italic* - modelled

Table 5.7.4 Resistance data for IFR Site 7, Marakabei

| **Discharge $Q$ (m³/s)** | **Manning's *n* between cross-sections** | | |
|---|---|---|---|
| | B - C | C - D | B - D |
| 0.41 | 0.99 | 0.84 | 0.96 |
| 0.59 | 0.81 | 0.75 | 0.78 |
| 5.6 | 0.19 | 0.21 | 0.18 |
| 5.9 | 0.17 | 0.20 | 0.17 |
| 16.9 | 0.12 | 0.11 | 0.12 |
| 200 | | | *0.035* |
| 800 | | | *0.030* |

*italic* - modelled

Table 5.7.5 Rating relationship coefficients for IFR Site 8, Marakabei

| **Cross-section** | **Discharge range $Q$ (m³/s)** | **Regression coefficients in equation 4.1** | | |
|---|---|---|---|---|
| | | $a$ | $b$ | $c$ |
| A - Left bank | $Q < 17.3$ | 0.070 | 0.709 | 0.936 |
| | $17.3 < Q < 212$ | 0.069 | 0.585 | 1.100 |
| A - Right bank | $Q < 1.8$ | 0.451 | 0.300 | 0.000 |
| | $1.8 < Q$ | 0.264 | 0.418 | 0.200 |
| B | $Q < 16.75$ | 0.193 | 0.512 | 0.980 |
| | $16.75 < Q$ | 0.085 | 0.549 | 1.400 |
| C - Left bank | $0.2 < Q < 12.9$ | 0.147 | 0.585 | -0.057 |
| | $12.9 < Q < 221$ | 0.556 | 0.332 | -0.700 |
| C - Right bank | $Q < 4$ | 0.274 | 0.311 | 0.519 |
| | $4 < Q$ | 0.133 | 0.501 | 0.650 |
| D - Left bank | $Q < 13$ | 0.105 | 0.663 | 0.168 |
| | $13 < Q < 185$ | 0.692 | 0.312 | -0.800 |
| D - Right bank | $Q < 14$ | 0.010 | 1.234 | 0.890 |
| | $14 < Q$ | 0.293 | 0.405 | 0.300 |

## 5.8 IFR SITE 8 - LOWER SENQUNYANE

Table 5.8.1 Bed elevations for IFR Site 8, Lower Senqunyane, relative to a local datum

| **Cross-section** | **Bed elevation, $z$ (m)** |
|---|---|
| A | 96.91 |
| B | 96.48 |

Table 5.8.2 Longitudinal distances between cross-sections for IFR Site 8, Lower Senqunyane

| **Cross-section** | **Longitudinal distance (m)** |
|---|---|
| A - B | 227.9 |

Table 5.8.3 Rating data for IFR Site 8, Lower Senqunyane

| **Survey date** | **Discharge** **$Q$ (m³/s)** | **Cross-section** | | | |
|---|---|---|---|---|---|
| | | A | | B | |
| | | **Stage** **$z$ (m)** | **Flow depth** **$y$ (m)** | **Stage** **$z$ (m)** | **Flow depth** **$y$ (m)** |
| 8/7/98 | 1.1 | 97.16 | 0.25 | 96.84 | 0.36 |
| 12/4/98 | 18.3 | 97.68 | 0.77 | 97.42 | 0.94 |
| 7/1/99 | 31.6 | 97.85 | 0.94 | 97.58 | 1.10 |
| | 200 | *98.85* | *1.94* | *98.53* | *2.05* |
| | 800 | *100.31* | *3.41* | *100.04* | *3.56* |

*italic* - modelled

Table 5.8.4 Resistance data for IFR Site 8, Lower Senqunyane

| **Discharge** **$Q$ (m³/s)** | **Manning's *n* between cross-section A - B** |
|---|---|
| 1.1 | 0.066 |
| 18.3 | 0.030 |
| 31.6 | 0.027 |
| 200 | *0.026* |
| 800 | *0.025* |

*italic* - modelled

Table 5.8.5 Rating relationship coefficients for IFR Site 8, Lower Senqunyane

| **Cross-section** | **Discharge range** **$Q$ (m³/s)** | **Regression coefficients in equation 4.1** | | |
|---|---|---|---|---|
| | | *a* | *b* | *c* |
| A | | 0.237 | 0.398 | 0.000 |
| B | $Q < 151$ | 0.354 | 0.331 | 0.000 |
| | $151 < Q$ | 0.288 | 0.378 | -0.056 |

## 5.9 An assessment of the accuracy of the rating relationships

As mentioned previously, the hydraulic modelling applied here is essentially concerned with the quantification of the rating relationships for the river cross-sections, with other determinants (with the exception of bed shear stress) readily computed from the cross-sectional geometry. The accuracy of the hydraulic relationships presented for the river cross-sections are therefore directly related to the accuracy of the stage-discharge functions.

With respect to the ratings, two issues require consideration: the first is the confidence in the extrapolated rating function for low flows as well as synthesised data for high flows, and secondly, the ability of the function (equation 4.1) to characterise the rating data (both measured and modelled). With respect to the first issue, it is difficult to assess the accuracy of the rating relationships at flows below those observed in the field. Where cross-sections have been located through morphological features displaying steep gradients such as rapids and riffles, it is reasonable to assume that the flow depth at the cessation of flow will be zero. Under such circumstances, the coefficient reflecting the flow depth at zero discharge in equation 4.1 (i.e., "*c*" coefficient) is equated to zero. This, however, is not the case for transects located through pool type geomorphological units, where there is backup of flow due to downstream controls, which result in a residual flow depth at the cessation of flow. If rating data are available at extreme low flows, the value of the appropriate coefficient in expression 4.1 may be specified or determined through regression - as is applied here. It is meaningful to compare the value of the residual flow depth estimated through extrapolation of the rating functions with that determined by interpretation of the longitudinal bed profile, where such survey data are available. Table 5.9.1 gives the values of the non-zero residual flow depths together with the backup estimate from surveys of the longitudinal profiles or by using the difference in cross-sectional bed elevations. For the few cases where survey data are available, the residual flows compare well, providing confidence in the modelled values adopted. It should be recognised, however, that one-dimensional longitudinal surveys only provide an estimate of the back-up depth, since it is difficult to distinguish the lowest elevation along the river during reasonably high flows when these data were collected.

With respect to the confidence in the synthesised rating data for flood flows, it is necessary to consider the sensitivity of discharge and flow depth to the estimated parameters applied in the modelling, i.e., the resistance coefficient (Manning's *n*) and energy slope. An assessment of Manning's resistance equation reveals that discharge is inversely proportional to the resistance coefficient, whilst being directly proportional to the square root of the energy slope, and hence less sensitive to the latter determinant. The change in flow depth is less sensitive than discharge to both of these parameters, reflected in the "*b*" coefficient in equation 4.1, which is invariably less than unity, with unity indicating direct proportionality.

As discussed previously, the calibrated variations in the flow resistance using observed rating data at each of the sites, together with data from the literature, have been used to derive an estimate of the Manning's resistance values for flood flows. The trend towards asymptotic resistance coefficient values with increased discharge has also been mentioned, and is clearly illustrated for each of the sites (tabulated data). For example, values of 0.026, 0.027 and 0.027 have been calibrated for the sites at Seaka (366 $m^3/s$), Lower Senqunyane (31.6 $m^3/s$) and Paray between cross-sections C and D (23 $m^3/s$). These are essentially considered asymptotic values for sand bed rivers (noting that the calibrated value has increased at Seaka from 0.019 at 110 $m^3/s$, possibly due to added resistance arising from large-scale bed forms) and have therefore been applied for flood discharges at Seaka and the Lower Senqunyane sites. A well-rated river section exists at Paray between cross-sections C and D (station 9008), and advantage has been taken of this rating to calibrate the reach averaged resistance coefficients at this site (0.039 at 200 $m^3/s$ and 0.033 at 800 $m^3/s$), and hence increase the overall confidence in the synthesized rating data for the cross-sections at this site.

A further issue that requires consideration with respect to the accuracy of stage-discharge relationships is the accuracy of fit of the power functions (equation 4.1). The average and maximum absolute deviation between flow depth estimates using the point measured and modelled data (Tables 5.#.3, where # is the site number) and rating functions (equation 4.1 with the appropriate coefficients obtained from Tables 5.#.5) are generally between 0.01-0.02 m and 0.02-0.03 m for all cross sections, respectively. The good fits may, however, be somewhat attributed to the relatively sparse data sets.

The accuracy of the rating relationships also depends on the accuracy with which the discharge may be determined, either using the local gauging or rated sections, or by manual measurements using the velocity-area method. It is reasonable to expect accurate measurement of discharge from the Crump Weirs located at IFR Sites 3 (Paray), 5 (Whitehill) and 7 (Marakabei) (± 10%), whilst lower accuracies will generally be concomitant with manual flow gauging and rated sections (± 20%, though dependent on the characteristics of the gauging site). There is concern over the accuracy of the rated sections at IFR Sites 1 (Matsoku) and 6 (Seaka), particularly at low flows. It appears that the rating for G042 (Matsoku) and G03 (Seaka) were last updated in 1971 and 1977, respectively. The physical characteristics of the river at Seaka are likely to result in temporal changes to the rating, whilst the bed at the Matsoku station is more stable. Manual flow measurements were used at IFR Site 2 (Katse) where available, since the accuracy with which the discharge may be measured when the Katse Dam is overtopping is questionable. Furthermore, a seasonal tributary exists between the Site and the Dam wall, and a rated section located in a pool upstream of the site is ineffective for measuring low flows.

The translation of an error in the determination of discharge into a difference in flow depth is a function of the parameter value of the power coefficient ( *b* ) in equation 4.1, which is invariably much less than unity. This indicates that the relative (percentage) change in flow depth is less than a given relative change in discharge, but conversely, small adjustments to flow depth will result in larger adjustments to the discharge. As an example, for IFR Site 1, cross-section A, a 20% increase in discharge at 0.5, 10 and 100 $m^3/s$ result in increases in the flow depth of 0.02 m (3%), 0.03 m (2%) and 0.14 m (7%), respectively. The sensitivity is a function of the value of the rating coefficients for each section, and may be calculated from the rating equations.

Table 5.9.1 Comparison between residual flow depths obtained through extrapolation of the rating functions and from survey data of the longitudinal bed profile

| **IFR Site** | | **Residual flow depth, *y* (m)** | | **Lowest observed discharge *Q* ($m^3/s$)** | **Comment** |
|---|---|---|---|---|---|
| | | Modelled | Survey | | |
| 1 | A | 0.24 | 0.26 | 0.31 | Survey based on longitudinal bed profile |
| | C | 0.02 | | 0.31 | Low residual depth |
| 2 | A | 0.51 | 0.77 | 0.75 | Survey based on longitudinal bed profile |
| 3 | A | 0.11 | 0.11 | 0.81 | Modelled using survey of longitudinal profile |
| | C | 0.20 | 0.13 | 0.81 | Survey based on longitudinal bed profile |
| | F | 0.43 | | 3.5 | Lowest observed discharge 3.5 $m^3/s$ |
| 4 | C - Left | 0.80 | | 2.2 | Possible local bed scour downstream of rapid |
| 5 | A | 1.60 | 1.11 | 3.7 | Survey based on bed elevations |
| | C | 0.80 | | 3.7 | Possible local bed scour downstream of rapid |
| 6 | A | 1.11 | | 2.4 | Indicated by rating data |
| | B | 1.21 | | 2.4 | Indicated by rating data |
| 7 | B | 0.98 | | 0.41 | Indicated by rating data |
| | C | 0.52 | | 0.41 | Indicated by rating data |
| | D - Left | 0.17 | | 0.41 | Indicated by rating data |
| | D - Right | 0.89 | | 0.41 | Indicated by rating data |

## 6 WORKSHOP FACILITIES

A cross-section analyser was developed for use at the IFR Workshop (see inside pocket on rear cover of this report.) The analyser facilitates the computation of the ecologically relevant hydraulics determinants (flow velocity, wetted perimeter, surface width and cross-sectional area) as a function of discharge or flow depth; provides a visual display of the water level across any of the cross-sectional profiles for up to 6 discharge values; and plots the location of important positions across the channel profiles as located by the geomorphological, invertebrate and riparian specialists during the site selection and initial data collection exercise.

# PART 4: RECOMMENDATIONS AND REFERENCES

## 7 RECOMMENDATIONS

The collection of reliable hydraulic data at the sites requires a fixed datum for the survey of river stages. Bench marks in the form of steel pegs in concrete beacons and painted markers were installed at the outset of the study to serve as local fixed datums. A number of bench marks were, however, vandalised during the course of the project and were re-installed and surveyed. If the sites are to be used for ongoing hydraulic related data collection, it is essential to ensure that the integrity of the survey datum is maintained through the installation of more robust bench marks (i.e., larger concrete beacons) and the use of a global (rather than local) coordinate positioning system, which will require specialist surveying.

The refinement of the hydraulic characterisations is often necessary due to the inability to collect an adequate range of data during the study period. The extent to which this is necessary in the present project will become apparent during the specialist meeting, since it is a function of the recommended flow rates and those observed in the field.

Local gauging stations, including both physical structures and rated cross-sections, have been used where they are located in the vicinity of the sites, to provide measurements of discharge rates. If the rating relationships for these gauge stations are amended (with particular reference to rated river sections G03 (Seaka) and G42 (Matsoku)), it will be necessary to amend the hydraulic characterisations accordingly.

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# PART 5: RESULTS

## 9 RESULTS

The hydraulic relationships for each of the cross sections at each of the IFR sites are presented in a software package called X-Sect. The software is supplied on disk in the inside pocket on the rear cover of this report.