River channel self-adjustment towards equilibrium: endogenic and exogenic influences on distinctly different river types in the Lake Eyre basin of arid central Australia

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PART II

RESULTS AND DISCUSSIONS
Chapter 6: channel morphology and estimated hydraulic adjustments along the Diamantina River

6.1 Introduction

This chapter examines the hydraulic geometry of the mud-dominated Diamantina River. The rivers of the Northern Plains (Chapter 7) are essentially bedload-dominated systems, moving mostly sand along a mixture of well-defined trapezoid channels, some of which are ridge-form anabranching. The Diamantina River offers a sharp contrast to these. It too is anabranching (in this case, anastomosing) (Nanson and Knighton, 1996) but it has relatively deep and narrow mud lined, almost canal-like channels supporting a dense tree and lignum cover along its banks, however, its sediment load is dominated by mud, some of which can be moved in the form of mud pelleted bedload (Maroulis and Nanson, 1996).

The purpose of this chapter is to assess hydraulic geometry and to examine how the calculated H numbers relate to the optimal value of 0.30 in this low-energy mud-dominated and well-vegetated anastomosing ephemeral system (Objectives 3 and 4, Chapter 1). The specific location for investigation is upstream, downstream and in the bedrock confined reach at Janets Leap and Hunters Gorge on the Diamantina River (Figure 6.1), which enables an additional objective: to determine whether the bedrock constriction has an effect in terms of channel efficiency and hence the prevailing equilibrium conditions.

6.2 Site selection and methods

The constriction of the Diamantina River at Hunters George and Janets Leap (Figure 6.1) within the Diamantina National Park was chosen as the study area because it provided a variety of Zones (I - IV) where channels were either completely unconstrained by the narrow valley (i.e. upstream at Zone I in Figure 6.1), approaching the rapid constriction (Zone II), in the actual constriction adjacent to Janets Leap (Zone
III), or recovering from confinement (i.e. downstream at Zone IV) (Table 6.1, Figure 6.1a). This figure illustrates these zones in the ~25 km long study reach, with four Google Earth Locations, Figure 6.1b, c, d, and e. Within each location the channels are divided into nine alphabetically labelled Sites P to Y, noting that there is no Site S. Where these sites have multiple cross sections, they are labelled in downstream order 1, 2, 3 etc., e.g. P1, P2, P3, P4, P5 in Figure 6.1b. In addition there are sites on transects, which are where there are laterally extensive channel/floodplain sections (Transects, 1 to 4) that capture more than one channel cross section in lateral extent. Within Janets Leap and Hunters Gorge, there appear to be five primary channels (PC1 to PC5, left to right, east to west), which were captured at least twice by the chosen sites and transects, except for PC5 (Table 6.1).

For this study of the Diamantina River, primary channels (PC) are defined as those which are active at moderate flows; secondary channels (SC) are those that are distinct channels but narrower than primary channels; and tertiary channels (TC) are those that occupy the inter-lignum channel areas (see Section 6.3.1.2). This is a similar classification to that used by Knighton and Nanson (1994b) for anabranching channels along Cooper Creek. Where ‘PC’ is utilised, it always relates to the same channel, irrespective of the transect; for example, PC2 was captured by Transects 2, 3 and 4. Where ‘SC’ is utilised, it is transect specific; for example, SC1 in Transect 2 is not necessarily the same channel as SC1 in Transect 3. ‘SC’ is simply used to identify the different secondary channels that hydraulic parameters have been calculated for along a transect.

In addition to these sites at Hunters Gorge and Janets Leap, a single site (Site Z) was surveyed on one of three rated primary channels adjacent to Birdsville 330 km farther downstream. This site was chosen because it offers a contrast to those in and around the bedrock confinement; the channel is larger, and the banks stepped. This complex array of sites in total was chosen in order to apply the H number model to a range of cross sections (totalling 64) within this mud-dominated alluvial setting.
Table 6.1: Nomenclature, location and brief description of the 64 topographical cross sections surveyed along the Diamantina River in June/July 2012. HG = Hunters Gorge, JL = Janets Leap, u/s = upstream, d/s = downstream.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Site</th>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Transect 1</td>
<td>18 km u/s of HG/JL</td>
<td>Captures some secondary channels 2 km left (east) of the primary channels</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>18 km u/s of HG/JL</td>
<td>Secondary channel ~2.3 km left of the primary channels</td>
</tr>
<tr>
<td></td>
<td>Q</td>
<td>18 km u/s of HG/JL</td>
<td>Secondary channel ~2.4 km left of the primary channels</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>2.5 km to 0.5 km u/s of HG</td>
<td>Primary channel upstream of HG; feeds PC5</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>2.5 km u/s of HG/JL</td>
<td>Secondary channel; dense vegetation on top of banks</td>
</tr>
<tr>
<td></td>
<td>U</td>
<td>2.5 km u/s of HG/JL</td>
<td>Secondary channel; dense vegetation on top of banks</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>1.5 km u/s of HG/JL</td>
<td>Secondary channel; light vegetation on top of banks</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>0.8 km u/s of HG/JL</td>
<td>Secondary channel; dense vegetation on top of banks</td>
</tr>
<tr>
<td>II</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transect 2</td>
<td>In JL</td>
<td>Captures PC1 to PC4 within JL</td>
</tr>
<tr>
<td></td>
<td>Transect 3</td>
<td>In JL</td>
<td>Captures PC1 to PC4 within JL; ~0.3 km d/s of Transect 2</td>
</tr>
<tr>
<td>III</td>
<td>Transect 4</td>
<td>2 km d/s of HG/JL</td>
<td>Captures all channels and at least 2 km of the high floodplain either side of them</td>
</tr>
<tr>
<td></td>
<td>X (PC4)</td>
<td>2.2 to 4 km d/s of HG/JL</td>
<td>Primary channel; aligns to PC4; light vegetation on top of banks</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>3.2 to 3.6 km d/s of HG/JL</td>
<td>Secondary channel; bifurcation of X; light vegetation on top of banks</td>
</tr>
<tr>
<td>IV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Birdsville reach</td>
<td>~330 km d/s of HG/JL (Birdsville)</td>
<td>Light vegetation on top of banks</td>
</tr>
</tbody>
</table>

Birdsville reach
Figure 6.1: a) Studied reach of the Diamantina River, central west Queensland. Image sourced from Bing Aerial Maps (ArcGIS).
Figure 6.1 (cont.): Locations labelled b) to e) are presented in more detail, to show the geomorphology of individual sites and transects, and locations of the cross sections within each site. Transect 4 is shown later in Figure 6.8. A cross section approximately 400 km downstream of Janets Leap and Hunters Gorge (at Birdsville) was surveyed and is shown in inset f). Images sourced from Google Earth.
The five primary channels (PC1 to PC5) all contained sub-bankfull flows during the field season in June/July 2012. A total of 64 channels within the Diamantina system were surveyed and are represented in 43 topographical cross sections (some cross sections include more than one channel) (Appendix A).

The primary channels of the Diamantina River immediately upstream, downstream and within the bedrock confinement of Janets Leap and Hunters Gorge appear canal-like and, with the exception of exposed tree roots generally confined to the upper third of the bank, they are consistently essentially smooth walled. The surficial material of the channel beds and banks across all channel types comprises massive clay to fine sand-sized mud pellets and some quartz sand. Grab samples from each site were collected and analysed with a Malvin Mastersizer 2000 at the University of Wollongong. The coarsest sediment (0.33 mm) was found to be associated with Cross Section Y1.

Previous field and flume studies have demonstrated that the muds typical of Channel Country rivers can be transported as bedload in the form of sand-sized pelleted mud aggregates (Nanson et al., 1986; Rust and Nanson, 1989; Maroulis and Nanson, 1996). Abundant mud pellets (aggregates) are also visible, especially in the floodplain of the Diamantina River. The mud aggregate size and specific density, as determined by Maroulis and Nanson (1996), is 0.13 mm and 2300 kg m$^{-3}$, respectively.

However, with the assumption that the river is likely to be adjusted to transporting the coarser-grained sediment, the size of 0.33 mm and specific density of 2650 kg m$^{-3}$ was utilised in the calculations of $\tau_{cr}$, $\tau_{0*}$ and $Q_s$ for all Diamantina River cross sections measured in this study, unless otherwise stated.

6.3 Results

The study reach of the Diamantina River has been divided into five zones: upstream of Janets Leap and Hunters Gorge (I); immediately upstream of Janets Leap and Hunters Gorge (II); within Janets Leap (III); immediately downstream of Janets Leap and Hunters Gorge (IV); and Birsdsville 300 km downstream of Janets Leap and Hunters Gorge.
Channel slopes or water surface slopes were not measured directly for this study. A water slope of 0.00013 was however calculated from the 2009 flood at a stage height of 6.36 m (QLD DERM, pers. comm., February 2013) and is utilised throughout as it is close to the long-distance slope through the study reach of 0.0002 calculated from Shutter radar topography mission (SRTM) data. Discharges were estimated using surveyed cross sections. Manning’s $n$ was estimated for each cross section based on previous work at Hunters Gorge and Janets Leap by Bullard et al. (2007), but also cross-checked with field and photo observations and comparison to channel reaches of known roughness coefficients (i.e. Hicks and Mason, 1991).

This results section (Section 6.3) is partitioned into four sub-sections: 1. descriptive geomorphology; 2. topographic cross sections; 3. vegetation; and finally 4. bankfull $H$ number calculations. All cross sections, hydraulic calculations and site photos are presented in Appendices A, B and C, respectively.

### 6.3.1 Descriptive geomorphology

Downstream variations in geomorphology along the Diamantina River are considerable. Some reaches are dominated by one large (primary) channel, whereas others comprise over fifteen smaller (secondary) channels. For the channel type classification utilised in this thesis for the Diamantina River, tertiary channels are confined to within the inter-channel lignum areas. A common characteristic amongst all primary, and many secondary channels downstream of Zone I, however, is their general cross-sectional form. They are typically canal-like in that they are quite straight and relatively narrow and deep (Appendix A).

#### 6.3.1.1 Zone I

Zone I is ~18 km upstream of Janets Leap and Hunters Gorge (Figure 6.1). Field accessibility to the eastern portion of the river in this zone was a problem, therefore only secondary channels a minimum of 2 km away from the primary channels were surveyed. There are two primary channels in this zone and these are more meandering than downstream of here in the study area. The floodplain surface is relatively flat but there are frequent minor undulations. Heading west towards the primary channels, these
undulations turn into secondary channels that twist and turn across the floodplain. In the absence of water, they can be most clearly traced on Google Earth due to the associated *Eucalyptus coolabah* trees that line the banks. Examples of the secondary channels surveyed in Zone I are shown in Appendix C photos a), b) and c).

### 6.3.1.2 Zone II

The Diamantina River, with its extensive channel network that can be up to 15 km wide upstream, is funnelled into two adjacent bedrock constrictions leaving a floodway between them totalling < 900 m wide where the Goyder Range and Hamilton Ranges almost meet (Figure 6.1a). Zone II represents the region where the river is guided towards these two constrictions.

Bullard et al. (2007) defines two types of inter-channel terrain. Within Janets Leap and the ~1 km upstream of it, a very low surface consists of undulations of grey cracking clays with dense networks of lignum, specifically *Meuhlenbeckia florulenta* (syn. *M. cunninghamii*) and scattered *E. coolabah* trees, a surface Bullard et al. (2007) refer to as a ‘lignum inter-channel area’, a term adopted here. The second type consists of low floodplain typically higher than the lignum inter-channel area, and vegetated with sparse grasses.

There appears to be one primary channel in Zone II, which bifurcates approximately 1.8 km upstream of Hunters Gorge. The main (right hand, or western) channel flows directly into the westernmost waterhole (PC5; Figure 6.1c). The typical morphological expression of the primary channel can be seen in Appendix C photo d). Examples of secondary channels surveyed in Zone II are shown in Appendix C photos e), f), g) and h).

### 6.3.1.3 Zone III

At the point where the Goyder Range and Hamilton Ranges are closest, they are separated by two gorges between which is a ~1 km wide residual bedrock outcrop. The western gorge, Hunters Gorge, is 130 m wide and the eastern one, Janets Leap, is 700 m wide. In flood the river utilises both gorges, occupying the western one with a waterhole.
(PC5) that essentially laps the base of the bedrock outcrops on each side, while an additional arrangement of four primary (PC1 to PC4), and multiple secondary channels squeeze through the eastern gorge. Photographs of where PC3 was surveyed along Transect 2 and PC1 was surveyed along Transect 3 are shown in Appendix C (photos i and j, respectively).

The western waterhole (PC5) is directly linked to the eastern gorge by a channel that traces the base of the northern face of the outcrop cliff, which becomes PC4. The other channels within the eastern gorge are connected by one channel that travels perpendicular to the main direction of flow. It can be clearly seen in Figure 6.1a (labelled ‘Hunters Gorge’) because at the time the satellite imagery was taken, water occupied this linking channel as well as PC1 to PC5 and numerous tertiary channels.

The lignum inter-channel areas can be difficult to navigate when the *M. florulenta* shrubs are thriving, as they were during the 2012 field season. The growth habit of these shrubs is very dense, however, they are generally confined to the banks and tops of the undulations, leaving these tertiary channels relatively clear (Figure 6.2). Small (< 20 cm high) opportunistic herbaceous shrubs are commonly present on the bed of tertiary channels.

![Figure 6.2: Examples of the inter-channel lignum areas within Zone III. a) Dense *M. florulenta* on the left bank of PC4 along Transect 3, which is also the western edge of a lignum inter-channel area. b) Looking slightly upstream from atop one of the many undulations. c) Looking upstream and d) downstream tertiary channels.](image-url)
During high flood stages, primary, secondary and tertiary channel definition is lost and Janets Leap simply becomes the passage of flow (Figure 6.3). Flow is temporarily separated as it divides around the bedrock outcrop, but immediately rejoins downstream.

![Figure 6.3: Oblique aerial view of Janets Leap and Hunters Gorge during flood, looking west towards the right bank. Image (date unknown) accessed 19 January 2013 from http://watermonitoring.derm.qld.gov.au.](image)

### 6.3.1.4 Zone IV

Downstream of the Janets Leap and Hunters Gorge bedrock constrictions, the Diamantina River immediately laterally expands, but not to the extent seen upstream of the confinement. PC4 appears to be the primary channel travelling away from the bedrock confinement. While analysis of aerial imagery indicates PC2 is larger, its definition dissipates in a downstream direction whereas PC4 continues, remains clearly distinguishable from the surrounding floodplain and is essentially straight for approximately 10 km, with only three meanders in this distance. It is flanked on both banks by a ~300 m wide vegetated floodplain, that is occupied by numerous secondary channels running parallel to PC4. Lines of *E. coolabah* trees occupy the banks of PC4 and secondary channels. The typical morphological expression of PC4 downstream of Janets Leap is shown in Figure 6.4, with additional examples shown in Appendix C, photos k) and l).
6.3.1.5 Birdsville reach

The ~300 km of the Diamantina River between Zone IV and the Birdsville reach have not been investigated in this study, but can be clearly traced on Google Earth. As it traverses south through the Sturt Stony Desert of this part of central west Queensland, the lateral extent of the floodplain between Hunters Gorge/Janets Leap and a second significant bedrock confinement at Monkira exceeds 40 km in places.

After the Diamantina River takes a right turn to head almost WSW approximately 100 km downstream of Monkira it abandons its extensive anabranching pattern to become one dominant channel with an occasional secondary channel. Site Z is located in this reach dominated by mostly single channels.

The primary channel surveyed at Site Z is well defined, about 50 m wide and it meanders. In further contrast to much farther upstream, both banks at Site Z are stepped and well vegetated with shrubs above and below the step. The channel is shown in Appendix C (Photo m). There are scattered secondary channels to the right (northwest) of the surveyed channel. Their general orientation is also southwest, but most of them appear disconnected, and are probably only linked during high flood stages.

6.3.2 Topographic cross sections

Within Janets Leap and Hunters Gorge, of the five primary channels (PC1 to PC5, left to right, east to west), PC1 to PC4 were all surveyed at least twice. PC5, the western waterhole in Hunters Gorge, was not surveyed and therefore not used for hydraulic
calculations. Downstream variations of the primary channel immediately upstream of Janets Leap and Hunters Gorge, and PC4 downstream of the gorges have also been captured by Sites R and X, respectively. The topographical cross-sectional data are presented in Table 6.1 and Appendix A.

### 6.3.2.1 Zone I

Eighteen kilometres upstream of Janets Leap and Hunters Gorge, the five secondary channels captured by Transect 1 have varying morphologies (Figure 6.5). Bankfull cross-sectional areas and estimated discharges range from 4 to 36 m$^2$ and 1 to 10 m$^3$ s$^{-1}$, and the two additional secondary channels (Sites P and Q, respectively) exhibit better definition than the secondary channels along Transect 1 along the 170 m and 150 m studied reaches, respectively (Figure 6.5). For all surveyed channels in Zone I, W/D ratios range from 7 (Q1) to 66 (Transect 1 SC1).

### 6.3.2.2 Zone II

Cross sections down a ~1.9 km reach of the primary channel upstream of Janets Leap and Hunters Gorge (Site R) reveal a deep and relatively narrow, but very well defined channel (Figure 6.6) directly feeding the westernmost waterhole (PC5). Bankfull cross-sectional area progressively decreases from R1 (185 m$^2$, Q = 162 m$^3$ s$^{-1}$) to R7 (77 m$^2$, Q = 43 m$^3$ s$^{-1}$) but W/D remains steady between 6 and 8 across the seven measured cross sections. The secondary channels represented by Sites T, U, V and W are approximately half the width, and half the depth (at bankfull) of Site R (the primary channel) (Figure 6.6). Small tertiary channel networks at bankfull height border the secondary channel at Site V.

### 6.3.2.3 Zone III

Transects 2 and 3 reveal a highly anabranched fluvial system within Janets Leap (Figure 6.7). It is understood that at low flows the channels fill from right (west) to left (east) (Bullard et al., 2007). The primary channels are each unique in form, and even within the distance between the two transects of ~300 m, morphological variations occur. For all except PC1, bankfull cross-sectional area and W/D ratios increase from 365 to 478
m$^2$ and 35 to 49, respectively (PC2), 22 to 50 m$^2$ and 4 to 16, respectively (PC3), 85 to 465 m$^2$ and 14 to 46, respectively (PC4) heading downstream. PC3 is the smallest of the primary channels ($Q_{bf} = 23$ m$^3$ s$^{-1}$ at Transect 3) and PC2 has the greatest capacity for discharge ($Q_{bf} = 389$ m$^3$ s$^{-1}$ at Transect 3).

6.3.2.4 Zone IV

Two channels have been surveyed at eight (Site X) and five (Site Y) locations within 4 km of the downstream end of Janets Leap and Hunters Gorge. Site X corresponds to PC4. While Site Y is considered a secondary channel, technically it is a spatially temporary bifurcation of PC4 (and Site X), departing from the primary channel between X3 and X4, and rejoining it again approximately 300 m downstream of X8. Bankfull cross-sectional areas across the five surveyed cross sections at Site Y reveal uniformity, around 63 m$^2$, despite differing morphologies (W/D ranges from 10 to 35, $Q_{bf} = 23$ to 39 m$^3$ s$^{-1}$), as seen in Figure 6.9. Bankfull cross-sectional areas, W/D ratios and estimated discharges for the Site X cross sections range between 57 and 227 m$^2$, 10 to 17 and 28 to 180 m$^3$ s$^{-1}$, respectively.

A complete cross section between the Goyder Range and the Hamilton Ranges was measured by Bullard et al. (2007) (Transect 4). It was surveyed 2 km downstream of Janets Leap and Hunters Gorge, and is used (Figure 6.8), with permission from the lead author.

6.3.2.5 Birdsville reach

Approximately 330 km downstream of Janets Leap and Hunters Gorge, the Diamantina River is defined by one channel (Site Z), and this channel has a width of just over 50 m and maximum depth (at topographically-defined bankfull) of 9.8 m, a W/D of 10 and a cross-sectional area of 285 m$^2$ (Figure 6.10). Morphologically, the channel proportions here are similar to those seen in Zones I to IV, yet the channel is larger with an estimated bankfull discharge of 184 m$^3$ s$^{-1}$. 
Figure 6.5: Several secondary channels were surveyed in Zone I. Five different but neighbouring channels were captured by Transect 1, and two additional channels were surveyed at five (Site P) and three (Site Q) locations. Each channel within Transect 1 is prefixed with ‘SC’ for secondary channel. Refer to Figure 6.1 for locations.
Figure 6.6: The primary channel immediately upstream of Janets Leap and Hunters Gorge (Site R) and four secondary channels (Sites T, U, V and W) were surveyed in Zone II. Refer to Figure 6.1 for locations.

Figure 6.7 (next page): Two transects were surveyed in Zone III (Janets Leap). Refer to Figure 6.1 for locations. Each channel within each transect is prefixed with either ‘PC’ or ‘SC’ for primary or secondary channel, respectively and TC1 to TC4 denote the tertiary channels hydraulic parameters were calculated for (see Section 6.3.4). The dotted lines indicate the elevations between transect sections are not comparable. That is, due to accessibility and logistical issues, sections separated by a dotted line were not joined up and the spaces between the sections are indicative only of the distance between the sections.
Figure 6.8: Cross section between the Goyder Range and Hamilton Ranges 2 km downstream of Janets Leap and Hunters Gorge (Bullard et al., 2007).
Figure 6.9: One of the primary channels (Site X, PC4) and another secondary channel (Site Y) were surveyed in Zone IV. Refer to Figure 6.1 for locations.
6.3.3 Vegetation

In contrast to the Northern Plains rivers to be discussed in the next chapter and where *Eucalyptus camaldulensis* or in some places *Melaleuca* spp. predominate, the most common tree found along the banks and floodplains in proximity to the Diamantina River channels is the *E. coolabah*, a species that prefers muddy channel, bank and floodplain sediment. Importantly, no trees grow on the bed of the Diamantina channels; they are confined to the upper third and tops of banks.

Research indicates *E. camaldulensis* has no soil preferences (Beadle, 1981), but there is a distinct shift in dominant tree species between sands or gravelly-rocky soils (*E. camaldulensis*) to clay soils (*E. coolabah*), and this explains why the latter is the main tree species along the Diamantina River. However, Silcock (2009) notes that *E. camaldulensis* trees are present around waterholes in the Channel Country.

A primary objective of cross section site selection was to obtain a range of channel styles between which the H number may vary. Related to this was the density of bank vegetation, to specifically investigate whether there is any noticeable relationship between observed bank vegetation densities and channel dimensions. Examples of dense vegetation are shown in Figure 6.2, and less dense vegetation in Figure 6.4. Table 6.2 summarises the studied sites and cross sections.
Table 6.2: Channel type and vegetation density. Refer to Figure 6.1 for locations and Figures 6.6 and 6.9 for morphology.

<table>
<thead>
<tr>
<th>Site</th>
<th>Channel type</th>
<th>Mean bankfull W/D ratio (no. of cross sections)</th>
<th>Vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>Primary</td>
<td>8 (7)</td>
<td>Dense</td>
</tr>
<tr>
<td>T, U, W</td>
<td>Secondary</td>
<td>11 (5)</td>
<td>Dense</td>
</tr>
<tr>
<td>X</td>
<td>Primary</td>
<td>13 (8)</td>
<td>Less dense</td>
</tr>
<tr>
<td>V, Y</td>
<td>Secondary</td>
<td>15 (6)</td>
<td>Less dense</td>
</tr>
</tbody>
</table>

Revisiting Figures 6.5 to 6.10 with this comparison of dense and less dense vegetation in mind, cross-sectional form is typically deep and narrow, irrespective of bank vegetation density. That being said, however, Table 6.2 indicates an increase in the density of bank vegetation is associated with a marginally lower W/D ratio.

Between the primary channels in the gorge (Zone III) and immediately upstream (Zone II) are extensive inter-channel networks that are often associated with extremely dense patches of the perennial shrub *Muehlenbeckia florulenta*. In Zones I and V, *M. florulenta* was absent, and was only scattered in Zone IV. This monoecious shrub is native to inland Australia and thrives in arid and semi-arid wetland habitats that experience periods of intermittent flooding and drying out. In some locations, the density of *M. florulenta* stems was so great that in the 2012 field season it was impassable without a machete. Most floodplain surfaces that season were also well vegetated with numerous grasses.

### 6.3.4 H number calculations

The H number theoretically demonstrates how efficient, in terms of sediment transport, alluvial channel flow uses energy (Huang and Chang, 2006). It is a relatively simple calculation requiring inputs of critical and actual shear stress, and W/D ratio. For convenience, Equation 4.9b is repeated here:

\[
H = \frac{\tau / \tau_{cr} - 1}{W/D - 2}
\]

Figure 6.11 is a plot of the bankfull discharge, W/D ratio and H numbers of all surveyed cross sections of the Diamantina River. It is not to be mistaken for a trend plot; the points for each cross section are to be viewed individually, although each point is plotted left to right across the figure roughly in rank order downstream. The
uncertainty ranges are derived from the values in Table 5.1 and Table 5.2 and subsequent text in Section 5.3.2.1. The average $H$ number estimated for bankfull conditions for the total number of cross sections is 0.92, well above the optimum of 0.30. Even with the uncertainty analyses, just 19% of the cross sections are at or within range of 0.30. Associated W/D ratios are also low, averaging 19, ranging from 4 (Transect 2 SC8) to 78 (Transect 4 PC2).

Indeed, the decision to utilise a grain size of 0.33 mm (instead of 0.13 mm; see Section 6.2) and specific density of 2650 kg m$^{-3}$ (instead of 2300 kg m$^{-3}$; see Section 6.2) was justified. Using 0.13 mm and 2300 kg m$^{-3}$ as inputs into the $H$ number model resulted in values of $H$ even more far removed from the optimum of 0.30 than those reported here.

Numerous lignum inter-channel area tertiary channels were surveyed during the process of measuring the primary and secondary channels within Zone III (e.g. Figure 6.2c, d). The bankfull hydraulic parameters for four tertiary channels from Transect 3 (Figure 6.7) have been calculated and are summarised in Table 6.3 below (full results in Appendix B Table B.1). These small channels are not included in Figure 6.11. A Manning’s $n$ estimate of 0.10 is utilised, in line with Bullard et al. (2007) and field observations. Interestingly, all reported tertiary channel $H$ number calculations, in contrast to their primary and secondary channel counterparts discussed below, are at or close to the optimum of 0.30 at bankfull.

<table>
<thead>
<tr>
<th>Cross Section</th>
<th>Maximum flow depth (m)</th>
<th>Total surface width (m)</th>
<th>W/D ratio</th>
<th>$Q$ (m$^3$s$^{-1}$)</th>
<th>$H$ Reported value</th>
<th>Uncertainty</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC1</td>
<td>1.27</td>
<td>8.02</td>
<td>10.57</td>
<td>0.55</td>
<td>0.30</td>
<td>0.17</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>TC2</td>
<td>1.05</td>
<td>5.81</td>
<td>7.95</td>
<td>0.37</td>
<td>0.39</td>
<td>0.23</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>TC3</td>
<td>1.35</td>
<td>9.42</td>
<td>11.58</td>
<td>0.74</td>
<td>0.30</td>
<td>0.17</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>TC4</td>
<td>1.08</td>
<td>8.98</td>
<td>13.17</td>
<td>0.53</td>
<td>0.21</td>
<td>0.12</td>
<td>0.29</td>
<td></td>
</tr>
</tbody>
</table>

When the $H$ number data for the primary and secondary channels are considered in clusters according to proximity to the constriction (Figure 6.11), the channels most upstream (18 km) of the constriction (the orange cluster in Figure 6.11) average $H = 0.20$ or close to the optimum (0.30), those leading towards the constriction (just 0.5 to
2.5 km upstream) (brown) average $H = 2.96$ and are therefore, well above optimum, those within the constriction (green) average $H = 0.74$ and are much closer to optimum, and those most downstream of the constriction (pink) average $H = 0.82$, farther away from the optimum again. An unpaired samples t-test was conducted to compare the average $H$ numbers from the green (0.74) and pink (0.82) clusters. There was not a statistically significant difference in the scores (p-value = 0.35, $\alpha = 0.05$).

To investigate what drives the variations in $H$ numbers between cross sections that look very similar in the field, clusters of different reaches are compared. Figure 6.12 compares Cross Sections R1, R2, R3 with X5, X6, X8, and Figure 6.13 compares Cross Sections Q1 with Q2 and Q3. Sites R and X are well-defined primary channels, Site Q, a secondary channel, is not as well defined. As expected, it is apparent in both figures that lower W/D ratios are associated with the higher $H$ numbers. Figure 6.14, where there is no vertical exaggeration to distort the correct form of the cross sections, exemplifies this. The sites chosen for illustration in Figures 6.12 and 6.13 were selected because, as will become apparent below, they illustrate differences between calculated $H$ numbers and optimum values. Thereby, they contrast channel characteristics for divergent $H$ number values in the study area.
Figure 6.11: Bankfull discharge (blue crosses), W/D ratio (red crosses), estimated Manning’s n (grey crosses) and H numbers (orange, brown, green and pink crosses) of all surveyed cross sections of the Diamantina River. Error bars attached to the H numbers capture the range of uncertainty derived from the H number inputs (τ, τcr, width, depth). Refer to Figure 6.1 for locations. This is not a trend plot although it does roughly trend downstream from left to right.
Figure 6.12: Bankfull discharge, W/D ratio and $H$ numbers of Cross Sections R1, R2, R3, X5, X6 and X8. Error bars attached to the $H$ numbers capture the range of uncertainty derived from the $H$ number inputs ($\tau$, $\tau_{cr}$, width, depth).

Figure 6.13: Bankfull discharge, W/D ratio and $H$ numbers of Cross Sections Q1, Q2 and Q3. Error bars attached to the $H$ numbers capture the range of uncertainty derived from the $H$ number inputs ($\tau$, $\tau_{cr}$, width, depth).
Figure 6.14: Comparison highlighting the variation in cross-sectional form for a selection of surveyed Diamantina River cross sections with varying W/D ratios and consequently, varying $H$ numbers. Importantly, these sections are drawn with no vertical exaggeration so they represent correct cross-sectional perspectives.

6.3.5 Comparing H number calculations with possible equilibrium conditions

Figures 6.15 and 6.16 depict the equilibrium bedload transport capacity ($Q_s$; Equation 4.12) versus W/D ratio curves for the cross sections chosen for representation in Figures 6.12 and 6.13. As discussed in Section 4.6, $H = 0.30$ (stationary equilibrium) $Q_s = Q_{s\text{ max}}$ where $S = S_{\text{min}}$ under bankfull conditions is represented by the peak of the curve. It would be extremely useful to compare the equilibrium bedload values represented by the curves in Figures 6.15 and 6.16 ($Q_s$) with accurately measured bedload for those same reaches of channel. This would provide definitive evidence as to whether these channels are, in terms of their bedload discharge, in a state of mass-balance equilibrium (i.e. in either dynamic or stationary equilibrium where the sediment load entering a reach equals that exiting). However, bedload is notoriously difficult to measure accurately, as it is to estimate accurately with hydraulic equations (e.g. Gomez, 1991). There was no prospect of undertaking the complex task of measuring bedload at multiple sites during this field study conducted in the dry season. Furthermore, estimates from the application of existing bedload functions would require accurately gauged sites, and this study has none of those either.

It is clear from additional independent evidence that the study reaches of the Diamantina are effectively in mass-balance equilibrium. Large trees (mostly $E.\ coolabah$) growing at the top of the channel banks are slow growing and estimated to be more than one hundred years old, yet they are not showing any signs of being inundated with alluvium. Clearly, the channels of the Channel Country rivers are not incising either; they overtop their banks and inundate vast areas of floodplain on a regular basis, especially so for rivers in such an arid region. In other words, the channels and floodplains of the Diamantina River are neither incising nor aggrading to any significant
extent. This evidence is corroborated by independent dating of alluvial accretion where even upstream of rising tectonic structures accretion rates are very low (Jansen et al., 2013). Other floodplain dating supports this (Nanson et al., 1988; Fagan and Nanson, 2004). Furthermore, despite extensive flooding on a decadal basis, time lapsed aerial photographs over more than 50 years show that the Channel Country rivers, overall, have been highly stable in planform (Nanson et al., 1988; Nanson, pers. comm., September 2013). This means that the actual bedload yield ($Q_{sa}$), if known and plotted onto Figures 6.15 and 6.16, would be equal to or <$Q_{s\text{ max}}$. That is, such values would plot somewhere at or below the peak of each curve. If $Q_{sa}$ were to plot above the curve, bedload would be in excess of any possible equilibrium on the curve and these reaches would be accreting. According to the plots in Figure 6.15, $Q_{sa}$ for Cross Sections R1, R2 and R3 will be < 0.003 m$^3$ s$^{-1}$ and for Cross Sections X5, X6 and X8, < 0.001 m$^3$ s$^{-1}$, or < 259 and < 86 m$^3$ 24 hr day$^{-1}$, respectively. Furthermore, as $H$ is > 0.30 in all cases, this means, from inspection of Equation 4.9, that for given values of excess flow-shear, W/D ratios are too low for stationary equilibrium to prevail. Hence $Q_{sa}$ in each case will fall somewhere on or close to the curve but to the left of the curve peak ($Q_{s\text{ max}}$). The higher the value of $H$, the farther to the left because a greater adjustment in W/D ratio is required to reach the optimum state ($Q_{s\text{ max}}$). Thus, $Q_{sa}$ for Cross Sections X5, X6 and X8 will be closer to the peak of the curve relative to Cross Sections R1, R2 and R3.
**Figure 6.15**: Equilibrium (dynamic and stationary) bedload transport capacities at Cross Sections R1, R2, R3, X5, X6 and X8. Refer to Figure 6.1 for locations. The vertical dashed line represents position of the measured W/D ratio.

**Figure 6.16**: Equilibrium (dynamic and stationary) and field bedload transport capacities at Cross Sections Q1, Q2 and Q3. Refer to Figure 6.1 for locations. The vertical dashed line represents position of the measured W/D ratio.
Assuming a constant W/D ratio, consideration of Equation 4.9 indicates significant changes to \( H \) require changes to \( \tau/\tau_{cr} \), which ultimately means changes to slope and/or sediment size, as these are the varying parameters in \( \tau \) and \( \tau_{cr} \). If the slope estimate of 0.00013 for the Diamantina is erroneous, this of course affects \( H \). However, an exceptionally low slope, say half of the utilised estimate (i.e. as low as 0.000065), only results in a reduction for Cross Section R2 from \( H = 3.40 \) to \( H = 1.62 \), still very much larger than the equilibrium value of 0.30. This indicates that the estimate of sediment size (hence \( \tau_{cr} \)) is the parameter most likely to have resulted in such large \( H \) values. To explore this, values of sediment size input into Equations 4.9b (\( H \) number model) and 4.13 (coefficients \( K_1, K_2, K_3 \)) for two cross sections were varied to investigate the effect that larger (less transportable) values of sediment size would have on the \( H \) number, \( Q_{s\text{max}} \) and W/D ratio at \( Q_{s\text{max}} \) (Table 6.4). Clearly, increasing the sediment size causes \( H \) to approach 0.30 and, importantly, the W/D ratio at \( Q_{s\text{max}} \) approaches the W/D ratio measured in the field.

**Table 6.4:** Resulting values of \( H \), \( Q_{s\text{max}} \) and W/D ratio at \( Q_{s\text{max}} \) when the sediment size (\( d \)) input into Equations 4.9b and 4.13 is varied for Cross Sections R2 and X5. Note that \( d = 0.00033 \) m is the average sand size used in the other calculations presented in this chapter, hence it is the lowest value used in this table.

<table>
<thead>
<tr>
<th>Cross Section R2 (field W/D = 8)</th>
<th>Cross Section X5 (field W/D = 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d \ (m) )</td>
<td>( H )</td>
</tr>
<tr>
<td>----------------</td>
<td>--------</td>
</tr>
<tr>
<td>0.00033</td>
<td>3.40</td>
</tr>
<tr>
<td>0.0005</td>
<td>2.19</td>
</tr>
<tr>
<td>0.001</td>
<td>1.01</td>
</tr>
<tr>
<td>0.002</td>
<td>0.42</td>
</tr>
<tr>
<td>0.0025</td>
<td>0.30</td>
</tr>
</tbody>
</table>

As explained above, any attempt to compare the values estimated here as optimal bedload values (\( Q_{s\text{max}} \)) with actual bedload measurements (\( Q_{sa} \)) would be desirable but simply not possible. Nevertheless, the manipulations of bedload grainsize in Table 6.4 do reveal how these channels are likely to be adjusting. This interpretation of adjustment will be outlined in the discussion below.
6.4 Discussion

In this discussion, because vegetation is an exogenic variable (not one of the variables in the three basic flow equations that predict the form of self adjusting channels in unconsolidated and relatively uniform sediment (Huang and Nanson, 2000), and because it can have an impact on channel morphology and hence channel equilibrium, vegetation patterns on the study reaches are briefly discussed before the theoretical channel efficiencies (H numbers) that have been obtained are assessed.

6.4.1 Vegetation and the clay-rich channel boundary

In terms of bankful or effective discharge, all the Diamantina River channels studied here are topographically-defined, as opposed to some rivers having their flow cross-sections altered by in-channel vegetation (see Chapter 7), where the vegetation can confine flow and create a channel boundary significantly different to the alluvial boundary (e.g. Tooth and McCarthy, 2004). The Diamantina channel cross sections vary from being associated with locally very sparse to mostly dense or very dense vegetation, but with vegetation in nearly all cases confined to the top of the banks and thereby leaving the channels themselves relatively free of obstacles. Although free of vegetation, the channels are formed in dense cohesive clays and appear very similar in form throughout the study reach (Section 6.3.3). They are inset in a floodplain that even in the confined reaches of Hunters Gorge and Janets Leap, consists of 2 - 6 m of clay-rich mud, the same thickness as the channels are deep (Nanson et al., 1988). The beds of the channels also consist of mud and sometimes indurated coarse sand, with isolated and surficial sand bars that have probably been deposited during declining flows. The channel-boundary clays are extremely difficult to hand excavate and can break mechanical augers. Such material clearly has a profound impact on channel form. Interestingly, however, mean W/D ratios in those channels with a dense bank-top vegetation of lignum (M. florulenta) have W/D ratios somewhat lower than those with less dense vegetation, so it appears that, despite such a cohesive clay boundary, there is some effect from the vegetation (Table 6.2). In summary, therefore, while bank-top vegetation plays some role, the alluvial banks and indeed even the channel beds are formed of sufficiently cohesive clayey mud as to create a surprisingly uniform, narrow and deep, channel morphology.
6.4.2 Channel efficiency (H number)

The general appearance of many of the primary and secondary channels studied along the Diamantina River would suggest that they are sculpted into almost ideal canal-like cross sections that exhibit relatively little variation along individual reaches. This might lead to the expectation that they operate at or close to stationary equilibrium. However, as shown in Figures 6.11, 6.12 and 6.13, in most cases their calculated H numbers are above and in some cases well above 0.30.

As stated by Nanson and Huang (2008, p. 934): The H number measures the available energy spent overcoming friction from both the channel bed and banks for a given sediment load, and the situation of H = 0.30 means that...the energy of alluvial channel flow reaches a minimum level for transporting a given water and sediment load. ...the H number can be regarded as a quantitative index for directly measuring the stability and the potential development of complex channel forms in situations where H ≠ 0.30. This theoretical determination relates to self-forming alluvial channels where there are no exogenous variables such as confining vegetation or a particularly resistant boundary that will distort a result obtained purely from the three basic flow equations (continuity, flow-shear and bedload transport). High values of τ mean that channels can potentially transport considerable bedload and this can result in H > or >> 0.30, with channel degradation (incipsion) being a likely outcome.

In Figure 6.12 Cross Sections R1, R2 and R3 have very low W/D values (< 10) and large H numbers (3.40 - 4.25), suggesting they would plot well to the left of the peak of the equilibrium curves in Figure 6.15, and indicating they could have substantial surplus energy and, therefore, be capable of significant degradation. Cross Sections X5, X6 and X8 have higher W/D values (15 - 20) and much lower H numbers (0.67 - 0.79) (Figure 6.12) and would probably lie relatively closer to (below and to the left of) the equilibrium curve peaks (Figure 6.15). They too, though, would be capable of incision. As revealed above, however, these channels have been stable for decades and probably centuries, and they show no evidence of incision.
The reason for selecting and analysing a large number of cross sections of the Diamantina near Hunters Gorge and Janets Leap was to see if various locations upstream, within and downstream of these bedrock constrictions would yield contrasting results in terms of channel efficiency and hence the prevailing equilibrium conditions. Figure 6.11 suggests that there are what appear to be some systematic differences between at least some of those cross sections that have been differentiated into the colour-coded clusters upstream to downstream. It appears that the most upstream channels (orange in Figure 6.11) have low $H$ numbers and this may mean that this section of the river may be relatively inefficient and be gradually aggrading. The three remaining colour clusters have $H$ numbers well above 0.30 and hence they have what appears to be excess shear. Those immediately above the constriction (the brown cluster) appear to have the greatest overall $H$ numbers, and it is unclear why this should be. The last two clusters (green and red) within and immediately downstream of the constriction are higher than 0.30 and not statistically different from one another.

An interesting set of results was obtained for the lignum inter-channel area tertiary channels in Table 6.3 ($H$ numbers very close to 0.30). These small channels are not cut deeply into the cohesive clayey floodplain but are inset less than 1.5 m below the surface. The self-mulching clays that characterise the soils of Channel Country floodplains form a boundary of abundant aggregates of pelleted mud that can form a bedload when floodwater reach these small channels (Nanson et al., 1986, 1988).

While some sites warrant discussion individually, such as lignum inter-channel area tertiary channels and Sites R and X in Figures 6.12, 6.13, 6.15 and 6.16, it is beneficial to consider the mud-dominated channels of the Diamantina as a whole. Figure 6.11 shows nearly all but the most upstream sites as having $H$ numbers greater than equilibrium values of 0.30. This would suggest the channels in this section of the Diamantina are capable of transporting higher $Q_s$ values than they do. There is, therefore, as shown above, considerable potential for incision. Clearly, however, the channels of the Diamantina, even in the most confined section, are not incising. While they may be eroding into the floor of the bedrock constriction, there is no appearance of this in the form of abandoned terraces hence this process, if occurring at all, must be very slow.
In developing an understanding of the flow conditions leading to the optimum transport of bedload it has been presumed that the Diamantina is transporting mud aggregates and/or sand particles with a \(d_{50}\) of 0.33 mm. This was assumed because this does represent the size of the sediment in the scattered sand bars present at low flow. However, the Diamantina appears to be transporting very little bedload (c.f. Gibling et al., 1998), probably almost none at high discharges when what little sand and pelleted mud visible on the dry riverbed is likely to move into suspension. There are four lines of evidence to support an almost total lack of bedload. Firstly, there are no extensive unconsolidated bed-material sheets or extensive bedforms present, even after large floods. Secondly, the channels are formed of a cohesive clay-rich mud boundary with abundant vegetation at the bank tops, a very resistant and stable combination. As a result, these anabranching channels are very likely adjusted to transporting mostly water over an erosion-resistant clay surface and thereby exhibiting relatively high flow efficiencies, with W/D values well below those of most bedload transporting systems. Thirdly, during the 1990 flood on Cooper Creek, attempts were made to measure bedload in Naccowlah Waterhole and its feeder channels at flows well over bankfull using a Helley-Smith bedload sampler. Despite numerous attempts, no bedload could be collected in the sampler leading to the conclusion that little or none was in transport (Nanson, pers. comm., September 2013). Finally, recent research around the Innamincka Dome, which obstructs Cooper Creek in its middle reach, demonstrates that almost no sediment from this 306,000 km\(^2\) fluvial system reaches Lake Eyre possibly because it is trapped in various sub-basins in the headwaters and middle reaches (Jansen et al., 2013).

The results presented in Table 6.4 provide a possible interpretation for the unusually high calculated \(H\) numbers for such stable, non-incising channels of the Diamantina. \(H\) numbers are calculated using critical flow-shear based on the bedload particle size. There is certainly some unconsolidated bed material being transported in the Diamantina channels and this is represented by the occasional sand bar and a scattering of loose pelleted clay particles over the bed in the form of a thin layer of ripples and dunes. Resolution of the three basic flow equations presumes that there is a mobile self-adjusting boundary. In reality, what limited bedload there may be initially probably goes into suspension at high flood stage. This would leave a flow largely free of bedload passing over a bed formed of cohesive clay. Because of the complex form of
sediment entrainment curves in very fine sediment (mud) it is difficult to determine the erosional resistance of such a boundary. Table 6.4 progressively increases the critical threshold of the grain size for the threshold for transport and shows that if these channels were formed of coarse clastic material, the material would be up to an order of magnitude larger (2.5 mm, Cross Section R2) and at least double (0.65 mm, Cross Section X5) the size that was assumed to be in transport (0.33 mm) for determining the $Q_s$ versus W/D ratio curves and for determining the $H$ numbers. It appears that the cohesive mud boundary, and to a lesser extent the role of the vegetation, are consolidating the boundary and distorting the operation of these channels in such a way that they are able to convey a much smaller bedload in narrow deeper channels with relative high excess flow-shear without destabilising.

6.5 Summary

The Diamantina River is a complex fluvial system. The main area of study here is a network of anabranaching channels, much like other portions of the river. However, the proximity of the Goyder Range to the Hamilton Ranges forces the > 6 km wide arrangement of anabranches through two bedrock confinements, the largest being just ~750 m wide (Janets Leap).

The channel cross sections studied are associated with sparse to dense bank-top vegetation and yet W/D ratios remain low and do not vary greatly. This indicates they have sediment- rather than vegetation-defined channel dimensions and that their bank and bed material is cohesive enough to form very stable low W/D ratio channels.

Numerous indicators suggest the Diamantina does not transport significant amounts of bedload despite having $H$ numbers well above equilibrium values. While the values upstream, within and downstream of the bedrock constriction vary, this variation is not attributed to the constriction. Indeed, the confinement does act as a nozzle, directing much of the flow into the more incised waterholes, but all of the Diamantina channels are alluvial (not bedrock), and have the capacity to resist, or counteract, the surplus energy without destabilising. It appears that the cohesive mud banks and the vegetation atop them serve to hold the channels together despite excessive $H$ numbers.
Chapter 7: channel morphology and estimated hydraulic adjustments along the Marshall and Plenty Rivers

7.1 Introduction

This chapter examines the hydraulic geometry of the sandy Marshall and Plenty Rivers located on the Northern Plains of the Northern Territory (Figure 7.1). Unlike the Diamantina’s channels which are narrow and deep, and inset in a muddy floodplain as is characteristic of suspended load rivers (Chapter 6), those on the Northern Plains, have large W/D ratios (commonly > 50 and many > 100) with wide active sandy beds with flow structures as evidence of bedload transport.

The purpose of this chapter is to assess hydraulic geometry and to examine how the calculated $H$ numbers relate to the optimal value of 0.30 in these sand-load rivers that vary between single thread and anabranching (Objectives 3 and 4, Chapter 1). The Marshall and Plenty Rivers also offer a stark contrast to the Diamantina River, and thereby an opportunity to further explore $H$ number model veracity (Objective 2, Chapter 1).

7.2 Site selection and methods

Together, the Marshall and Plenty Rivers drain a combined catchment area exceeding 18,000 km$^2$. The Plenty is a longer river, rising approximately 80 km farther west of the Marshall headwaters. The Marshall River rises in the Dulcie and Mopunga Ranges and the Plenty River in the Harts Range, both largely comprised of Proterozoic crystalline rocks but with the Dulcie and Mopunga Ranges also overlying exposed Palaeozoic sedimentary rocks (Freeman, 1986). The Marshall does carry a coarser bedload (mean bed material size of 1.3 mm compared to the Plenty’s mean size of 0.45 mm) partly due to its headwaters comprising coarser-grained rocks (Tooth and Nanson, 2004).
The Marshall and Plenty sand-load rivers, although different to each other (Figure 7.2), were selected for study as they offer a distinct contrast to the mud-transporting environment of the Diamantina River. The Marshall River alternates downstream along the study reach between single thread and anabranching whereas the Plenty is entirely single thread and sometimes beaded in planform. The anabranching on the Marshall varies between ridge-form and island anabranching (Figure 7.3) whereas the single channel beaded form of the Plenty is particularly pronounced in places (Figures 7.2e and 7.1h,i).

Cross sections with a prefix ‘M’ indicate they are on the Marshall River and those with a ‘P’ prefix are on the Plenty River. All cross sections are at least 40 kilometres downstream of the headwaters on the low-gradient plains typical of much of this region known as the Northern Plains. In the study area, the Marshall and Plenty Rivers are in close proximity to each other (Figure 7.1), have almost exactly the same gradient and usefully they have been the focus of previous detailed geomorphological research by Tooth (1997, 2000b), Tooth and Nanson (1999, 2000a, 2004).

All study locations were dry during the field season in April/May 2012. A total of 10 new cross sections were surveyed along the Marshall (4) and Plenty Rivers (6), to supplement the six previously surveyed on the Marshall and four on the Plenty by Tooth (2000b) and Tooth and Nanson (2004). Figure 7.1a illustrates these study reaches, with ten Google Earth Locations; Figure 7.1b, c, d, e, f, g, h, i, j and k. Within each location there are Cross Sections, and for multiple-channelled cross sections the prefix ‘S’ is used to identify the cross sections of individual sub-channels. These are labelled left to right 1, 2, 3 etc., e.g. Cross Section M2 has S1, S2, S3 (see Appendix D). For cross sections where the sub-channels are further subdivided, these are labelled a, b, c etc., e.g. Cross Section M2 has S1, S2a, S2b, S2c, S3a, S3b, S3c (see Appendix D).

At cross sections where morphology and/or vegetation did not provide a clear indicator of bankfull height, hydraulic parameters were calculated more than once, denoted by ‘T1’, ‘T2’ and ‘T3’ with increasing bank height for the lowest, second lowest and highest bank, respectively. For example, Cross Section M1a is associated with T1, T2 and T3 (see Appendix D).
Figure 7.1: a) Studied reaches of the Marshall and Plenty Rivers, Northern Plains, Northern Territory. Image sourced from Bing Aerial Maps (ArcGIS).
Figure 7.1 (cont.): Locations labelled b) to g) and h) to k) are presented in more detail, to show the geomorphology of individual cross sections along the Marshall and Plenty and Rivers, respectively. Images sourced from Google Earth.
Figure 7.2: a) and b) Oblique aerial view of the anabranching form of the Marshall River; c) and d) ridges on the Marshall River; and e) oblique aerial view of the beaded planform of the Plenty River. For additional photographs of the Marshall River see Figures 3.2bc,d and Appendix F Photos a - j, and for the Plenty River, see Figure 3.6b, Appendix F photos k - t.

Figure 7.3: A schematic of island-form and ridge-form anabranching channels (modified from Nanson and Knighton, 1996).

Channel gradients for the two rivers were taken from Tooth (2000b) and Tooth and Nanson (2004) (map gradients checked with field surveying), as were Manning’s n estimates (Table 7.1).
Table 7.1: Manning’s roughness coefficients estimates for the previously surveyed cross sections (from Tooth, 2000b and Tooth and Nanson, 2004). These values were used as a comparison to estimated values for the additional cross sections surveyed for this thesis.

<table>
<thead>
<tr>
<th>Cross Section</th>
<th>Manning’s n</th>
<th>Channel gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1, P2, P3</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td>P4</td>
<td>0.03</td>
<td>0.0013</td>
</tr>
<tr>
<td>M1, M2, M3, M4 sub-channels</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>M1, M2, M3, M4 total channel</td>
<td>0.045</td>
<td></td>
</tr>
</tbody>
</table>

Depending on cross-sectional width and morphology (i.e. number of sub-channels), up to four grab samples were collected from each cross section location and sieved at the University of Wollongong to determine average and median particle sizes for the bed material (size fractions and method outlined in Section 5.3.1). Given the overall general consistency in sediment size, the $d_{50}$ fraction is considered representative and thus employed in the critical shear stress calculations (Appendix E). The bed material size on the Marshall River averaged 1.3 mm whereas that on the Plenty was significantly finer and averaged 0.45 mm.

Vegetation surveys were undertaken, as it was intended to further explore the finding on by Jansen and Nanson (2004, 2010): that the most effective discharge for sediment transport along Magela Creek averages 2.1 times bankfull. Bank-top trees were found to constrain these flows over the channel bed, making possible effective discharges that appear to be well in excess of that determined by the alluvial-defined bankfull condition. Stem density, basal area coverage, dominance and absolute frequency of trees along an in-channel ridge at Cross Section M5 on the Marshall River was measured using the point-centred quarter method (PCQM), originally adapted by Curtis (1950) for ecological use. The method is discussed by Cottam et al. (1953), Cottam and Curtis (1956) and Müller-Dombois and Ellenberg (1974), and summarised in Figure 7.4. Because of the linear nature of riparian vegetation that is distributed along river banks, in some locations it was deemed more practical, and equally suitable, to undertake simple linear surveys, and thereby instead measuring distances between stems, and recording stem circumferences. Table 7.2 shows where these were done.
Figure 7.4: Simplified diagram of the point-centred quarter density method. Quadrat labeling is designated by distance from sampling point to stem; the quadrat with the shortest distance = Quadrat 1, the quadrat with the next shortest distance = Quadrat 2, etc. (Cottam et al., 1953). From the point, distances are measured to the closest tree in each quadrat to give the stem density and frequency. The species and breast-height circumference of the closest tree in each quadrat is recorded.

Table 7.2: Locations where linear surveys capturing species, distances between stems and their circumferences. Refer to Figure 7.1 for study sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>M4u</td>
<td>Across the channel</td>
</tr>
<tr>
<td>M4</td>
<td>Left bank</td>
</tr>
<tr>
<td></td>
<td>In-channel ridge</td>
</tr>
<tr>
<td></td>
<td>In-channel ridge</td>
</tr>
<tr>
<td></td>
<td>In-channel ridge</td>
</tr>
<tr>
<td></td>
<td>In-channel ridge</td>
</tr>
</tbody>
</table>

7.3 Results

The results are partitioned into two sub-sections; the Marshall River 7.3.1 and the Plenty River 7.3.2. Within each sub-section further subdivisions include: 1. topographic cross sections; 2. vegetation; and finally 3. bankfull H number calculations. Unlike the previous chapter, the limited number of sites and their relative similarity means that there are no sections dedicated to describing the geomorphology of individual sites on the Marshall, and Plenty Rivers. The general geomorphology of the two rivers is addressed at various points in the chapter. All cross sections, hydraulic calculations, and photos from the studied Marshall and Plenty Rivers are presented in Appendices D, E and F, respectively.

7.3.1 Marshall River

The Marshall River rises in the Dulcie and Mopunga Ranges and drains a ~3500 km² catchment before becoming the Hay River at its confluence with Arthur Creek. The
The study reach is characterised by numerous channels dividing and rejoining around long narrow ridges or wider islands. Tooth and Nanson (1999) noted that ridge-form anabranching within a typically straight channel-train dominates. Indeed, the Marshall and other Australian ridge-form anabranching rivers are globally probably the longest straight rivers to have been studied to date, as they commonly run straight for $>> 10$ times their channel width. Leopold et al. (1964) argued that very few rivers run straight for more than $5 - 7$ times their channel width, so these ridge-form anabranching rivers are exceptional in that regard. Huang et al. (2004) and Nanson and Huang (2008) have shown theoretically that straight channels, if naturally so and hence stable, represent the minimum-energy stationary equilibrium state. Cross Sections M1a, M1b, M2, M3, Linking anabranch (LA), M4 and M5 were surveyed by Tooth and Nanson (1999, 2004), while M2u, M3u, M4u and M5u were surveyed specifically for this project. These new surveys were between 300 m (M3u) and 5 km (M2u) upstream (designated by ‘u’) of the associated cross sections surveyed by Tooth and Nanson (e.g. M3 and M2, respectively).
7.3.1.1 Topographic cross sections

Eleven cross sections have been measured along the 80 km study reach, capturing the anabranching, and single thread expressions of the Marshall River. The topographical cross-sectional data are presented in Appendix D.

Channel cross-sectional form varies along the study reach (Figure 7.5). For the cross sections that are not anabranching (i.e. M1a, M2u, M3u, M4u and M5u), bankfull cross-sectional areas and estimated discharges range from 400 to 600 m$^2$ and 100 to 650 m$^3$ s$^{-1}$, respectively. The channel train exceeds 1000 m in width at M2, and is less than 300 m at M1a, M2u, M3u and LA. Given that ridge-form anabranching dominates the study sites and results in multiple channels with numerous dimensions, bankfull W/D ratios are widely ranging; < 30 to > 170.

Figure 7.5 clearly demonstrates that ridge morphology also varies, particularly ridge height, whereas islands are typically level and at the height of the adjacent floodplain, although their widths are not consistent. Median grain size across all study cross sections ranges between coarse sand (0.73 mm) and very fine gravel (2.3 mm).

Table 7.3: Marshall River cross section order upstream to downstream. ‘M’ denotes Marshall River, ‘u’ upstream and ‘LA’ linking anabranch. * Cross sections were measured downstream from the source of the trunk stream.

<table>
<thead>
<tr>
<th>Cross Section (upstream to downstream)</th>
<th>Approx. distance downstream* (km)</th>
<th>Distance from next upstream cross section (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1a</td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td>M1b</td>
<td>41.8</td>
<td>1.8</td>
</tr>
<tr>
<td>M2u</td>
<td>51.5</td>
<td>9.7</td>
</tr>
<tr>
<td>M2</td>
<td>56.5</td>
<td>5</td>
</tr>
<tr>
<td>M3u</td>
<td>67.5</td>
<td>11.5</td>
</tr>
<tr>
<td>M3</td>
<td>67.8</td>
<td>0.3</td>
</tr>
<tr>
<td>LA</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M4u</td>
<td>87.8</td>
<td>20</td>
</tr>
<tr>
<td>M4</td>
<td>88.5</td>
<td>0.7</td>
</tr>
<tr>
<td>M5u</td>
<td>116</td>
<td>27.5</td>
</tr>
<tr>
<td>M5</td>
<td>117</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total distance</strong></td>
<td></td>
<td><strong>77.5</strong></td>
</tr>
</tbody>
</table>
Figure 7.5: Seven cross sections (M1a, M1b, M2, M3, LA, M4, M5) were surveyed along the Marshall River (adapted from Tooth and Nanson, 2004). An additional four cross sections (M2u, M3u, M4u, M5u) were surveyed for this study. Refer to Figure 7.1 for locations.
Channel beds are colonised by *Eucalyptus camaldulensis* individuals while banks, ridges and islands are vegetated with trees, shrubs and grasses; *E. camaldulensis, Acacia* spp. and *Melaleuca* spp. (e.g. *M. glomerata*) being the dominant tree and shrub species. In proximity to M5u and M5, species dominance shifts from *E. camaldulensis* to *M. glomerata*.

M5 is also the only studied location along the Marshall River where vegetation (*Melaleuca* spp.) is dense enough (on the ridges) that it could act as a significant barrier to flow and affect channel dimensions (Appendix F photo j). A point-centred quarter stem density count on one of the ridges indicated there are 20 stems/100 m².

Many in-channel *E. camaldulensis* are partially buried by bed material in the form of incipient ridges (e.g. Figure 7.6a); this was seen along the Plenty River as well. Further, Figure 7.6b also demonstrates how at least partial ridge development (i.e. sediment deposition) can occur in association with established in-channel vegetation.

**Figure 7.6:** a) In-channel *E. camaldulensis* are partially buried, which b) over time can lead to partial ridge development.

Tooth and Nanson (2000a) suggested that ridges and islands dominated by *E. camaldulensis* are typically stable and well defined, whereas those in reaches dominated by *Melaleuca* spp. represent a continuum of features, forming and developing in association with *Melaleuca* spp. growth. These observations are supported here, and discussed in Section 7.4.1.2.
### 7.3.1.3 $H$ number calculations

The reader is reminded again of the form of the $H$ number given as Equation 4.9b, for this explains why it varies:

$$H = \frac{\tau / \tau_{cr} - 1}{W / D - 2}$$

Optimum channel efficiency occurs when this ratio is 0.30. The $H$ number calculations for the Marshall River are presented below.

#### 7.3.1.3.1 Topographically-defined bankfull

A plot of bankfull discharge, W/D ratio and $H$ numbers of all surveyed channels and sub-channels of the Marshall River is shown in Figure 7.7. This figure is not to be mistaken for a trend plot although the sites are roughly plotted in a downstream direction; the points for each cross section are to be viewed individually, although it does roughly trend downstream left to right. Figure 7.7 demonstrates that the most efficient cross sections ($H = 0.30$) are in to the two significantly anabranched cross sections, specifically, within M4 S1 and M5 S1. That being said, more than half (22/42) of all cross sections have uncertainty ranges that overlap $H = 0.30$. The uncertainty values are those from Tables 5.1 and 5.2 in Section 5.3.2.1.

Island or ridge-form anabranching is particularly well developed at Cross Sections M1b (island form) and M2, M4 and M5 (ridge form; Figure 7.5). Removing the ridges and re-calculating $H$ numbers using the cumulative discharges revealed, in all cases, far less efficient channels (Table 7.4).
Figure 7.7: Bankfull discharge (blue crosses), W/D ratio (red crosses), estimated Manning’s n (grey crosses) and H numbers (green crosses) of all surveyed channels and sub-channels of the Marshall River. Error bars attached to the H numbers capture the range of uncertainty derived from the H number inputs (τ, τcr, width, depth). This is not a trend plot although it does roughly trend downstream from left to right.
Table 7.4: Comparison within anabranching reaches, between ridges being present, and removed. Discharges listed are anabranches totalled, and then the H numbers for these discharges calculated with ridges removed. S = sub-channel.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Cross Section</th>
<th>Ridges present</th>
<th>Ridges removed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q (m$^3$s$^{-1}$)</td>
<td>H</td>
<td>Q (m$^3$s$^{-1}$)</td>
</tr>
<tr>
<td>M2 S2</td>
<td>S2a</td>
<td>44</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>S2b</td>
<td>44</td>
<td>0.21</td>
</tr>
<tr>
<td>M2 S3</td>
<td>S3a</td>
<td>201</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>S3b</td>
<td>183</td>
<td>0.3</td>
</tr>
<tr>
<td>M4</td>
<td>S1a</td>
<td>12</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>S1b</td>
<td>108</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>S2e</td>
<td>123</td>
<td>0.13</td>
</tr>
<tr>
<td>M5 S1;</td>
<td>S1a</td>
<td>127</td>
<td>0.23</td>
</tr>
<tr>
<td>option 1</td>
<td>S1b</td>
<td>151</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>S1c</td>
<td>95</td>
<td>0.22</td>
</tr>
<tr>
<td>M5 S1;</td>
<td>S1d</td>
<td>54</td>
<td>0.23</td>
</tr>
<tr>
<td>option 2</td>
<td>S1e</td>
<td>19</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>S1f</td>
<td>46</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>S1g</td>
<td>59</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>S1h</td>
<td>29</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>S1i</td>
<td>30</td>
<td>0.47</td>
</tr>
<tr>
<td>Mean H number</td>
<td>0.30</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

Taking the cumulative discharge of the primary anabranches in M4 (S1a+S1b+S2e; 244 m$^3$s$^{-1}$) and calculating the associated H numbers in the single channel cross sections (M1a, M2u and M3u) indicates M1a operates more efficiently than at bankfull but M2u and M3u do not (Appendix E Table E.1).

Selected comparisons between single and multi-channelled cross sections that exhibit significantly different H numbers, are shown in Figures 7.8 and 7.9. Relatively speaking, the H values for the M1 sub-channels are larger than those from M4, however, all are still H < 1 (Figure 7.8). The [significantly anabranched] M4 sub-channel W/D ratios, which produce better H values, are smaller than the M1 sub-channels. In contrast, the sub-channels with H numbers closer to 0.30 are associated with higher W/D ratios when comparing M5u and [significantly anabranched] M5 sub-channels (Figure 7.9).
Figure 7.8: Bankfull discharge, W/D ratio and $H$ numbers of Cross Sections M1b and M4. Error bars attached to the $H$ numbers capture the range of uncertainty derived from the $H$ number inputs ($\tau$, $\tau_{cr}$, width, depth).

Figure 7.9: Bankfull discharge, W/D ratio and $H$ numbers of Cross Sections M5u and M5. Error bars attached to the $H$ numbers capture the range of uncertainty derived from the $H$ number inputs ($\tau$, $\tau_{cr}$, width, depth).
Further comparison of M1b S1b, S2b with M4 S1a, S1c, S1d, S1e and M5u S1, S2 with M5 S1a, S1b, S1c, S1d, this time in terms of equilibrium bedload transport capacity \( (Q_s) \) versus W/D ratio, is shown in Figure 7.10 and 7.11, respectively. As discussed in Chapter 6, relating equilibrium bedload values represented by the curves to accurately measured bedload for those same reaches of channel would be ideal. However, as with the Diamantina River, field work here had to be conducted in the dry season. Even if there had been flow, the demanding and complex task of measuring bedload in this remote region (essentially inaccessible in wet periods) would have not been possible. With no gauging stations in the Marshall River study reach, accurate estimates from bedload equations were also not possible.

That being said, previous studies (e.g. Tooth and Nanson, 1999, 2000a,b, 2004) and field observations reveal that the Marshall River in the examined reach is at or very close to mass-balance equilibrium. Well-established *E. camaldulensis* trees on the channel banks, atop the in-channel ridges and in the channel itself (e.g. Figures 3.2b,c, 3.6a and 7.6) bear no evidence of a channel undergoing extensive aggradation or degradation. Because these rivers are in mass-balance equilibrium, if the actual bedload yield \( (Q_{sa}) \) was known and plotted onto Figures 7.10 and 7.11, it must plot somewhere at or below the peak of each curve (i.e. \( < Q_{s \text{ max}} \)). If it plotted above the curves in Figures 7.10 and 7.11, that would mean \( Q_s \) would be in excess and that \( S_f \) was below the minimum required (see Figure 4.4) and that the channels were underpowered and accreting bedload. Plotting at or below the peak means that they are either at stationary equilibrium (at the peak) or that they have energy (excess \( S_f \) in Figure 4.4) and they are expending that energy dynamically and hence not eroding (incising). According to the plots in Figure 7.10, \( Q_{sa} \), for the channels at M1b bedload would be \( < 0.266 \) m\(^3\) s\(^{-1}\) and for the channels at M4 it would be \( < 0.005 \) m\(^3\) s\(^{-1}\). For the plots in Figure 7.11, it would be \( < 0.032 \) and \( 0.047 \) m\(^3\) s\(^{-1}\) for M5u and M5, respectively.

Where \( Q_{sa} < Q_{s \text{ max}} \) (Figure 4.4b), it has been demonstrated by Huang and Nanson (2007) that the system has surplus energy. Channels below and to the left of the curve peak \( (H > 0.30, \text{channels in Cross Sections M1b and M5u}) \) (Figure 7.10 and 7.11), then holding \( \tau/\tau_c \) constant, would need to widen and/or reduce their depth to increase their W/D ratio. Those below and to the right \( (H < 0.30) \) would need to narrow and/or
deepen and consequently decrease their W/D ratio. Because the anabranches (channels within Cross Sections M4 and M5) are close to $H = 0.30$ (0.22 - 0.39), the deviation from $Q_{s_{\text{max}}}$ is low. In line with their $H$ numbers, some of the anabranches (M4 S1a, M5 S1a, M5 S1d) plot marginally to the right ($H < 0.30$) and others with $H \approx 0.30$ (M4 S1c, M4 S1d, M4 S1e, M5 S1b) essentially at the curve peak.

What is clear from Figure 7.10 is that when the Marshall River is divided into just two large anabranches the $H$ numbers are large, indicating excessive surplus flow-shear to W/D ratio. Interestingly, their channel planform is essentially straight and they are not braided either, presumably so that flow deformation in bends or around and over obstructing bars is not consuming what energy is available for sediment transport. This could indicate that these reaches have accumulated excess sediment in the past and that is now being reworked through; in other words they are currently exporting more bedload than they are receiving. Those reaches with more than two anabranches in the form of small channels are also straight (Figures 3.2c,d and 7.11). From their $H$ numbers they appear be very close to stationary equilibrium. Of course one condition of stationary equilibrium is that they must be straight, otherwise they cannot be operating at maximum flow efficiency (MFE) (Huang et al. 2004; Nanson and Huang, 2008).
Figure 7.10: Equilibrium (dynamic and stationary) bedload transport capacities at channels M1b S1b, M1b S2b, M4 S1a, M4 S1c, M4 S1d and M4 S1e. Refer to Figure 7.1 for locations. The vertical dashed line represents position of the measured W/D ratio.
**Figure 7.11**: Equilibrium (dynamic and stationary) bedload transport capacities at channels M5u S1, M5u S2, M5 S1a, M5 S1b, M5 S1c and M4 S1d. Refer to Figure 7.1 for locations. The vertical dashed line represents position of the measured W/D ratio.

### 7.3.1.3.2 Vegetation-adjusted bankfull

M5 reveals a distinctly anabranching cross section, with what appears to be three main sub-channels (S1a, S1b, S1c) on the left side of the channel train (Figure 7.9, Appendix D). These sub-channels are not completely separate at the topographically-defined bankfull discharges calculated above (i.e. at bankfull they are combined to form S1). However, when vegetation is included as a significant lateral boundary to flow (as per Jansen and Nanson, 2004, 2010), the separate sub-channels are believed to operate more effectively. Within each sub-channel there are more ridges, but they are less well defined and may be semi-permanent bedforms. Vegetation has been incorporated into
channel dimensions of the three main sub-channels and the discharge and resulting H numbers at the water level of topographically-defined bankfull are shown in Table 7.5.

Table 7.5: Comparison of discharge and sediment transport efficiency when vegetation is factored into hydraulic calculations. S = sub-channel.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Discharge and H number when channel dimensions defined by sediment bank height</th>
<th>Discharge and H number when channel dimensions defined by vegetation</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Q$ ((m^3s^{-1}))</td>
<td>$H$</td>
<td>$Q$ ((m^3s^{-1}))</td>
</tr>
<tr>
<td>M5 S1a</td>
<td>127</td>
<td>0.23</td>
<td>122</td>
</tr>
<tr>
<td>M5 S1b</td>
<td>151</td>
<td>0.38</td>
<td>119</td>
</tr>
<tr>
<td>M5 S1c</td>
<td>95</td>
<td>0.22</td>
<td>77</td>
</tr>
</tbody>
</table>

7.3.2 Plenty River

The Plenty River drains an area of $>15,000$ km$^2$, and the study sites along the river are situated along a 50 km reach upstream of Jervois Station (Figure 7.1). Geomorphological expression along the 50 km reach is relatively constant, with the river being defined by a single-thread shallow and wide channel that is somewhat beaded in places, meaning that the width narrows and swells downstream (Figure 7.1h,i). Channel meanders are typically gentle and in places the thalweg meanders between the channel banks.

Cross Sections P1 to P4 were surveyed by Tooth and Nanson (2004), while the PB series (6) were specifically done for this project to investigate the differences in geomorphological expression between the narrow and wide reaches within a localised beaded section. Similar, and in close proximity to the Marshall River, the channel gradient for the Plenty River is the same as that of the Marshall River; 0.0013 (Tooth and Nanson, 2004).

7.3.2.1 Topographic cross sections

A total of ten cross sections have been measured; these are not spread equidistant within the 50 km study reach (Table 7.6) but are considered to suitably represent this reach of
the Plenty River. P1 to P4 will be discussed collectively, as will PB1n, PB1w, PB2n, PB2w, PB3w and PB3n. The cross-sectional data are presented in Appendix D.

Table 7.6: Plenty River cross section order upstream to downstream. ‘P’ denotes Plenty River, ‘B’ beaded section, ‘w’ wide and ‘n’ narrow. * Cross sections were measured downstream from the source of the trunk stream.

<table>
<thead>
<tr>
<th>Cross Section (upstream to downstream)</th>
<th>Approx. distance downstream* (km)</th>
<th>Distance from next upstream cross section (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>125</td>
<td>-</td>
</tr>
<tr>
<td>PB1n</td>
<td>126.8</td>
<td>1.8</td>
</tr>
<tr>
<td>PB1w</td>
<td>128</td>
<td>1.2</td>
</tr>
<tr>
<td>PB2n</td>
<td>128.9</td>
<td>0.9</td>
</tr>
<tr>
<td>PB2w</td>
<td>129.65</td>
<td>0.75</td>
</tr>
<tr>
<td>PB3w</td>
<td>135.55</td>
<td>5.9</td>
</tr>
<tr>
<td>PB3n</td>
<td>136.65</td>
<td>1.1</td>
</tr>
<tr>
<td>P2</td>
<td>138.15</td>
<td>1.5</td>
</tr>
<tr>
<td>P3</td>
<td>154.15</td>
<td>16</td>
</tr>
<tr>
<td>P4</td>
<td>175.15</td>
<td>21</td>
</tr>
<tr>
<td><strong>Total distance</strong></td>
<td><strong>50.15</strong></td>
<td></td>
</tr>
</tbody>
</table>

Channel cross-sectional form is consistent between P1, P3 and P4 (Figure 7.12); the channel is approximately 400 m wide and < 3 m deep, whereas P2 laterally extends for 700 m. Bankfull cross-sectional areas range from 275 to 1000 m² and estimated discharges from 450 to 2000 m³ s⁻¹ (Appendix E Table E.2). Bankfull W/D ratios range from 112 to 505. P2, P3 and P4 are associated with a larger, main channel, and smaller secondary channel separated by vegetated ridges. This is particularly defined at P4. Median grain size across the four cross sections is medium to coarse sand.

Within the localised beaded section of the Plenty River, the channel cross section varies from less than 300 m wide (PB2n) to up as much as 500 m wide with bed features producing two (PB1n, PB1w, PB2w) or more (PB3w) distinct sub-channels (Figure 7.12). These sub-channels are divided by what are essentially sand bars about 1 m high, not permanently vegetated and overtopped at bankfull flow, and hence the channel is not anabranching. Apart from being wider, PB3n shares a similar geomorphological definition to PB2n. At all cross sections the channel is less than 2.8 m deep (PB1n) at the deepest point to bankfull, and W/D ratios vary between 171 and 394. Median grain size is fine to coarse sand (0.20 to 0.73 mm).
Figure 7.12: Four cross sections (P series) were surveyed along the Plenty River (adapted from Tooth and Nanson, 2004). An additional six cross sections (PB series) were surveyed along a 10 km localised section of the Plenty River where its form shifts from narrow to wide and back again over reasonably short distances. Refer to Figure 7.1 for locations.
7.3.2.2 Vegetation

*Eucalyptus camaldulensis* is the dominant species along the Plenty River banks and on its bed. It commonly occurs along most cross sections, exhibiting a variety of circumferences (up to 5 m) in the channel while smaller and presumably younger individuals generally line banks.

A variety of grass species are scattered along the channel bed, particularly in the beaded section where in-channel *E. camaldulensis*, albeit present, seem less common than elsewhere along the study reach. Here, these trees are largely confined to the banks and generally within 10 metres of the channel edge.

At none of the study locations is vegetation considered dense enough to act as a barrier to flow, and thereby redefine channel boundaries or to constrain flow. In stark contrast to the Marshall River, nor does vegetation typically define and stabilise in-channel morphological features. In-channel ridges along the Plenty River are subdued.

7.3.2.3 $H$ number calculations

$H$ number calculations are presented below to demonstrate the efficiency of the Plenty River at each measured section. They are plotted in Figure 7.13, which is not to be mistaken for a trend plot; the points for each cross section are to be viewed individually, although the distribution does roughly trend downstream left to right. Of particular interest, however, is that all three variables plotted in the downstream direction (discharge, W/D and $H$ number) oscillate with channel width, in line with the beaded character of the channel planform.

Large discharges are required for the banks to be overtopped at each cross section. At such discharges, $H$ numbers (uncertainty ranges inclusive) are below $H = 0.80$ (Figure 7.13). The average value for the entire study reach is $H = 0.27$. This suggests that, should the river operate at bankfull, it will be doing so reasonably efficiently. Interestingly, in the beaded section, the channel expansions are associated with low $H$ numbers (0.16, 0.11, 0.13) compared to the narrower portions ($H = 0.15, 0.37, 0.52$).
Figure 7.13 establishes the variation within discharge values, W/D ratio values and H number values is less than for the Plenty (Figure 7.7). Just 38% (8/21) of the H number uncertainty ranges for all surveyed Plenty channels capture $H = 0.30$ (the uncertainty values are those from Table 5.1 and Table 5.2 in Section 5.3.2.1). However, the average bankfull H number across all surveyed cross sections on the Plenty River is $H = 0.27$, so they are approaching optimum bedload transport efficiency. Comparison of the respective $Q_s$ versus W/D ratio curves reveals that the P1 $Q_s$ values are approximately double those of PB1n (Figure 7.16). The bedload transport capacity is greater at P1 where the bankfull flow capacity is greater.

Comparing the two sub-channels at P4 is perhaps unrealistic given it is likely that S1 operates more as an overflow channel rather than a primary conveyer of bedload (Appendix D). Nevertheless, the contrast in bankfull H numbers (P4 S1 = 0.10 versus P4 S2c = 0.38) warrants a comparison. Interestingly, the W/D ratios are similar, yet the bankfull flow capacities are not (Figure 7.15). This disparity is best reflected by the $Q_s$ versus W/D ratio plots (Figure 7.17).

Channel width through the beaded section is by definition variable; aerial photographs studied by Tooth and Nanson (2004) show that these fluctuations were evident pre 1970s, but that bank erosion resulting from significant flooding in the mid 1970s and early 1980s intensified them. The mean H numbers of the constrictions and expansions, vary, at $H = 0.35$ and 0.13, respectively. This evidence indicates that locally, parts of the Plenty River are less stable compared to the Marshall. However, similar to the Marshall River the Plenty is overall close to, if not at, mass-balance equilibrium (overall mean $H = 0.27$) and it maintains stable bed levels (Tooth and Nanson, 2004). Large trees (again mostly $E.\ camaldulensis$), although less abundant compared to on the Marshall, are also well established along the banks and are particularly so in the channel (e.g. Figure 3.6b).

This means that $Q_{sa}$, if known and plotted onto Figures 7.16 and 7.17, would plot somewhere below the peak of each curve (i.e. $< Q_{s_{max}}$), less than 0.731, 0.384, 0.012 and 0.222 m$^3$ s$^{-1}$ for the represented channels at P1, PB1n and P4, respectively. For the four cross sections represented in Figures 7.16 and 7.17, H is $\approx$ or $< 0.30$. PB1n and P4
S1 fall to the right of the curve peak because their current morphologies are shallower and wider than required for the transported bedload, P1 slightly to the left of the peak with slightly lower than optimum W/D ratios and P1 and P4 S2c essentially at the peak ($H = 0.34$ and $0.38$, respectively).
Figure 7.13: Bankfull discharge (blue crosses), W/D ratio (red crosses), channel width (orange crosses), estimated Manning’s n (grey crosses) and H numbers (green crosses) of all surveyed channels and sub-channels of the Plenty River. This is not a trend plot. Error bars attached to the H numbers capture the range of uncertainty derived from the H number inputs (r, τcr, width, depth).
Figure 7.14: Bankfull discharge, W/D ratio and $H$ numbers of Cross Sections P1 T2 and PB1n T1. Error bars attached to the $H$ numbers capture the range of uncertainty derived from the $H$ number inputs ($\tau$, $\tau_c$, width, depth).

Figure 7.15: Bankfull discharge, W/D ratio and $H$ numbers of the two sub-channels in Cross Section P4 (S1 and S2c). Error bars attached to the $H$ numbers capture the range of uncertainty derived from the $H$ number inputs ($\tau$, $\tau_c$, width, depth).
Figure 7.16: Equilibrium (dynamic and stationary) bedload transport capacities at channels P1 T2 and PB1n T1. Refer to Figure 7.1 for locations. The vertical dashed line represents position of the measured W/D ratio.

Figure 7.17: Equilibrium (dynamic and stationary) bedload transport capacities at channels P4 S1 and P4 S2c. Refer to Figure 7.1 for locations. The vertical dashed line represents position of the measured W/D ratio.
7.4 Discussion

Similar to the results section above, this discussion is partitioned into a section for each river. Comparison between the Marshall and Plenty Rivers is then undertaken.

7.4.1 Marshall River

7.4.1.1 Channel efficiency ($H$ number)

In general the Marshall River appears to be well adjusted to a condition approaching stationary equilibrium conditions. Overall, the average $H$ number at bankfull flow is 0.40 ($n = 27$). The average for the anabranching channels (ridge-form and island anabranching) is 0.39 ($n = 18$) and that for the single thread cross sections is 0.36 ($n = 5$). There is not a statistically significant difference between these two averages ($p$-value = 0.51, $\alpha = 0.05$). The river would appear to be well adjusted in both planform situations.

Interestingly, in the reaches of the Marshall River dominated by ridge-form anabranching, the average $H$ number is 0.30, indicative of conditions at stationary equilibrium (Table 7.4). If the ridges are assumed not to be present and the hydraulic parameters are then recalculated for a theoretical single channel condition (carrying the cumulative discharge the anabranches can convey), $H$ numbers average only 0.05, well below the optimum value (Table 7.4). That is, at those locations (M2, M4 and M5), an anabranching system is more efficient than a single channel and it can be assumed likely that the anabranches are adjusted to the channel-forming discharge. Indeed, calculating bankfull $H$ numbers for the well-developed sub-channels of the most established ridge-form anabranching Cross Section (M5) suggests that it is likely they exist to make the bankfull flow volumes more efficient. That is, the ridges develop to confine the width of the channel and depth of flow. M5 S1 can be further subdivided into six anabranches (S1d to S1i) that have bankfull water levels within 6 cm of each other and $0.23 < H > 0.52$ (Appendix D).
However, the anabranch depths elsewhere are not always so uniform (e.g. M4). Therefore, it may be that the ridges may develop to confine the width of the channel, and there is an optimum depth of flow within these widths determined by the ridges.

Anabranching is understood to be a mechanism to increase flow transport capacity and flow efficiency; a finding supported by this study. Nanson and Knighton (1996) proposed this as the general reason why many rivers may anabranch; Tooth and Nanson (1999, 2000a) proposed it as the reason that a number of the rivers of on the Northern Plains anabranch; Jansen and Nanson (2004, 2010) provided convincing evidence from measurements of bedload that anabranching on Magela Creek created more efficient cross sections for bedload conveyance; Huang and Nanson (2007) showed with mathematical modelling that anabranching can create more flow-efficient cross sections but that anabranching could also be, in some cases, an energy consuming mechanism for rivers with excess energy.

7.4.1.2 Vegetation patterns

The density of *M. glomerata* and *M. dissitiflora* shrubs along the left bank and ridges within the left sub-channel of M5 is thick enough that an exercise to compare the hydraulic parameters with and without this vegetation included in channel dimensions was undertaken (Section 7.3.1.3.2). Unfortunately this comparison is based on just three channels within M5 (Table 7.5). However, when the cross sections are topographically-defined only, two of the affected channels (M5 S1a and M5 S1c) moved closer to an H number of 0.30. The other one (M5 S1b) that had a H number in excess of 0.30 when the effect of vegetation was ignored, moved even farther away from the optimum when vegetation was taken into account. A tentative conclusion is that vegetation may be a significant component influencing channel equilibrium dimensions, but clearly this proposal requires further investigation.

Regardless of this outcome, there are advantages to having vegetation in this section of the Marshall River; the role it plays in the formation and maintenance of the Marshall anabranching channels downstream of the linking anabranch has previously been reported on (Tooth and Nanson, 2000a; see also Section 3.6 and Figure 3.8). Field
observations suggest depositional mechanisms, a result of sediment accretion in the lee of deep-rooted trees or shrubs on the river bed, have been more important than erosional mechanisms in the formation of the ridges and islands on anabraning rivers (Tooth et al., 2008). By increasing flow roughness, the in-channel trees or shrubs can make the single channel sections relatively inefficient. The same vegetation, however, can initiate ridges and their ensuing colonisation by additional trees in the dry phases will further stabilise the ridges. This will encourage further sediment deposition during subsequent floods (Tooth et al., 2008). Similar to the three-stage sequence proposed for the Marshall River (Figure 3.8), as ridges continue to grow, they interact with neighbouring ridges to eventually form extensive ridges that separate distinct anabranes, the latter concentrating flow energy, limiting further colonisation of the river bed by trees seeking subsurface water, and leaving the anabranche channels as efficient conduits for water and bedload at times of flood (Tooth and Nanson, 2000a).

7.4.2 Plenty River

The Plenty River is a single-thread system with width fluctuations along the entire study reach, but they are most prominent in the unusual 10 km long beaded section where width oscillates with distinct regularity with an expansion-contraction wavelength of about 1.3 km (Figure 7.18). Marked fluctuations in channel width are seen elsewhere on the Northern Plains. Tooth (2000b) observed a similar pattern on some reaches of the Sandover, Bundey and Woodforde Rivers, thought to at least partially reflect sediment storage and sediment transport zones (c.f. Church and Jones, 1982). However, this remains unconfirmed (Tooth, 2000b), and it does not seem beading, such as that along the Plenty River, is described or explained for rivers elsewhere.

Figure 7.18: The beaded section of the Plenty River.
7.4.2.1 Channel efficiency (H number)

Bankfull discharges at all 10 cross sections yield an average H number of 0.27, close to the optimum (Figure 7.13), suggesting that sediment transport under bankfull flow conditions is remarkably efficient. The planform is relatively straight but beaded and the average H number for the three wide sections is 0.13, a considerable departure from optimum, whereas that for the 3 narrow cross sections is 0.35, close to optimum.

Why the beaded section in the upper part of the study reach of the Plenty River exists is not clear. There are no obvious associations exclusive to either the wider or narrower reaches except that the average bed-material grain size is significantly coarser (0.45 mm) in the wide sections compared to the narrow sections (0.28 mm). Low, sandy islands occupy parts of the mid-channel in both, and not all narrow reaches are associated with outcrops, terraces or aeolian sand deflecting the river course (Tooth and Nanson, 2004). These authors suggest that the channel in the wider reaches is locally less stable than in the adjacent narrow reaches and that interpretation is supported by the wider reaches having H numbers significantly further from the optimum.

With reference to other Northern Plains rivers (Sandover, Bundey and Woodforde), Tooth (2000b) proposes that there might be an association between vegetation and channel width, in that it is difficult for large trees to establish down larger and steeper banks. As a result, there may be less protection against basal scour and undercutting, and thus channel widening occurs there. The narrower reaches along the Plenty River are typically associated with lower banks and a more consistent line of vegetation on the banks and, although still relatively scarce, there do appear to be more in-channel trees in the wider reaches.

Remarkably, the deviations from 0.30 for the wider and narrower reaches are similar, albeit in opposite directions. That is, if Qs versus W/D ratio curves were plotted for Cross Sections PB1n, PB2n, PB3n and PB1w, PB2w, PB3w, the deviation to the left of the peak of the curve (stationary equilibrium, H = 0.30) for the ‘n’ collection would be similar to the deviation to the right of the curve peak for the ‘w’ collection. It would be interesting to calculate the values of H for the reaches between the narrowest and widest
sections surveyed for this study and see how close to \( H = 0.30 \) they are. However, they were not surveyed. Excluding all other factors, if the W/D ratios for the narrow and wide sections are too low and too high respectively, it is a reasonable hypothesis that the intermediate sections are more efficient as the W/D ratio changes from one to the other. It may be that the beaded section represents some form of adjustment where the channel overshoots then undershoots as it attempts to adjust to an optimum \( H \) number of 0.30.

While the above discussion focuses on differences between selected sites, when considering the sandy channels of the Plenty River as a whole, it is clear the system is operating with considerable competence because the values of \( H \) hover close to 0.30. The cause of the beaded nature of the system remains an interesting issue for further investigation.

7.4.2.2 Vegetation patterns

*Eucalyptus* spp. and various shrubs (e.g. *Acacia* spp. and *Melaleuca* spp.) consistently line the banks of the Plenty River (one large tree per 4 - 10 m of bank line, Tooth and Nanson 2004), and large *E. camaldulensis* also grow on the channel beds (< 1 tree per 1000 m\(^2\)). However, and unlike along other fluvial systems studied for this thesis, this vegetation does not appear to have a key role in defining channel shape (by affecting W/D ratios). Perhaps it is a case of what Tooth and Nanson (2004, p. 815) propose: *a single-thread channel, relatively free of trees and receiving only limited tributary inflows, is hydraulically capable of conveying a sandy bed-material load.*

7.4.3 Comparisons between the Marshall and Plenty Rivers

The Marshall and Plenty Rivers essentially run parallel for ~70 km, commonly less than 3 km apart. Not long after being connected by the linking anabranch, the two rivers diverge, with the Marshall following a due east, and the Plenty a southeast orientation. Both rivers cross the southeastern corner of the Northern Plains before entering the northern Simpson Desert, and subsequently experience similar climatic conditions. However, the Marshall and Plenty exhibit distinct differences, and the results and
discussions above reveal that both, with \( H \) numbers close to 0.30, are at or approaching an equilibrium state despite their varying planforms within and between the two rivers. This suggests that they are not only well adjusted to the planform situations, but that they are self-forming, adjusting towards a stationary equilibrium state. Why though, despite the similar environmental setting, are the most efficient planforms for the Marshall and Plenty Rivers so different?

The Marshall is joined by numerous tributary inflows (Figure 7.19a) and the Plenty by only a few (Figure 7.19b). Tributary inflows join the Marshall River along its entirety, but many are small and seem to have minimal effect on channel form in the first 30 km of the trunk stream (Figure 7.1a). After 35 km, an anabranching pattern is the rule rather than the exception on the Marshall River, yet there are fewer tributary inflows in this lower reach. Therefore, it seems unlikely that the anabranching is solely a response to the tributaries, although three inflows are noted along the Marshall River study reach, and each one is associated with an increase in the number of channels.

Based on field observations, Tooth and Nanson (2004) suggested that a single-thread channel that is largely free of in-channel vegetation and receives only limited tributary inflows is hydraulically proficient to transport a sandy bedload. In contrast, along a channel that receives minor discharge and coarser sediment from tributaries, which subsequently encourages the growth of in-channel trees, anabranching better conveys the coarser sediment load. However, as indicated by this study, in the context of the Marshall and Plenty Rivers, this interpretation may only partly be correct.

Consideration of the channel gradients reveals that upstream of the Marshall River study reach, where anabranching is much less abundant, the bed is nearly twice as steep (0.0025) as that in the study reach (0.0013). It would appear that the river competently transports its coarser load (mean = 1.3 mm compared to the Plenty’s mean size of 0.45 mm) over steeper gradients without having to anabranch, but once reaching the lower gradient parallel with the Plenty, resorts to anabranching to maintain an equilibrium system.
The Marshall River is characterised overall by a narrower channel and more bank vegetation. While the Marshall anabranches and this vegetation is involved in stabilising the ridges (Figure 7.20a), the Plenty is largely single thread and bank vegetation is often scarce (Figure 7.20b). The latter has an overall wider channel, but there are more fluctuations in width.
Figure 7.19: Number of channels heading down the a) Marshall; and b) Plenty Rivers, based on assessment of the number of channels at 1 km intervals from Google Earth imagery, except for kilometre 35 to 112 along the Marshall (data reproduced from Tooth and Nanson, 2004). * denotes location of a major tributary inflow, and ^ a minor one. It is acknowledged determining the number of channels across a given cross section is subjective, however, general trends can be established.
Figure 7.20: Contrast in vegetation density along in-channel features on the a) Marshall River at Cross Section M2 and b) Plenty River at Cross Section PB1w.

7.5 Summary

The Northern Plains rivers studied here traverse similar physical settings and experience comparable climatic regimes. Yet there are distinct differences between the Marshall and Plenty Rivers that ultimately reflect the influence, and importance of, local factors and how they interact. Despite these differences, $H$ number calculations with uncertainty factored in indicate that the channels constituting both rivers capably convey sediment under bankfull conditions. That is, they are at or approaching the equilibrium condition.

It appears that abundant ridge-form anabranching has developed along the Marshall River in response to the imposed coarser sediment load (1.3 mm) through a lower gradient reach. The Plenty, with its finer average sediment size (0.45 mm) can seemingly move its load without resorting to an anabranching fluvial form. This supports previous research that anabranching is a mechanism by which flow efficiency can be enhanced. These results also confirm how vegetation can significantly affect river morphology; *M. glomerata* has been shown to control the sequential development of the ridges and islands that separate these anabranches on the Marshall River.

The $H$ number model seems applicable to the Marshall and Plenty channels, and in contrast to the mud-dominated Diamantina River, the model also appears to more accurately reflect the sediment transport dynamics of these channels.
PART III
SYNTHESE
Chapter 8: summary and synthesis

8.1 Introduction

This study had four primary research objectives: (1) to apply the H number model, developed theoretically, to rivers in their natural settings; (2) to assess how effectively the H number model differentiates the specific equilibrium conditions that prevail on rivers of distinctly different character; (3) to evaluate the capacity for the H number model to identify why rivers adopt particular geometric characteristics; and (4) to determine how close individual reaches of river are to the optimal equilibrium state. In addressing these objectives, this research has established that exogenic variables that cannot readily be included in the hydraulic computations within dynamic and stationary equilibrium models, such as riparian vegetation and highly cohesive alluvial clays, have a profound impact on the resulting equilibrium form of a river channel. This research has revealed that:

1. The mud-dominated Diamantina River, with average H numbers well above the stationary equilibrium state, can remain highly stable while confining flow to narrow, deep, erosion-resistant and often tree-lined channels with high excess flow-shears that are capable of moving a more abundant bedload than is present;
2. The almost straight Marshall River switches from single thread to anabranching to convey its relatively coarse bedload along a lower gradient, and that it does so with H numbers that average very close to the stationary equilibrium optimum of 0.30 while;
3. The single-thread, almost straight and somewhat beaded Plenty River moves its relative fine sand load along a channel of the same gradient as the immediately adjacent Marshall River, but without anabranching and with less well vegetated banks, and that it does so competently with an average H of 0.24, only slightly below the optimum; and
4. In the past, the equilibrium status of a river has commonly been assessed based on the mass-balance of sediment transport or the stability of channel dimensions over time. The H number model now enables river
channel equilibrium to be determined directly, precisely and more immediately by assessing the energy balance in a reach.

This final chapter draws together the results and discussions from the study rivers. It also outlines the insights obtained by calculating the H number to assess the dynamic and stationary equilibrium states of these rivers, and it emphasises the important role played by vegetation in the adjustment of channel form and process. A brief discussion on the limitations of the H number model follows, before suggestions for future research are considered.

8.2 **Comparison of H number and equilibrium results**

That river channels under natural conditions tend toward an equilibrium state has become progressively accepted over more than the past 130 years (e.g. Gilbert, 1877; Mackin, 1948; Chang, 1986; Huang and Nanson, 2000). For alluvial bedload-transporting channels, energy and sediment dictate the equilibrium state. Under the conditions where the energy expenditure is high enough to transport all the sediment from upstream, minimum energy expenditure maximises sediment movement using the least amount of energy (Jia, 1990; Huang and Nanson, 2000; Huang and Chang, 2006). With that in mind, there are some similarities and differences between the study reaches of the Diamantina, Marshall and Plenty Rivers, as briefly reviewed below.

8.2.1 **Similarities**

Across the two distinctly different fluvial settings represented by the muddy Diamantina and the sandy Marshall and Plenty Rivers, there are some consistencies. Numerous lines of evidence indicate in the particular reaches investigated for all three rivers, the actual bedload yield \( (Q_{sa}) \) if known and plotted onto Figures 6.15, 6.16, 7.10, 7.11, 7.16 and 7.17, would be equal to or greater than stationary equilibrium maximum bedload transport capacity \( (Q_{s \text{ max}}) \) over a minimum or somewhat greater energy gradient (see Figure 4.4). That is, all three rivers are self-forming systems at, or adjusting towards, a stationary equilibrium state. Therefore, all rivers with energy in excess or equal to
transport their sediment load have the potential to achieve dynamic equilibrium (i.e. lie on the curve) or stationary equilibrium (at the peak of the curve) (Figure 4.4).

It is clear from qualitative evidence that the study reaches of the Diamantina, Marshall and Plenty Rivers are effectively at or very close to mass-balance equilibrium. Along the Diamantina, large trees (mostly *Eucalyptus coolabah*) are not showing any signs of being inundated with alluvium at their base; such inundation would be apparent if the channels and adjacent floodplain were aggrading. Furthermore, these rivers are not incising; they overtop their banks and inundate vast areas of floodplain on a regular basis. This evidence is supported in the Channel Country by independent dating of alluvial accretion (Nanson et al., 1988; Fagan and Nanson, 2004). Indeed, even upstream of a rising tectonic structure accretion rates are very low (Jansen et al., 2013). Furthermore, despite extensive flooding on a decadal basis, time lapsed aerial photographs over more than 50 years show that the Channel Country rivers have, overall, been highly stable in planform (Nanson et al., 1988; Nanson, *pers. comm.*, September 2013). Similarly, aerial photographs reveal that the anabranching rivers on the Northern Plains have changed little between the 1950s and 1980s (Tooth and Nanson, 1999). Stable bed levels (Tooth and Nanson, 2004) and well-established *E. camaldulensis* trees on the channel banks, atop the in-channel ridges and in the channel itself bear no evidence of channels undergoing significant aggradation or degradation.

Tooth and Nanson (2000b) compared Channel Country and Northern Plains rivers to the equilibrium conditions that Richards (1982) suggested would identify an equilibrium state: mean channel form remains constant over time; sediment input equals sediment output; strong correlation between system variables; and an adjustment towards maximum efficiency. Although their research was qualitative, they concluded that both types of river system did indeed appear to illustrate the first two of Richards’ parameters. Establishing maximum efficiency was not possible to demonstrate at that time due to the lack of the simple means of determining it. The development of the H number has meant that these qualitative interpretations, especially that of optimum efficiency, can now be tested on the basis of a quantitative theoretically based model. Further research will clarify the validity of this approach; a question remains as to interpreting the meaning of deviations from the optimal value of 0.30.
8.2.2 Differences

A clear and revealing distinction is that along the muddy Diamantina River $H > 0.30$ whereas along the sandy Marshall and Plenty Rivers, $H \approx 0.30$. The significantly higher $H$ numbers obtained along the Diamantina are interpreted to result from the estimate of grain size (hence $\tau_{cr}$). Increasing the $\tau_{cr}$ by increasing the presumed grain size for two cross sections caused $H$ to approach 0.30 and the W/D ratios at $Q_{s \text{ max}}$ to approach those measured in the field (Table 6.4). This suggests that if the channels were formed and were stable in coarse material, the sediment would need to be at least double the size that was sampled from bars on the bed of the Diamantina and assumed to represent the bedload in transport. That is, the Diamantina channels are capable of transporting more and coarser bedload than they do. Clearly therefore, exogenic factors, such as vegetation and cohesive muddy banks, affect the flow and sediment transport dynamics of the Diamantina by enabling it, without destabilising, to convey a much smaller bedload in narrow deeper channels that have relative high excess flow-shears. The $H$ number, which is based on interpreting the behaviour of entirely endogenic variables in a self-adjusting alluvial system within its own uncohesive alluvium, does not reflect this highly stable, erosion-resistant boundary.

Of particular interest is the difference between the Marshall and Plenty Rivers, with the former changing from a single thread river in its steeper upper reach (gradient = 0.0025) to a combination of single thread and anabranching in its less steep lower reach (gradient = 0.0013) where it runs parallel to and at the same gradient as the Plenty. It appears that over steeper gradients the Marshall can competently transport its coarser load (1.3 mm compared to 0.45 mm in the Plenty) as a single thread river, but once reaching the lower gradient, anabranches to convey its bedload. The average $H$ numbers for the single thread and anabranching channels are 0.36 and 0.39, respectively, indicating that the Marshall River is well adjusted to both planform situations. In the Marshall River where the anabranching is specifically very straight and ridge-form, the $H$ numbers average the optimum value of 0.30. Interestingly, within the beaded section of the Plenty River the bankfull values of $H$ are also close to the optimum of 0.30 (they range from 0.11 to 0.52, with a mean value of 0.24, and average 0.13 in the expanded reaches and 0.35 in the confined reaches). These values were obtained from just six
cross sections but they do suggest that the system is competently conveying its bedload despite, or possibly because of, having a strongly beaded planform.

It would appear that, unlike the Diamantina, exogenous factors such as highly cohesive clays do not override self-adjustments to the flow conditions and sediment conveyance in the Marshall and Plenty Rivers. Here vegetation on sandy banks is able to provide sufficient bank erosional resistance to allow the channels to form optimum W/D ratios and hence appropriate flow shear stress values. Indeed, vegetation appears to facilitate the formation of sandy but highly stable within-channel ridges and hence multiple channels in the lower gradient reach of the Marshall where the coarser bedload of this river would otherwise not be adequately transported.

### 8.3 Role of vegetation in channel hydraulics

The increasingly recognised importance of vegetation in fluvial geomorphology is reviewed in Chapter 3. It can greatly modify channel form and significantly influence sediment transport efficiency and hence channel equilibrium. The direct interaction of vegetation with fluvial hydraulics can be illustrated by vegetation growing on the channel bed and thereby increasing boundary roughness and flow resistance (e.g. Graeme and Dunkerley, 1993). Jansen and Nanson (2004, 2010) determined that the most effective discharge for sediment transport along Magela Creek averages 2.1 times bankfull, with bank-top trees constraining these flows over the channel bed and making possible effective discharges that appear to be well in excess of that determined by the alluvial-defined bankfull condition. In the latter case, because vegetation is acting as an extension of the alluvial channel boundary, it can be directly incorporated into the W/D ratio and hence into the H number model. Vegetation was considered dense enough at Cross Section M5 on the Marshall River (Section 7.3.1.3.2 and Appendix E, Table E.1) to alter the cross section substantially and hence alter the cross-sectional characteristics of flow. The vegetation at this particular location causes the effective W/D ratio at bankfull to decrease, thereby increasing the associated value of H. The implications of this are significant because, perhaps for the first time, the direct influence of vegetation on river behaviour and channel efficiency can be shown quantitatively.
Another example of the direct influence that vegetation can have on channel hydraulics is the development of anabranching, which can reduce W/D ratios and increase flow efficiencies (e.g. Nanson and Knighton, 1996; Jansen and Nanson, 2004, 2010). The growth of vegetation is fundamental for the development of between-channel ridges and hence anabranching itself (Wende and Nanson, 1998; Tooth and Nanson, 1999, 2000a; Tooth, 2000; Tooth et al., 2008). Davis and Gibling (2010, 2011) have shown how the evolution of land plants has greatly influenced the evolution of channel styles over geological time. Huang and Nanson (2007) provided a quantitative theory to explain the occurrence of anabranching and demonstrated theoretically how it can improve sediment transport efficiency. The present study shows how anabranching on the Marshall River results in \( H \) numbers close to 0.30 and facilitates the continued transport of its coarse sediment load through a lower gradient reach.

The extent to which vegetation plays a role on the major channels of the Diamantina River is less clear. Because the alluvial clays there are so extremely cohesive, it appears that channels will form with low W/D ratios entirely in response to this. Trees in the form of \( E. coolabah \) line the bank-tops in many locations and there are often dense thickets of lignum (\( Meuhlenbeckia florulenta \)) as well. However, there are also places where the vegetation is sparse but the channel form remains much as it does when vegetation is present. It would appear that the cohesive clays that characterise the Channel Country river play a dominant role in determining channel form, with vegetation not a particularly significant factor. These narrow deep channels appear to transport very little bedload and to adopt a form more suitable for the transmission of large flows with what sediment load there is largely in suspension.

Interestingly, where the floodplain channels on the Diamantina are small and only inset in the upper friable cracking clays (Figure 6.2), the channel apparently does transport pelleted muds and they adopt \( H \) numbers very close to the optimum (Table 6.3).

### 8.4 Limitations and advantages of the \( H \) number model

In its application of the \( H \) number model to three rivers in arid or semi-arid Australia, this study has demonstrated that it has merit in identifying their equilibrium status.
Because the H number remains largely untested across a range of fluvial environments however, it is currently difficult to appreciate the absolute values that might be expected in different fluvial systems. In other words, while an H number of 0.30 at a cross section indicates maximum efficiency, how many units away is it to be defined as being inefficient? Clearly, there needs to be a more detailed investigation of the significance of H numbers that diverge from the theoretical optimum.

It is important to remember that geomorphological equilibrium states are scale-dependent, so it has been proposed that the selection of appropriate temporal and spatial scales are required for determining which reaches of a river are in equilibrium (Graf, 1988). Estimates of equilibrium timescales are rare and, according to Doyle and Harbor (2003), most are from modelling studies (e.g. Whipple and Tucker, 1999). The empirical studies that do exist suggest time to equilibrium via channel adjustments following catastrophic disturbances range between 1 and 10 years (Costa, 1974; Pitlick, 1993; Simon and Thorne, 1996; Ritter et al., 1999). Intuitively, the timescale for adjustment varies depending on the channel’s sensitivity to change (Chang, 1986). If equilibrium is to be determined by assessing the mass-balance of sediment transport over time, or assessing adjustments of channel dimensions such as width, depth or planform over time (Richards, 1982), then indeed many years of observation may be required for the equilibrium status of a system to be evaluated (e.g. Tooth and Nanson, 2000b). This is because geomorphologists generally assess equilibrium indirectly using such morphological parameters, rather than in terms of immediate energy balances; channel morphology takes time to adjust to changes in energy balance. If instead, equilibrium is defined as a physicist would define it, in terms of energy, then evaluating the H number circumvents the problems encountered by the geomorphologist beholden to taking repetitive field measurements over time or to measuring the mass-balance of bedload transport. The measurement of the energy balance at a single cross section may be subject to a degree of chance, but if it is assessed for a reach of river, as in this study, then the average energy status of the reach can be assessed and there is very little prospect of a chance result atypical of the general condition of the reach overall. For example, it is clear from this study that: (1) there are significant differences in the equilibrium conditions operating on the Diamantina River compared to rivers on the Northern Plains; (2) the ridge-form anabranching channels of the Marshall are closer to
the stationary equilibrium state than are other reaches on the same river; and (3) that there are likely to be differences in the energy state of the expanded compared to the confined reaches of the Plenty River. These interpretations have been obtained almost immediately and have not required time-lapsed morphological or mass-balance studies taking decades or longer.

Of importance to this particular study, is recognising that the H number model not only provides an opportunity to assess the bankfull equilibrium status of a channel at a point in time but instantaneously at numerous locations in the system. Determining how stable an individual channel section is over the longer term would require repeated measurements at the same cross section. Such measurements could also then be compared with similar measurements up and downstream, and thereby the response of the fluvial system as a whole could be monitored.

8.5 Suggestions for future research

Clearly, the H number model requires further application both within the Australian arid context and fluvial systems generally. The data contained in this thesis indicate the theoretical model is applicable to a wide range of river styles, but there are limitations (Section 8.4). For example, application of the H number model to rivers where bedload transport is known to be almost negligible creates values which are not close to optimal. The meaning of these values might be evaluated in clear-water rivers, such as at lake outlets, where sediment loads are effectively zero. Additional testing of the model across a range of fluvial systems will also assist in clarifying what each reported H number represents and specifically how different from optimum otherwise stable rivers can be.

Measurements of actual bedload transport in conjunction with evaluating the H number model would also be beneficial. This would determine whether these channels are, in terms of their bedload discharge, in dynamic or stationary equilibrium.

Finally, investigation of additional examples of topographic-defined versus vegetation-adjusted channel cross sections would be valuable. The body of literature dedicated to
the role of vegetation in fluvial geomorphology is steadily growing (e.g. Chapter 3), yet its direct incorporation into channel form and process in any quantitative way appears limited. Indeed, only one existing study, that by Jansen and Nanson (2010), was found to incorporate vegetation as part of the flow boundary.

Quantifying the effects of riparian vegetation in and along river channels is clearly a difficult task, but failing to attempt to do so means the physical science of fluvial geomorphology is, as Hickin (1984) said, flawed because it ignores processes that are not easily quantifiable and physically or statistically manipulable. The H number represents a means of quantifying the roles vegetation may perform in affecting channel process and form.

8.6 Conclusions

This research had three primary objectives pertaining to the theoretically based non-dimensional H number of Huang and Chang (2006), which establishes how close an alluvial channel is to stationary equilibrium. Through application of the model to three rivers within two highly contrasting fluvial settings in the arid Australian Lake Eyre basin, this study has advanced our understanding of some of Australia’s dryland rivers and the applicability of the H number.

In terms of the objectives set out in Chapter 1, this research has: (1) applied the H number model to rivers in their natural settings; (2) assessed the specific equilibrium conditions of these rivers; (3) evaluated the capacity of the H number model to identify why these rivers adopt particular geometric characteristics; and (4) determined how close individual reaches of these rivers are to the optimal equilibrium state. With their calculated H numbers, the Marshall and Plenty Rivers are shown to be at or very close to their self-adjusting stationary equilibrium state. In contrast, the Diamantina River has H numbers significantly higher than the optimum and suggesting potential instability, but independent evidence (long term observations) indicates a relatively stable system where surplus energy is consumed and therefore in some form of dynamic equilibrium.
While the three basic flow equations (continuity, flow resistance and bedload transport) and four self-adjusting endogenic variables (width, depth, velocity and slope) can predict the theoretical conditions required for the development of self-forming equilibrium channels, the maintenance of an optimal channel form under natural conditions appears to often require the introduction of vegetation, an exogenic variable that cannot yet be readily included in hydraulic computations.
References


CSIRO Centre for Plant Biodiversity Research, 2006. EUCLID [electronic resource]: eucalypts of Australia. CSIRO publishing, Collingwood.


Knighton, A.D. and Nanson, G.C., 1994a. Flow transmission along an arid zone anastomosing river, Cooper Creek, Australia. Hydrological Processes, 8: 137-54.


Appendix A:
Diamantina River cross sections
Transect 1

SC1, $H = 0.04$

SC2, $H = 0.09$

SC3, $H = 0.08$

SC4, $H = 0.09$

SC5, $H = 0.13$

Sub-channel

Distance (m)
P2

Distance (m)

1 m

H = 0.36
Distance (m)
$H = 0.09$
$Q_1 \quad H = 0.68$
$H = 3.40$
$H = 4.25$
Distance (m)

$H = 2.35$
\[ H = 0.57 \]
U2

\[ H = 1.09 \]
$H = 0.91$
W2

H = 1.58

Distance (m)

1 m

0  10  20  30  40
Elevations between the 4 sections not relative to each other
S Sub-channel

PC1, H = 0.63
SC1, H = 0.64
SC2, H = 0.59
SC3, H = 0.76
SC4, H = 0.50
SC5, H = 0.18
PC2 T1, H = 0.09
PC2 T2, H = 0.44
SC6, H = 0.60
SC7, H = 0.97
SC8, H = 0.51
PC3, H = 2.99
PC4, H = 0.87

Distance (m)

0 100 200 300 400 500 600 700 800

1 m
Transect 3

- PC1, \( H = 0.25 \)
- SC1, \( H = 0.69 \)
- SC2, \( H = 0.48 \)
- SC3, \( H = 0.19 \)
- PC2, \( H = 0.32 \)
- PC3, \( H = 0.54 \)
- PC4, \( H = 0.33 \)

Elevations between the 2 sections not relative to each other

S: Sub-channel
Transect 4

PC2, $H = 0.14$

SC1, $H = 0.08$

SC2, $H = 0.38$

PC4, $H = 0.79$

PC5, $H = 0.32$

$500 \text{ m}$
Distance (m)

H = 1.35
$H = 0.67$
$X_7$

$H = 1.54$
$H = 0.72$
Y1

Distance (m)

H = 1.43
Distance (m)

1 m

H = 0.16

Y2

Distance (m)
Appendix B:
Diamantina River hydraulic calculations
### Table B.1: Diamantina River hydraulic calculations

<table>
<thead>
<tr>
<th>Site</th>
<th>Cross section</th>
<th>Slope</th>
<th>Manning’s (C)</th>
<th>Absolute area (m²)</th>
<th>Total surface area (m²)</th>
<th>Average flow depth (m)</th>
<th>Maximum flow depth (m)</th>
<th>W/D</th>
<th>Slope ratio</th>
<th>Mainstream gradient</th>
<th>Hydraulic radius (m)</th>
<th>Flow resistance (m)</th>
<th>Average channel discharge (m³/s)</th>
<th>Average shear stress (kN/m²)</th>
<th>River stage (m)</th>
<th>Flood stage (m)</th>
<th>Uncertainty</th>
</tr>
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<tr>
<td>PC1</td>
<td>(116611)</td>
<td>0.019</td>
<td>1.000</td>
<td>5.89</td>
<td>6.000</td>
<td>0.000</td>
<td>7.500</td>
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<td>0.25</td>
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<td>0.05</td>
<td>22.07</td>
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<td>R</td>
<td>(116611)</td>
<td>0.038</td>
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<td>10.18</td>
<td>10.18</td>
<td>0.029</td>
<td>17.09</td>
<td>0.42</td>
<td>0.75</td>
<td>0.941</td>
<td>10.00</td>
<td>0.980</td>
<td>10.73</td>
<td>1.39</td>
<td>10.70</td>
<td>11.10</td>
<td>±0.01</td>
</tr>
<tr>
<td>Q</td>
<td>(116611)</td>
<td>0.054</td>
<td>1.054</td>
<td>14.99</td>
<td>14.99</td>
<td>0.051</td>
<td>17.20</td>
<td>0.43</td>
<td>0.75</td>
<td>0.941</td>
<td>10.00</td>
<td>0.980</td>
<td>10.73</td>
<td>1.39</td>
<td>10.70</td>
<td>11.10</td>
<td>±0.01</td>
</tr>
<tr>
<td>R</td>
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<td>19.22</td>
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<td>20.60</td>
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<td>0.980</td>
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<td>1.39</td>
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<td>±0.01</td>
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<tr>
<td>P</td>
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<td>0.088</td>
<td>1.088</td>
<td>23.38</td>
<td>23.38</td>
<td>0.088</td>
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<td>0.980</td>
<td>10.73</td>
<td>1.39</td>
<td>10.70</td>
<td>11.10</td>
<td>±0.01</td>
</tr>
</tbody>
</table>

Where:
- **PC** = primary channel
- **SC** = secondary channel
- **TC** = tertiary channel
- **W** = waterbody
- **TI** = bankfull depth as defined by lower bank
- **T2** = bankfull depth as defined by second lowest bank

*Note: Data rounded to two decimal places.*
Appendix C:
Diamantina River photos
a) Transect 1 SC4 (looking upstream)

b) Cross Section P3 (looking downstream)

c) Cross Section Q2 (looking downstream)

d) Cross Section R1 (looking downstream)

e) Cross Section T1 (looking downstream)

f) Cross Section U1 (looking upstream)
g) Cross Section W1 (looking upstream)

h) Cross Section V2 (looking downstream)

i) Transect 2 PC3 (looking downstream)

j) Transect 3 PC1 (looking upstream)

k) Cross Section X1 (looking upstream)

l) Cross Section Y1 (looking upstream)

m) Cross Section Z1 (looking upstream)
Appendix D:
Marshall and Plenty Rivers cross sections
$T_1, H = 0.21$

$T_2, H = 0.45$

$T_3, H = 0.59$
$S_{1b}, H = 0.70$

$S_{1a}, H = 1.16$

$S_{2b}, H = 0.83$

$S_{2a}, H = 0.27$
$T_1, H = 0.13$
\(S_1, H = 0.04\)

\(S_2, H = 0.42\)
S1, \( H = 2.09 \)
S2, \( H = 1.18 \)
S3, \( H = 0.50 \)

\( M5u \)

Distance (m)
Cross section when ridge(s) removed
Vegetation-defined channel width
Note: vegetation not to scale and schematic only
PB1n

T1, \( H = 0.15 \)

S1b, \( H = 0.75 \)

S1a, \( H = 0.68 \)

S2, \( H = 0.28 \)
$T_1, H = 0.37$

$T_2, H = 0.97$

$T_3, H = 0.81$

$T_4, H = 0.26$ (at greater $d_{50}$)
T1, $H = 0.11$

S1, $H = 0.214$

S2, $H = 0.27$

PB2w
PB3w

T1, H = 0.13
S1, H = 0.61
S2, H = 0.13
S3, H = 0.16

Distance (m)
T1, H = 0.52

T2, H = 0.24 (at greater d50)

PB3n
Distance (m)

T1, H = 0.11

T2, H = 0.10
Distance (m)  

S1, H = 0.10  

S2b, H = 0.34  

S2c, H = 0.38  

S2a, H = 0.10
Appendix E:
Marshall and Plenty Rivers hydraulic calculations
Table E.1: Marshall River hydraulic calculations

<table>
<thead>
<tr>
<th>Site</th>
<th>Class section</th>
<th>Slope</th>
<th>Manning’s n</th>
<th>Absolute resistance</th>
<th>Cross-sectional area (m²)</th>
<th>Total surface width (m)</th>
<th>Average flow depth (m)</th>
<th>Maximum flow depth (m)</th>
<th>W/D</th>
<th>Shear rate</th>
<th>Applied shear stress (kPa)</th>
<th>Total stream power (kW)</th>
<th>Base stream power (kW)</th>
<th>Replicate number</th>
<th>Final number</th>
<th>Shear stress (kPa)</th>
<th>Critical shear stress</th>
<th>Resistance</th>
<th>Probability</th>
<th>Uncertainty range</th>
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<td>Site</td>
<td>Cross section</td>
<td>Slope</td>
<td>Meaning’s</td>
<td>Absolute water level</td>
<td>Cross-sectional area (m²)</td>
<td>Total surface width (m)</td>
<td>Mean flow depth (m)</td>
<td>W/D</td>
<td>Slope rate</td>
<td>Water perimeter (m)</td>
<td>Hydraulic radius (m)</td>
<td>Manning’s n</td>
<td>Applied chair stress (N/m²)</td>
<td>Critical chair stress (N/m²)</td>
<td>Shear stress (W/m²)</td>
<td>Reynolds number</td>
<td>Number of fans</td>
<td>Female number</td>
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<td>Critical stress (pascal)</td>
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<td>-----------</td>
<td>---------------------</td>
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<td>0.023</td>
<td>2.13</td>
<td>486.42</td>
<td>298.39</td>
<td>1.62</td>
<td>22.13</td>
<td>184.49</td>
<td>0.789</td>
<td>288.66</td>
<td>1.62</td>
<td>0.99</td>
<td>964.34</td>
<td>20.68</td>
<td>1228.89</td>
<td>41.13</td>
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<td>1.62</td>
<td>22.13</td>
<td>184.49</td>
<td>0.789</td>
<td>288.66</td>
<td>1.62</td>
<td>0.99</td>
<td>964.34</td>
<td>20.68</td>
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<td>2464780.79</td>
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<td>P1</td>
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<td>20.68</td>
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<td>1.62</td>
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<td>288.66</td>
<td>1.62</td>
<td>0.99</td>
<td>964.34</td>
<td>20.68</td>
<td>1228.89</td>
<td>41.13</td>
<td>2464780.79</td>
<td>0.53</td>
<td>20.679942</td>
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</table>
Appendix F:
Marshall and Plenty Rivers photos
Marshall River

a) M1a (looking upstream)  
b) M1b (looking downstream)

c) M2u (looking downstream)  
d) M2 (looking downstream right channel)

e) M3u (right side of channel)  
f) M3 (looking downstream right channel from island)
g) M4u (looking upstream)

h) M4 (looking downstream 2nd channel from right bank)

i) M5u (looking downstream)

j) M5 (looking downstream left channel)
Plenty River

k) P1 (looking upstream)

l) P2 (looking downstream)

m) P3 (looking downstream)

n) P4 (looking downstream)

o) PB1n (looking upstream)

p) PB1w (looking downstream right channel (can see end of low bench on left hand side))
q) PB2n (looking upstream)  
r) PB2w (looking downstream)

s) PB3n (looking downstream)  
t) PB3w (looking downstream)
Appendix G:
Wentworth classification chart
### Wentworth Classification Chart

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Size (µm)</th>
<th>Wentworth Size Class</th>
<th>Phi (φ) (where φ = - log₂ diameter in mm)</th>
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<td>Very large boulder</td>
<td>-8</td>
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<td>1024 - 2048</td>
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<td>Large boulder</td>
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<td>512 - 1024</td>
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<td>Medium boulder</td>
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<tr>
<td>256 - 512</td>
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<td>Small boulder</td>
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<td>180 - 256</td>
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<td>Very large cobble</td>
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<td>32 - 64</td>
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<td>Very coarse gravel</td>
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<td>8 - 16</td>
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<td>0.0078 - 0.0156</td>
<td>7.8 - 15.6</td>
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<td>0.00006 - 0.0039</td>
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<td>Clay</td>
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Appendix H:
Sensitivity analysis of Manning’s n estimates
Sensitivity analysis of hydraulic calculations to changes in Manning’s n estimates

<table>
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<tr>
<th>River</th>
<th>Cross section</th>
<th>Slope</th>
<th>Manning’s n</th>
<th>Cross-sectional area (m²)</th>
<th>Total surface width (m)</th>
<th>Average flow depth (m)</th>
<th>W/D</th>
<th>Hydraulic radius (m)</th>
<th>Average flow velocity (m/s)</th>
<th>Cross-sectional discharge (m³/s)</th>
<th>Total stream power (W/m)</th>
<th>Unit stream power (W/m²)</th>
<th>Froude number</th>
<th>Shear stress (pascal)</th>
<th>Critical shear stress (pascal)</th>
<th>H number</th>
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<tr>
<td>Diamantina River</td>
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<td>35419.07</td>
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Notes:
* utilised measurement in study