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The hydraulic geometry of narrow and deep channels; evidence for flow optimisation and controlled peatland growth

Rachel Nanson
The University of Adelaide

Gerald C. Nanson
University of Wollongong, gnanson@uow.edu.au

He Qing Huang

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Abstract

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The hydraulic geometry of narrow and deep channels; evidence for flow optimisation and controlled peatland growth

Rachel A. Nanson^{a,*}, Gerald C. Nanson^b, He Qing Huang^c

^a University of New South Wales at the Australian Defence Force Academy, Northcott Drive, Canberra, 2600, Australia

^b School of Earth and Environmental Sciences, University of Wollongong, New South Wales, 2522, Australia

^c Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 11A Datun Road, Chaoyang District, Beijing, 100101, China

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1. Introduction

Freshwater peatland channels transport almost no sediment and exhibit self-adjusting channel morphologies and flow hydraulics very different from most alluvial systems that move bedload between relatively unconsolidated banks. While the general morphology of freshwater peatland channels has been the focus of some research (Garofalo, 1980; Jurmu and Andrie, 1997; Jurmu 2002; Smith and Perez-Arlucea, 2004; Nanson, *in press*), and the effect of their unusual cross-sectional and bend morphologies on flow patterns has been documented (Nanson, 2009b), their hydraulic geometry has received

only modest attention (Watters and Stanley, 1997; Tooth and McCarthy, 2004). Some data are available from tidal salt marshes (e.g., Myrick and Leopold, 1963; Ashley and Zeff, 1988; Zeff, 1988, 1999), but, despite similarities between freshwater and estuarine peatland channel geometries, the controls on these systems are obviously very different, particularly with respect to the directions of flow and relative effectiveness of riparian vegetation in providing bank strength. The objective of this research is to document the hydraulic geometry of narrow, deep, largely sediment-free peatland channels at Barrington Tops, New South Wales (Fig. 1), in order to: 1. Determine what controls their at-a-station and bankfull (downstream) hydraulic geometry relationships and 2. Compare these hydraulic relationships with those of alluvial streams transporting bedload. Our findings demonstrate that just a causal relationship exists between many alluvial channels and their floodplains (Wolman and Leopold, 1957; Nanson and Croke, 1992), so a causal relationship exists for the Barrington channels and the swamps that they occupy.

* Corresponding author. Current address: Australian School of Petroleum, The University of Adelaide, SA 5005, Australia. Tel.: +61 8 8303 8023; fax: +61 8 8303 8030.

E-mail address: rachel.nanson@adelaide.edu.au (R.A. Nanson).

Fig. 1. (a) Study area, and (b) location of cross sections. (Barrington River (B), Edwards Creek (E) and Polblue Creek (P). Note the scale difference between the two aerial photographs.

In the following [Sections 2 and 3](#), the unusual morphology, bank strength, evolution and hydrology of the Barrington Tops peatlands streams are briefly outlined to provide the reader with some knowledge of these rarely documented systems. A review of at-a-station and bankfull hydraulic geometry is then provided in the context of these unique characteristics in [Sections 4 and 5](#).

2. Barrington peatland channels: general observations

The swamps of Barrington Tops are situated on a plateau approximately 1500 m above sea level that extends over 1000 km², approximately 200 km north of Sydney, NSW. The swamps have developed over basalt lithology and often lie adjacent to outcrops of granodiorite. Accumulations of boulders and cobbles of these rock types

have constricted the valley outlets in which the swamps formed. The channels draining these swamps typically have narrow and deep cross sections ($w/d < 3$; [Nanson, 2009a](#)), near-vertical resistant banks of grass- and tussock-rooted peat, relatively flat beds, and are nearly symmetrical in cross section ([Fig. 2a](#)). Bankfull flow events were observed approximately eight times over three field seasons and measured bankfull water surface slopes ranged from 0.0007 to 0.0154 ([Table 1](#)). Despite these frequent bankfull flows, the channels were observed to transport no bedload and exhibit low w/d ratios close to the optimum for transporting water alone ([Chow, 1959](#); [Huang and Nanson, 2000](#); [Huang et al., 2002, 2004](#)). That these channels frequently accommodate bankfull flow and rarely flood overbank suggests that they are self-forming systems adjusted to contemporary flow conditions. Over the past ~1000 years these channels have reduced in size from

larger channels or gullies, and have developed inset, organic floodplains (Nanson, 2009a). While in places the channels appear depth-constrained by a resistant cobble basement to the swamps, they are otherwise essentially free to adjust their cross-sectional and planform geometry within a matrix of peat. For this reason the channels are assessed here in the same way as are self-adjusting systems in alluvium.

Despite the lack of observed bedload movement at bankfull flows, bedforms are present at some locations. These large dune-like but now-stable structures indicate that there must have been occasions when relatively coarse sediment was supplied (almost certainly from the forested headwaters) and reworked through the swamp channels. The hydraulic geometry of self-adjusting channels currently free of bedload transport has rarely been investigated (cf. Watters and Stanley, 2007) and is the focus of this study.

The almost continuously clear water at Barrington Tops enables ready observation of the vertical and sometimes overhung vegetated

banks as well as the roots that bind the peat banks together. An immediate assumption may be that the geometry of these channels is primarily from high bank strength and, hence, is a botanical—rather than a hydraulic—control. However, while bank vegetation remains relatively constant along their lengths, the geometry of the channels does vary and, consequently, motivates an examination of those controls in addition to vegetation.

3. The effect of bank strength on channel form

Micheli and Kirchner (2002a,b) focused on the particularly high bank strength afforded by wet meadow vegetation and found that such banks have erosion rates only one-tenth of otherwise comparable banks. Similarly, Smith (1976) demonstrated that banks with an effective root mat can be 20,000 times more resistant than those with the same sediment composition but lacking such a mat. Zimmerman

Fig. 2. (a) Individual cross sections. Stations P11, B4, B5 and B6 are depth-constrained by basement material and Stations P2, P7, E1, E2 and B1 are bedform constrained. (b) Views of the narrow deep peatland channels and method for velocity data collection using an OTT C2 current meter (bottom and inset).

Fig. 2 (continued).

et al. (1967) documented that narrower channels are maintained in sod as compared to forested settings and that in the Sleepers River in North America there was no downstream increase in width until catchment areas exceeded $\sim 13 \text{ km}^2$. From this they concluded that small streams are subject to exaggerated bank vegetation influences through the provision of either high bank strength or increased roughness imposed on the flow. Eaton and Giles (2008) obtained a similar finding in relatively unstable gravel bed streams, showing that vegetation dominated the geometry of relatively small streams but had virtually no effect on large ones. Watters and Stanley (2007) examined peatland channels in Wisconsin and concluded that biological forces had overridden physical drivers such as discharge and sediment load in determining peatland channel morphologies in those systems.

High bank strength provided by fine, cohesive sediment (Schumm, 1960; Knighton, 1975; Millar and Quick, 1993) or vegetation and the associated tensile strength of roots (Zimmerman et al., 1967; Andrews, 1984; Hickin, 1984; Hey and Thorne, 1986; Thorne, 1990; Abernethy and Rutherford, 1998, 2000, 2001; Huang and Nanson, 1998; Simon and Collison, 2002; Eaton and Giles, 2008) can allow for steep channel banks and low width hydraulic geometry exponents. The protection of banks through the provision of bank roughness by vegetation is also well documented (e.g., Kutija and Hong, 1996; Simon and Collison, 2002). In keeping with other research, the constraining effect of bank vegetation will be shown to be clearly evident in the Barrington peatland channels, where specific stream power values (typically $< 5 \text{ W/m}^2$, Table 1) are balanced by relatively high bank strengths. Unlike channels in some other peatland systems (Watters and Stanley, 2007), we will demonstrate that the morphol-

ogies of the Barrington peatland channels are the product of both botanical and physical (discharge and sediment load) controls.

4. Hydraulic geometry

Leopold and Maddock (1953) obtained empirically derived values of 0.5, 0.4, and 0.1 from a wide range of rivers as the exponents for b , f , and m in log-linear relationships between width, depth, and velocity (respectively) with downstream changes in the mean annual flood discharge (approximating bankfull discharge) as the independent variable. These exponents, or values close to them, have now been obtained in a wide range of rivers internationally (Knighton, 1998) and they compare reasonably well with those used in regime equations developed from canal data (Blench, 1952). This regularity in exponents in a downstream direction can primarily be ascribed to four typical controlling conditions: decreasing slope and sediment size with increasing bankfull discharge and increasing w/d ratio, the last of which is because of limitations in depth adjustment from insufficient bank strength (Church, 1992). Disproportionate channel widening leads to the deformation of the cross-sectional shape away from narrow and deep to one of greater total flow resistance. The net effect is no change or only a modest increase in velocity with increasing downstream discharge. The overall outcome in terms of downstream hydraulic geometry is the oft-quoted relation $b > f > m$ (e.g., Rhodes, 1987). In other words, width changes more rapidly than depth, which changes more rapidly than velocity.

A desire to explain the consistency of hydraulic geometry relationships in a wide range of settings has lead to the development of a number of theories. Leopold and Langbein (1962) drew an analogy between open thermodynamic systems and rivers and deduced that the primary condition controlling rivers was that of *minimum variance*, which resulted in rivers undertaking the least amount of work to move their water and sediment load. Drawing on the same thermodynamic analogy, Yang (1971, 1976, 1987) proposed *minimum energy dissipation rate* as a general theory of river action. However, such analogy-based approaches have not provided a convincing explanation for how sediment transport, typically bedload, affects river morphology. By investigating the interactions among the three essential components of a river (flow resistance, channel geometry, and bed load transport) in an explicit form, Huang and Nanson (2000), Huang et al. (2002, 2004), and Nanson and Huang (2008) demonstrated that the complex behaviour of alluvial channel flow is governed by the *least action principle* (LAP). Specifically, this work showed that optimum flow conditions are reached when the cross-sectional shape of a channel achieves the maximum sediment transporting capacity per unit available stream power, a concept first proposed by Pickup and Warner (1976) and Kirkby (1977). This can also be expressed as the minimum stream power required to transport the imposed sediment load (e.g., Chang, 1979). Huang and Nanson (2000) called these two sides of the same coin *maximum flow efficiency* (MFE).

Chow (1959) showed that, among channel sections of the same cross-sectional area, a semicircle has the least wetted perimeter and hence is the most hydraulically efficient. For rectilinear channels, Huang et al. (2004, p. 6) stated, "Only when $Q_s = 0$ is the most efficient alluvial channel geometry exactly the same as the best hydraulic section defined in frictional flow without transporting sediment, for both occur at $\zeta_m = 2$ ". (Q_s is the sediment discharge and ζ_m is the optimum w/d ratio). Such geometry is rarely attained in natural channels, primarily because bank strength is insufficient to maintain that form but also because nearly all channels carry bedload and require a relatively wide bed to do so. As the peatland channels at Barrington Tops transport almost no sediment, they provide an opportunity to re-examine the maximum flow efficiency proposal. A key objective of this study is to see how hydraulic geometry responds when bank strengths are exceptionally high and essentially uniform, and when there is essentially no bedload in transport.

Table 1
At-a-station hydraulic geometry values and associated site calculations for all stations, including average values for hydraulic geometry and w/d values.

Station	Number of measured flows	Width		Depth		Velocity		Manning's n		R^2	Q_{bf} (m^3/s)	w/d	Fr number	Depth of peat (m)	Reach bedform steepness	D_{50} (mm)	Reach slope	ω (W/m^2)
		b	a (coefficient)	R^2	f	c (coefficient)	R^2	k (coefficient)	R^2	y	t (coefficient)							
P1	5	0.07	1.59	0.60	0.43	1.17	0.97	0.50	0.54	0.95	0.05	0.19	0.08	1.35	0.01	0.14	0.0020	2.55
P2	6	0.06	2.70	0.64	0.60	1.67	0.94	0.35	0.22	0.8	0.11	0.20	0.05	1.30	0.03	0.10	0.0007	0.53
P3	6	0.02	0.96	0.28	0.29	1.16	0.97	0.68	0.90	0.99	0.01	0.23	0.10	1.25	0.03	2.47	0.0007	1.55
P4	6	0.12	0.94	0.30	0.21	1.03	0.96	0.67	1.03	0.94	0.02	0.24	0.12	1.38	0.03	2.92	0.0014	3.25
P5	5	0.01	1.19	0.08	0.33	1.06	0.72	0.67	0.79	0.94	0.03	0.31	0.14	1.18	0.03	None	0.0014	3.53
P6	5	0.05	1.27	0.54	0.16	0.91	0.69	0.78	0.81	0.98	0.02	0.26	0.09	1.23	0.03	3.13	0.0014	2.81
P7	5	0.01	1.50	0.46	0.48	1.02	0.98	0.50	0.65	0.98	0.04	0.27	0.15	1.10	0.03	0.51	0.0014	2.58
P8	6	0.08	1.18	0.48	0.32	1.33	0.96	0.60	0.63	0.99	0.03	0.30	0.10	1.15	0.03	0.02	0.0014	3.78
P9	6	0	1.29	0.02	0.29	1.31	0.94	0.71	0.59	0.98	0.04	0.30	0.07	1.15	0.03	1.65	0.0014	3.12
P10	6	−0.01	1.17	0.03	0.42	0.91	0.86	0.58	0.94	0.91	0.03	0.34	0.17	0.73	0.03	0.06	0.0030	8.30
P11	6	0.04	2.23	0.26	0.29	0.45	0.80	0.67	0.99	0.92	0.04	0.33	0.26	0.23	None	None	0.0052	7.74
B1	4	0	3.40	0	0.65	0.82	1.00	0.35	0.36	1.00	0.03	0.72	0.13	0.85	None	None	0.0016	3.32
B2	5	0	1.80	0	0.26	0.55	0.95	0.74	1.02	0.99	0.02	0.43	0.23	0.70	None	None	0.0024	5.57
B3	5	0	2.10	0	0.15	1.29	0.75	0.85	0.37	0.99	0.05	0.29	0.03	1.50	0.06	0.48	0.0007	0.94
B4	5	0	1.80	0	0.41	0.74	0.99	0.59	0.75	0.99	0.05	0.26	0.15	0.58	0.03	5.03	0.0034	4.73
B5	5	0	3.15	0	0.44	0.38	0.97	0.56	0.83	0.98	0.02	0.3	0.27	0.48	None	None	0.0154	14.2
B6	5	0.01	2.99	0.04	0.22	0.49	0.77	0.77	0.68	0.99	0.03	0.28	0.15	0.35	None	None	0.0154	13.69
E1	4	0.18	3.77	0.89	0.42	0.58	0.79	0.40	0.45	0.89	0.06	0.27	0.12	1.43	0.11	0.14	0.0020	1.94
E2	4	0.41	5.47	0.78	0.24	0.42	0.43	0.35	0.43	0.90	0.05	0.31	0.13	0.85	0.11	0.11	0.0020	2.11
av.		0.06			0.35		0.6			−0.42		2.20						

“Downstream hydraulic geometry” was so termed because it originally interpreted the characteristics of river cross sections *mostly* in that direction at close to bankfull stage. However, even Leopold and Maddock's (1953) own data set contravened this directional constraint which is in fact misleading when undertaking an analysis of how the behaviour of the bankfull flow changes with increasing discharge but without the decline in slope that commonly accompanies river profiles downstream. Here we adopt the term “bankfull hydraulic geometry” for such non-directional bankfull comparisons.

5. Methods

Nineteen hydraulic geometry stations were established on three swamp channels: six on the Barrington River, two on Edwards Creek and eleven on Polblue Creek (Fig. 1b). To minimise bend-induced asymmetry, these were each located at inflection points between bends where the channels were representative of that channel reach. The end points of each cross section were established 1–2 m landward from the bank tops of essentially equal elevation and were marked using wooden stakes. An aluminium plank was placed between these points; for the duration of the project, the cross section dimensions were rechecked before flow measurements were repeated and these remained essentially static throughout the study period.

Flow measurements were made using an OTT C2 current meter averaged at each point over a 30 s period. Verticals were spaced ~0.1–0.3 m apart, depending on channel width, and point velocity measurements were taken at 0.6 of the depth of flow if the total depth of flow was <0.5 m and at 0.4 and 0.6 of the flow depth (subsequently averaged) if the depth of flow was ≥0.5 m. The number of verticals varied from 3 to 6 across the stream, depending on channel width, resulting in 3 to 10 points in any cross section. This provided the maximum number of data points for each cross section that could be obtained at all stations within that stream for the constrained period of time representing a given flow event. A total of six flows were measured through all stations from very low (base) flow to bankfull (Table 1).

The peatland channel banks at Barrington Tops are comprised of firm peat and are well defined, enabling bankfull flow to be readily determined by observing channel flow during several high flow events. Following the methodology of several authors, bankfull stage height was assessed visually as the major break in slope between the vertical channel banks and the swamp surface (e.g., Myrick and Leopold, 1963; Hey and Thorne, 1986). The single recorded bankfull event showed a remarkably consistent bankfull condition along the length of the channels.

Cross section dimensional and velocity data were used to calculate the average width, depth, velocity, and channel cross-sectional area for each flow in each cross section using simple linear regression. Linear regression was chosen here because it is by far the most common method used previously, and therefore the values obtained here can be compared directly with those obtained by others, and in particular with Rhodes's (1977) diagrams. Furthermore, the dependent variables are regressed against discharge in order to evaluate how (on average) they change as discharge changes, and they are discussed below in that context. The exponents b , f , m , and y , representing the rates of change in width, depth, velocity, and Manning's n ($n = v^{-1} R^{*2/3} s^{1/2}$), respectively, were calculated from these results (v = velocity; R^* = hydraulic radius; s = slope).

6. Results and analyses

6.1. At-a-station hydraulic geometry

At-a-station flows were measured for discharges that varied by an order of magnitude. The exponents and R^2 for all power function regressions fitted to each data set are summarised in Table 1. The high R^2 values for depth and velocity presented in Table 1 indicate that these are indeed logarithmically related to changes in discharge in

these channels, as is Manning's n . Hydraulic geometry exponents for the study streams for width (b), depth (f) and velocity (m) averaged 0.06, 0.35 and 0.60, respectively. These results indicate that with changing at-a-station discharge, rapid changes in velocity are accompanied by moderate changes in depth and almost no change in width. Although not specifically included in the hydraulic geometry sections selected for this research, we observed that in some reaches where banks are undercut width may actually decline slightly with increasing discharge. As width is severely constrained by bank strength, not surprisingly depth and velocity accommodate the required changes. It is useful to compare the values obtained here with results from a variety of environments studied by others, using both average and individual station values.

6.1.1. Regional differences

With the aid of a ternary plot of the b , f and m exponents, Park (1977) attempted to delineate at-a-station hydraulic geometry exponents on the basis of climatic zones. His findings showed large variations in the exponents within regional, climatic zones and he concluded that local conditions rather than regional, climatically controlled trends determine a river's hydraulic geometry. Fig. 3 illustrates that the Barrington Tops peatland channels plot mostly within Park's regional division of tropical or humid-temperate channels. The latter zone could be consistent with Barrington Tops, but clearly there is nothing tropical

about the study area. The Barrington peatland channels also plot close to the zone of tidal estuaries defined by Myrick and Leopold (1963). They obtained average values for the exponents b , f and m of 0.09, 0.08 and 0.78, respectively, for the flood tide through a set of six cross sections in a small tidal estuary, representing what they describe (p.1) as "one of the extremes in the continuum of river channels". However, subsequent investigations into estuarine channels have found that some display similar hydraulic geometry to the upland channels presented here (Myrick and Leopold, 1963; Zeff, 1988) and some do not (Zeff, 1988) (Fig. 3).

6.1.2. Hydraulic controls

In Fig. 4, the Barrington data set is plotted on Rhodes (1977) ternary plot of b , f and m exponents for at-a-station changes, whereby plot divisions indicate distinct hydraulic characteristics. Rhodes's diagram is used as a simple illustrative means of comparing data obtained here in swamps with that obtained by others from numerous alluvial channels. Sixteen of the 19 sites here plot in the region which exhibits the following characteristics: $b < f$, $m > f$, $m > f/2$, $m > 0.5$, and $m/f > 2/3$. However, Stations E1, E2, P2, and B1 do not satisfy all of these criteria. Despite the data here having been collected from channels within a very small geographical area, there is considerable variation. The cause must lie in locally variable controls on the

Fig. 3. Ternary plot of at-a-station hydraulic geometry exponents from the Barrington Tops swamp channel stations, in comparison with planform, environment, and climate zone regions of the plot. P — Polblue Creek, B — Barrington River, E — Edwards Creek.

Fig. 4. Ternary plot of at-a-station hydraulic geometry exponents from the Barrington Tops swamp channel stations. The dashed line indicates stations (below it) at which b is less than one-third of f . Modified from Rhodes (1977).

channels, which are best examined through the implications for each of the divisions in Rhodes's (1977) diagram (Fig. 4).

(i) $b < f$ on the Rhodes diagram

Eighteen of the 19 sites (i.e. excluding site E2) exhibit this condition that Rhodes (1977) defined to describe three general characteristics: (a) with increasing discharge, width increases more slowly than depth (i.e. more rectangular rather than trapezoidal channels); (b) the suspended load exceeds the bedload (Leopold and Maddock, 1953), or there is very little sediment load of any kind; (c) the strength of the banks is unusually high. In the Barrington peatland channels, b is much less than f , and in fact is often less than one-third of f (Fig. 4), implying that these characteristics are present in the extreme, as discussed below.

Channel geometry: The symmetry and slot-like shape of the Barrington peatland channel physically account for low width exponents. Only Station E2 and to some extent E1 deviate from this characteristic, owing to the presence of bedforms. Their cross-sectional asymmetry results in higher b values because the rising stage fills a wider proportion of the channel bed before encountering the near-vertical channel banks. Similar channel geometries were observed in several wetland streams across North America by Jurmu and Andrieu (1997) and Jurmu (2002).

Sediment load and bank strength: The division $b < f$ in Rhodes's (1977) diagram implies a predominance of suspended load over bedload, however, in this case suspended load is absent and it is the effect of banks reinforced by vegetation and cohesive peat that results in this

characteristic. The channels have average w/d ratios of 2.2 (mean depth is used in this ratio throughout this study), closely approximating the optimal geometry of 2 for the most efficient transport of water free of bedload in rectangular channels. Stations E1 and E2 support this conclusion by being very different in form; they are wider and shallower, with w/d ratios of 6.5 and 7.1, respectively, and they possess large bedforms, indicative of there having been, at least in the past, some bedload transport. However, the majority of stations present extremely low width–depth ratios and width exponents. Huang et al. (2004) suggested that, despite such narrow geometries being theoretically optimal for sediment-free rectangular channels, insufficient bank strength in natural streams must limit their occurrence. The Barrington peatland channels with their well-vegetated cohesive banks provide, for the first-time, data that indicate the occurrence of such optimal channels where bank conditions are suitable. The banks of the study channels are nearly vertical in profile and are comprised of dense vegetative matter in their upper portion, below which is up to 1.5 m of blocky to smooth peat with variable densities of intruding roots. The bank geometries of some estuarine channels are also vertical and have resulted in similarly low width exponents, but this is due to high silt and clay content rather than vegetative support (Table 1) (Myrick and Leopold, 1963). The hydraulic erodibility of stream banks is difficult to determine quantitatively on most streams (e.g., Millar and Quick, 1993; Abernethy and Rutherford, 1998, 2000, 2001), because of the problems experienced in obtaining appropriate hydraulic erodibility measurements. An indirect measure of bank strength is therefore useful. Schumm (1960) plotted the weighted mean percentage of silt–clay in

a channel bank (termed the M value) against channel w/d and demonstrated a very convincing relationship ($R^2 = 0.91$): high bank silt-clay content corresponds to low w/d channel sections. Back calculation of theoretical M values for measured bankfull w/d values in the Barrington peatland channels range from 14 in broad, shallow sections to 143 in narrow, deep sections; Schumm's (1960) results indicate that the average M value of 76 obtained for the Barrington channels implies a high silt-clay content and is a surrogate for very resistant banks. Numerous auger holes adjacent to the banks reveal very little silt and clay but highly consistent peaty sediment and uniform vegetation along the length of each swampy channel. This suggests that bank strength is almost uniform and that the variations in back-calculated M values are not due to equivalent variations in bank composition or strength, but rather to some other factor. While the bank strength is essentially uniformly high, the stream beds are quite variable, consisting of cohesive clays, bedrock, coarse cobble lags and, in a few locations, coarse armoured bedforms in the form of immobile dunes. Clays, bedrock and cobbles form a variable basement depth across each swamp. It is this that greatly alters the w/d ratios and the back-calculated M values.

Fig. 5a illustrates how the depth of channel varies with the thickness of peat. At most stations, channel depth is close to the depth of deformable peat material ($R^2 = 0.74$), within the range of measurement error. Several stations (P11, B4, B5 and B6 in Fig. 2a) are located at the entry and exit points of the swamps where channel

slopes increase as the channels flow over confining basement sills. Here, the channel sections widen and shallow to accommodate depth-constrained geometries.

(ii) $f < m$

(iii) $m > 0.5$ on the Rhodes diagram

This part of Rhodes's (1977) diagram (Fig. 4) defines channels where velocity increases more rapidly than depth ($f < m$) and indeed where velocity accommodates more than 50% of the increase in discharge ($m > 0.5$).

For the Barrington swamp stations, with the exception of just three locations (E1, P2 and B1), the velocity exponent $m > f$ (Fig. 4). In other words, rapid increases in velocity accompany increases in discharge at most cross sections. Indeed, with the added exception of E2, $m > 0.5$ at all stations. Stations that do not conform to $m > 0.5$ (Stations E1, E2, P2, and B1) provide evidence for the cause of the dominance of increasing velocity in accommodating increased discharge. The exceptions represent stations where depth is constrained from the presence of stationary bedforms. As a consequence, these sites have relatively large w/d ratios. As is illustrated in the Manning equation, increased velocity is dependent on increasing slope but even more so on increasing depth (or hydraulic radius). As slope can be assumed to increase slowly with increasing at-a-station discharge (Leopold and Maddock, 1953), increases in depth and commensurate decreases in flow resistance (Hicks and Mason, 1998) are the most likely causes for rapid increases in

Fig. 5. (a) The relationship between the thickness of peat at each station and the maximum depth of channel, and (b) the relationship between the thickness of peat at each station and the bankfull w/d ratio. Open circles indicate stations with bedforms; these are not included in the regression analysis.

at-a-station velocity in most cross sections (Table 1). By contrast, the sites exhibiting exception to these conditions (E1, E2, P2, and B1) have limited channel depths, they are also subject to increased form resistance with increasing discharge (their fixed, armoured bedforms are dunes; Nanson, 2006) that dampens any increase in velocity (see Simons and Richardson, 1966). This is discussed in more detail in the following section.

(iv) $m/f > 2/3$ on the Rhodes diagram

This portion of Rhodes's (1977) diagram (Fig. 4) includes stations that decrease in roughness with increasing discharge (Table 1). The distances of the plotted stations to the left of this line illustrate the extent to which their roughness decreases, and indeed, the Barrington peatland channels tend to decrease their roughness more rapidly than most alluvial channels that have been studied. This includes all the stations described in the section above where velocity increases more rapidly than depth. Only Station B1 increases resistance with increasing discharge, and Station P2, very close to the line, and Stations E1 and E2 decrease their roughnesses only slightly (y values, Table 1). Importantly all four of these sections have bedforms that provide increasing form resistance with increasing flow stage (Simons and Richardson, 1966).

An explanation for these velocity and roughness characteristics lies in cross-sectional shape, bedforms, and bed-boundary material of the channels. In narrow and deep channel reaches, which includes most of the stations, the frictional resistance of the channel boundary rapidly decreases with slight increases in depth (with increasing discharge), resulting in rapid increases in velocity with discharge and hence high m values. In wide, shallow reaches the effects of boundary resistance are not so easily overcome. The considerable skin resistance provided by large cobbles on the bed at Stations P11, B5 and B6 at low flow are more easily overcome with increasing flow stage than is the form resistance provided by the stable, large, steep bedforms present at Stations E1, E2 (reach-averaged steepness (amplitude/wavelength) = 0.11), and B1 (reach-averaged steepness = 0.03), all of which are also relatively wide and shallow ($w/d > 5.14$). Station P2 also has bedforms, but these are less steep (< 0.03). Large bedforms can exert considerable resistance on the flow at stages up to bankfull (Simons and Richardson, 1966), and velocity therefore increases more slowly through sections that have these forms. Apparently, although bedload transport is negligible, residual bedforms are an important feature of flow resistance in those channels that have in the past been supplied with mobile sediment, whereas cobble lags provide significant resistance only at low flow. Coupled with the implications for increased hydraulic efficiency with increasing discharge, such as described above, Rhodes (1977) asserted that the condition $f < 0.5 < m$ defines channel cross sections that must exhibit very high bank strengths.

(v) $m > f/2$ on the Rhodes diagram

With increasing discharge, all the Barrington peatland channels display increasing Froude number up to 0.27 (Table 1). This implies that, given sufficient bedload of a transportable calibre, a variety of bedforms are theoretically capable of forming, however, interestingly no active bedforms were observed.

6.1.3. At-a-station summary

In the absence of significant bedload and where there is sufficient depth of unconsolidated material for a full or almost full depth adjustment, the Barrington peatland channels have developed average w/d ratios of only 2.2 (Table 1 and Fig. 2). This is very close to that for maximally efficient channel flow without bedload. Adjustments in flow width, depth, and velocity at-a-station in the Barrington peatland channels are directly related to variations in discharge (Table 1) but also to the available thickness of peat (Fig. 5a). From the shape of individual cross sections (Fig. 2) and their plotting position, which is uniformly low on Rhodes's (1977) diagram (Fig. 4),

it is apparent that adjustments in width, depth and velocity are a response to high bank strengths. However, in some places unconsolidated bed material has limited channel depths whereas in other places the limited depth to basement appears to be restricting optimum depth. Here w/d ratios range from ~ 7 to ~ 14 . This indicates that, even in peatland channels with resistant banks, channels must widen when depth is constrained.

6.2. Bankfull hydraulic geometry

6.2.1. Variations of exponents b , f and m

Absolute variation in bankfull discharge between the smallest and largest channels at bankfull was only $0.53 \text{ m}^3/\text{s}$; this constituted a nearly fourfold increase in discharge from $0.19 \text{ m}^3/\text{s}$ upstream at Polblue Creek Station 1 (P1) (Fig. 1) to $0.33 \text{ m}^3/\text{s}$ at P11, and from $0.28 \text{ m}^3/\text{s}$ at Barrington River Station 6 (B6) (upstream) to $0.72 \text{ m}^3/\text{s}$ at B1. Both Edwards Creek stations (E1 and E2) lie within these discharge values. If a continuum is assumed between the two swamps, bankfull flow then varies from 0.19 to $0.72 \text{ m}^3/\text{s}$ through 19 cross sections.

Barrington peatland channel bankfull hydraulic geometry data are summarised in Table 2 and illustrated in Fig. 6a; their combined data provided average width (b), depth (f) and velocity (m) exponents of 0.53 ($R^2 = 0.14$), -0.15 ($R^2 = 0.01$), and 0.62 ($R^2 = 0.20$), respectively. If data are considered separately for each swamp, the resulting exponents are 0.21 ($R^2 = 0.08$), 0.38 ($R^2 = 0.07$), and 0.41 ($R^2 = 0.10$) for the Edwards/Barrington Swamp system and -0.2 ($R^2 = 0.02$), -0.33 ($R^2 = 0.04$), and 1.53 ($R^2 = 0.58$) for the Polblue Swamp system. While localised variations in thickness of peat throughout each swamp result in much scatter in these relationships (e.g., Fig. 6a), the most convincing result is provided by the high bankfull velocity exponent produced for Polblue Creek ($m = 1.53$ with $R^2 = 0.58$) that illustrates a general characteristic of these systems. Owing to exceptional bank strength, there is very little change in width with discharge. Less obvious is the lack of change in depth; however, restrictions in both leave velocity to accommodate nearly all of the discharge variation. This is in stark contrast to rivers in clastic alluvium that results in limited bank strength, as illustrated by Leopold and Maddock's (1953) bankfull (downstream) hydraulic geometry exponent values for b , f and m (width, depth and velocity, respectively) of 0.50 , 0.40 and 0.10 (respectively) in midwestern United States streams. It appears that where the bank strengths are capable and the depth of deformable material is sufficient, velocity will accommodate most of any change in discharge.

Gradzinski et al. (2003) describe an anastomosing river in Poland where the peat is vertically aggrading at 1.0 – 1.5 mm/year to form erosion-resistant channels with w/d ratios of 2 – 10 . However, these are very different to the sediment-free Barrington system because accreting sandy bedload is decreasing depths and eventually blocking the channels and causing avulsion. Watters and Stanley (2007) examined deep peatlands in Wisconsin formed by the long-term vegetative infilling of lakes. W/d ratios (mean depth) averaged 20 and the b , f and m exponents were -0.79 , 0.40 and 1.5 (for b , f and m , respectively) This is remarkably different from the Barrington system, probably because these very low-energy groundwater-fed channels have no mineral substrate but rather a bed of loose semi-fluid, amorphous organic matter and banks, sometimes unstable, of living plants. Myrick and Leopold (1963) obtained values of 0.76 , 0.20 and 0.05 (for b , f and m , respectively) for small tidal estuaries, indicating that width accommodated by far the largest proportion of a change in discharge. This is probably because approaching base level limits increases in depth, and ocean backwater effects restrict increases in velocity as rivers approach the sea. Tooth and McCarthy (2004) obtained unusual downstream hydraulic geometry values for wetland streams in Africa of 0.45 , 0.21 and 0.34 (Maunachira River) and 0.83 , -0.01 and 0.18 (Okavango–Nqoga River) (for b , f and m , respectively). For reasons they explain, this data was not collected at a uniform return period

Table 2

Bankfull hydraulic geometry values for all stations combined, then separately for Polblue Creek only and Edwards and Barrington combined.

	Number of sites	Width			Depth			Velocity		
		<i>b</i>	<i>a</i>	<i>R</i> ²	<i>f</i>	<i>c</i>	<i>R</i> ²	<i>m</i>	<i>k</i>	<i>R</i> ²
Overall	19	0.53	0.14	0.14	−0.15	0.01	0.01	0.62	0.20	0.20
Polblue	11	−0.20	0.02	0.02	−0.33	0.04	0.04	1.53	0.58	0.58
Barrington and Edwards combined	8	0.21	0.08	0.08	0.38	0.07	0.07	0.41	0.10	0.10

along this essentially continuous river with declining downstream flow, however, the data are reasonably comparable downstream because of only minor stage variations over time. The latter two rivers transport an abundance of sandy bedload. Depth can change little with discharge between porous ‘banks’ formed of sedges and as a result, increases in discharge are accommodated by an increase in width and velocity, both aiding the movement of bedload. The Barrington peatland channels, which transport little or no bedload and which have average *b*, *f* and *m* values of 0.53, −0.15 and 0.62 (for *b*, *f* and *m*, respectively; Table 2; Fig. 6a), do not compare closely with any of these datasets. Although the *R*² values are low, the individual cross sections and the available thickness of peat (Figs. 2 and 5a and b) show that narrow, deep channels, efficient for the conveyance of water free of bedload, readily form where the swamps are deep enough to enable this to occur. Where depth is sometimes constrained by the limited thickness of the adjustable material in the form of peat, the channels may widen as they exit the swamps over shallow basement sills.

6.2.2. Controls on channel and swamp characteristics

The poor correlation between increasing bankfull discharge and channel depth in Fig. 6a and b appears to be caused by variability in

the depth of erodible peat. Fig. 7 shows that where the thickness of peat allows freely forming bankfull channels to deepen, width and velocity will decline commensurately. The swamps have formed in upland catchments above basin outlet sills that are comprised of coarse basalt cobbles and granite boulders. In such basins, the thickness of peat thins in the most upstream areas and again toward the exit sills. However, even where the peat is deepest in the central basins, the channel beds are comprised mostly of the basement material that underlies the peat. These swamps exhibit a remarkable coincidence; although sometimes less, their thickness of peat is rarely more than that required to form an optimally efficient channel with a *w/d* ~2 (Fig. 5b). This condition would be highly unlikely unless channel hydraulics exert a controlling influence on swamp formation.

As a result of strong banks and the sometimes limited adjustments in depth, changes in bankfull discharge are usually accommodated by marked changes in velocity. In particular, Polblue Creek shows a substantial increase in velocity with bankfull discharge (*m* = 1.53 and *R*² = 0.58) (Fig. 6b). High bank strengths mean that, unlike channels in clastic alluvium, width in these channels can be finely tuned to optimum flow conditions and velocities can increase without the banks collapsing. Rapid bankfull flows evacuate floodwaters and limit overbank flooding, thereby restricting vertical growth of the swamp.

Fig. 6. Bankfull hydraulic geometry relationships for (a) all stations combined and (b) Edwards Swamp (including Barrington River) and Polblue Creek, plotted separately.

Fig. 7. Bankfull w , d and v (w = black dots; d = open dots; v = grey dots) plotted against the thickness of peat.

Fig. 5a shows an almost one-to-one relationship between peat and channel depths and Fig. 5b shows that only at the swamp entrances and exit sills, or where now-stable bedforms offer obstruction to flow, do the channels depart from w/d ratios of ~ 2 (Stations P11, B5, B6, and B4).

7. Discussion and conclusions

At-a-station and bankfull hydraulic geometry analyses have shown adjustments in self-forming peatland channels in the absence of sediment load. Despite some constraint on channel depth caused by a limited depth to basement at a number of locations, most stations have near-vertical banks, at-a-station width exponents approaching zero, and w/d ratios of ~ 2 . Because the banks are strong and can form an optimally efficient cross-sectional ratio with depth, boundary resistance is minimised and discharge adjustments are accommodated largely by variations in velocity. These findings for optimally efficient channels are consistent with the MFE model proposed by Huang and Nanson (2000, 2002) and Huang et al. (2004) for the transport of sediment-free water.

At a few locations (especially at Stations E1 and E2 on the Edwards River), large bedforms of coarse sand and granules occur, but even at high flows virtually no bed sediment movement is apparent through the clear water. While there must occasionally be, or have been in times past, bedload in transport to construct such bedforms, they are now armoured and even at bankfull flow are highly stable. As a result of the additional roughness generated by such forms, these locations exhibit dampened rates of increase in velocity and compensating increases in width with increasing discharge.

Interestingly, unless severely depth-constrained (such as near swamp entrances and outlets or where large stable bedforms exist) both the larger Barrington channel system and the smaller Polblue system have attained average w/d ratios very close to two. Related to this, the thickness of peat in both swamps is no more than that required to form a bankfull channel with such an optimum ratio. Channel depths in freely adjusting, laterally active channels formed within clastic alluvium are well understood to be related to the formation of floodplains where the thickness of alluvium is closely related to the height of bankfull flows that occur regularly every few years (Leopold and Wolman, 1957; Wolman and Miller, 1960). A similar condition appears to apply to the Barrington swamps that are formed almost entirely of organic matter (Nanson, 2009a). However, in order to maintain a highly organic swamp, bankfull flows need to be relatively frequent or the vegetation at the surface of the swamp will die – swamp vegetation is highly dependent on the adjacent water table. Furthermore, sustained elevated water tables are essential in peatlands to prevent the decomposition and deflation of the peat (cf. Watters and Stanley,

2007). At Barrington Tops, bankfull flows are known to occur many times each year, and channels show remarkably uniform maximum capacities along their length. Furthermore, significant overbank flooding is rare. Once the channels have attained an optimal cross section through the vertical accretion and growth of a system of inset floodplains (Nanson, 2009a), further growth of the swamp vertically, which is highly water dependent, is limited by bankfull stage. The development and maintenance of the hydraulic geometry of the Barrington peatland channels is both biogeomorphic and biohydraulic in nature and yet is in accordance with the same optimising principles that govern the formation of self-adjusting channels in clastic alluvial floodplains.

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