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The impacts of alternating flood- and drought-dominated regimes on channel morphology at Penrith, New South Wales, Australia

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ABSTRACT Long flood records for the Hawkesbury-Nepean River have been used to define alternating flood-(FDRs) and drought-dominated regimes (DDRs). In the former, flood magnitudes and frequencies are higher with mean annual flood discharges ($Q_{2.33}$) from 2 to 4 times greater than for the latter. If channel size is assumed to be related to some level(s) of discharge, then such regime variations create the potential for channel change or adjustments. Surveys since 1863 at Penrith provide some insight into adjustments related to regime changes. In FDRs channel widths generally increase and depths decrease, while in DDRs, these changes are reversed. Human impacts in and beyond the channel modify the nature of adjustment or response.

Impact des régimes dominés par l'alternance d'inondation et de sécheresse sur la morphologie des chenaux à Penrith, Nouvelle-Galles du sud Australie

RESUME Les dossiers concernant les longues inondations du fleuve Hawkesbury-Nepean ont été utilisés afin de définir les régimes dominés par l'alternance d'inondation (FDRs) et de sécheresse (DDRs). Dans le premier cas, les amplitudes et les fréquences d'inondation sont plus élévées, la moyenne annuelle d'inondation ($Q_{2.33}$) etant de 2 à 4 fois plus élevée que dans le second cas. Si l'on assume que la largeur du fleuve est reliée à certains, niveaux de décharge, alors de telles variations dans le régime provoquent la potentiel de changements et d'adaptations fluviaux. Les relevés à Penrith depuis 1863 fournissent un moyen de comprendre les adaptations reliées aux changements de régime. En général dans le cas des FDRs en general, la largeur du fleuve augmente et sa profondeur diminue, alors que dans le cas des DDRs, ces changements sont inversés. La nature de l'adaptation ou de la réaction est modifiée par l'impact humain a l'intérieur et au-dela du chenal.

Introduction

Coastal southeast Australia receives precipitation at any time of the year. Winter rains of the south merge with summer-dominant rains of the north. However, totals are variable and irregular, and consequently flow regimes are very flashy. Superimposed on these highly variable annual conditions are periods of higher and lower mean rainfall lasting up to five decades. In wetter times, flood magnitudes and frequencies are very much higher than in drier periods. The former have been called flood-dominated regimes (FDRs) (Hickin 1983) and the latter, drought-dominated regimes (DDRs) (Erskine pers. comm.).

On the Hawkesbury River, west of Sydney, flood-stage records have been collected at Windsor since 1799. Upstream, where this river is called the Nepean, it has been gauged at Penrith since 1891 (Figure 1). From these records it has been possible to define alternating FDRs and DDRs at least since European settlement in 1788. Additionally, since this was one of the first areas settled outside of Sydney, there are several old surveys of the river which allow some insight into channel changes over the last 120 years. The major aim of this paper is to examine these changes and their possible relations with flood- and drought-dominated regimes.

After describing the study area, evidence for regime changes is reviewed and likely impacts on channels are discussed. There follows a description of the changes derived from old and new surveys in the study reach. These are then discussed in terms both of adjustments to regime variations and of human impacts in the catchment and channel.

The area

The Nepean River at Penrith drains 11,000 sq.km of mainly sandstone uplands southwest of Sydney (Figure 1c). At Windsor, the drainage-basin area has increased to about 13,000 sq.km. In this paper flood records have been used from both sites but most of the observations on channel changes have been made on the 5 km reach upstream of the Penrith weir (Figure 1b). Much of this channel is inset in alluvium and a Pleistocene terrace, whilst the upper part towards Glenbrook delta is in a deep sandstone gorge. The modern alluvia are narrow zones flanking the older terrace and these have been subject to many changes in the last 120 years. These recent materials form narrow benches in places (incipient flood plains) but the main bank tops in this "alluvial gorge" are above the 100 year flood level. Consequently, in spite of ponding by the weir, and the flattening of gradients, most high-event energy is expended within the channel, rather than overbank. Net changes associated with intervening events can be established by cross-section surveys through time. These began at the railway bridge in 1863.

Human impacts affecting this reach include: some clearance mainly of flood plains and adjacent shalelands of the Cumberland Plains, some urbanization (including the western parts of the Sydney metropolitan area), four small water-supply dams on the upper Nepean (affecting 1,700 sq.km), the large nearby Warragamba Dam (8,500

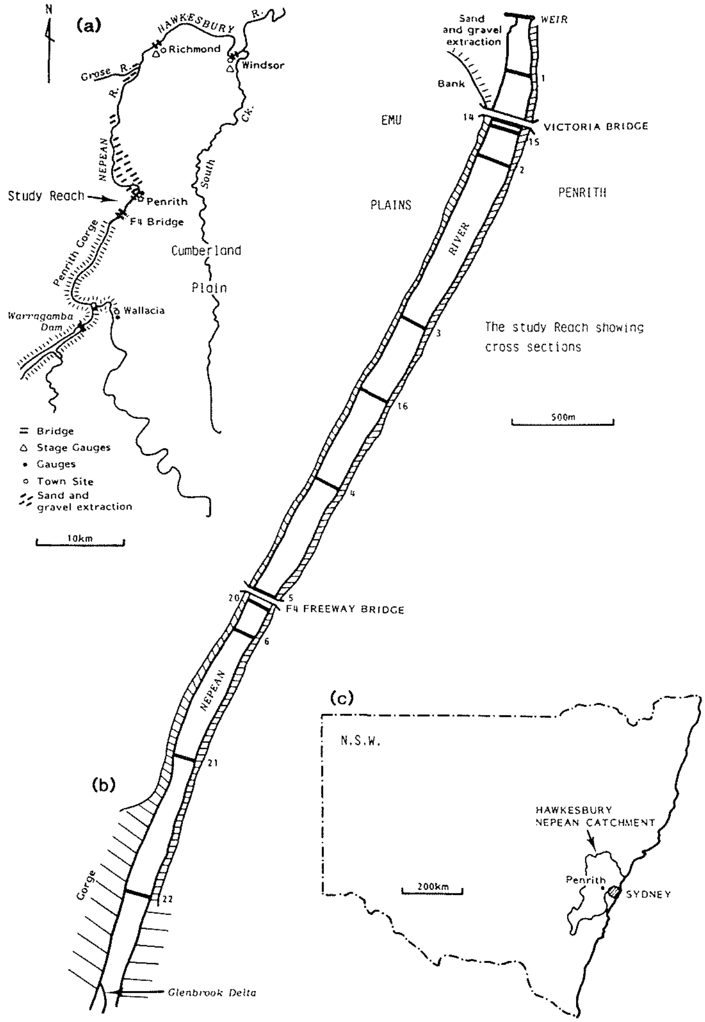

Figure 1

sq.km), the weir (1910), some recent channel-bank improvement works, and large-scale sand and gravel extraction from the channel, flood plains and terraces for 20 km downstream of Penrith. The Glenbrook delta (Figure 1b) now occupies more than half the gorge floor. A May 1944 flood removed about 250,000 m^3 of sandstone blocks from the lower Glenbrook gorge and deposited them in the Nepean. Much of the material had been derived from a railway cutting blasted out from the north side of the gorge. The delta now behaves like a partial weir interrupting the movement of bed load. Boulders from upstream have been trapped and scour has occurred downstream (Warner 1984).

The flood record

Flows above the 6 m stage A.H.D. (Australian Height Datum) are available for Windsor from 1799 (Riley 1980), the first big flood

(15.4 m) after colonization of N.S.W. in 1788. In the next 21 years (part of a FDR?), there were 11 floods above the 10 m stage (a large flood) (Table 1) and three above 6 m (a low flood). These caused much damage and some farming activities were relocated to South Creek (Jeans 1972).

Table 1 Windsor: floods over 6m and 10m and frequencies

Period	Regime	6m	10m	Years	6m yr^{-1}	10m yr^{-1}
1799-1819	FDR	14	11	21	0.7	0.5
1820-1863	DDR	15	7	44	0.3	0.2
1864-1900	FDR	43	14	37	1.2	0.4
1901-1948	DDR	24	4	48	0.5	0.1
1949-1978	FDR	48	9	30	1.6	0.3
TOTAL		143	45	180	0.8	<0.3

Source: Riley (1980: Table 1)

A DDR followed from 1820 to 1863 when there were only seven 10m floods in 44 years (Table 1) and the mean stage dropped from 13.0 to 9.6m. In the next 37 years (FDR), there were fourteen 10m and twenty-nine 6m floods, including the highest at 19.42m in 1867. The large number of 6m floods helped to reduce the mean stage to 9.5m.

In the following DDR (1901-1948), when the mean stage was only 8.1m, only four 10m and twenty 6m floods were recorded in 49 years (Riley 1980). Since 1949, another FDR has had a mean stage of 9.1m, with nine 10m and thirty-nine 6m floods in only 30 years (Table 1).

The high mean stages up to 1863 were thought by Riley (1980) to be associated with a different climate. However it is conceivable that not all 6m floods were recorded, that the main channel had smaller dimensions and that higher overbank roughness (before total deforestation of the extensive flood plains) had something to do with higher stages. A pre-1872 map at Windsor ferry supports the idea of a smaller channel.

Based on annual series analysis, the most probable ($Q_{1.58}$), the mean annual flood ($Q_{2.33}$) (Dury 1969) and the five-year flood (Q_5) levels do not show such a wide variation (Table 2). In FDRs, the

Table 2 Windsor: stages for $Q_{1.58}$, $Q_{2.33}$ and Q_5 (m)

Period	Annual Series			Partial Duration Series		
	$Q_{1.58}$	$Q_{2.33}$	Q_5	$Q_{1.58}$	$Q_{2.33}$	Q_5
1799-1819	N.A.	9.3	14.6	6.3	14.0	14.5
1820-1863	N.A.	<6.3	6.3	N.A.	<6.3	8.9
1864-1900	7.1	9.1	11.8	8.3	9.5	11.9
1901-1948	N.A.	6.3	7.8	<6.3	6.6	7.8
1949-1978	6.3	9.4	11.7	9.4	9.7	11.6

$Q_{1.58}$ most probable mean annual flood; $Q_{2.33}$ mean annual flood; Q_5 one in five-year flood. N.A. not available.

Source: Riley (1980: Table 1)

$Q_{2.33}$ stage is 9.1 to 9.4m, while in DDRs they are at least 3m lower. The Q_5 in the first FDR was 14.6m, repeating perhaps the conditions described above, while in later FDRs it was 11.8 and 11.7m.

Partial duration series analysis increases $Q_{2.33}$ in FDR regimes by 4.7, 0.4 and 0.3m respectively. $Q_{1.58}$ values are also greatly increased (Table 2).

The flood record at Penrith began in 1891. In this case, the three later regimes can be confirmed with discharge data (Table 3). However, the effects of the 2000 mill m^3 storage at Warragamba have attenuated flood peaks since 1960.

Table 3 Penrith: discharges for $Q_{1.58}$, $Q_{2.33}$ and Q_5 from annual series (m^3s^{-1})

Period	$Q_{1.58}$	$Q_{2.33}$	Q_5
1891-1900	2800	4900	6500
1901-1948	400	1100	2600
1949-1959	900	2900	7000 (pre Warragamba Dam)
1949-1978	700	2000	6000

Source: Water Resources Commission Data.

The same pattern is evident for Wallacia (Pickup 1976a) and for the Warragamba gauge (Figure 1a). However backwater effects of the Nepean have made this difficult to rate. Windsor stages are also influenced by backwater effects from the Colo River, by tidal conditions, as well as by variable inputs from Penrith and from the Grose River (Figure 1a).

Potential effects of regime variations on channel dimensions

If channel-forming discharges are related to some measure of discharge such as most probable ($Q_{1.58}$) or mean annual flood ($Q_{2.33}$) (Dury 1969, Leopold et al 1964), or even to both most effective (Q_{me}) and bankfull discharges (Q_{4-10}) (Pickup and Warner 1976), then changes in these discharges must have some impact on the channel. From the FDRs to DDRs there is a marked reduction in frequency (Table 1) and a big increase in the other direction. Magnitude changes for $Q_{1.58}$, $Q_{2.33}$ and Q_5 have also been considerable (Tables 2 and 3).

Increases in both water (Q^+) and sediment discharge (Q_s^+) should according to Schumm (1971) cause width increases (w^+) and depth decreases or increases ($d^\pm$), but normally the former. Decreases in water and sediment discharges would involve $w^- d^\pm$. Where sediment load is decreased ($Q^+Q_s^-$), as with conservation, interruption to sediment movement by dams and weirs, and the later stages of urbanization, depths would be expected to increase (Schumm 1971).

No details of the 1799 channel have been found. It may have been a mixed-load stream (Schumm 1977) in 1872 because gravels and sand were recorded in the first Windsor bridge survey. In an undated earlier ferry map, seven cross sections over 300m revealed maximum depth variations of 3.7 to 10.7m, hardly characteristic of a wholly sand-bed river. By 1891, well into a FDR, the maximum depth here was only 3m and the channel was wider (w^+d^-).

FDRs are characterised by frequent and larger floods, where bank erosion and bed accretion seem to be the normal responses. DDRs are quieter where bank recovery and depth increases are more common. So far most observations have been based on accelerated bank erosion from the late 1940's onwards (DDR-FDR) (see later discussion). Bank erosion is common, pools have filled in and channels are very different to those depicted in 1940s air photographs.

In DDRs, which have yet to be observed at close hand, channels are subject to lower channel-forming discharges. Bank recovery takes place, low benches are added to the channel floor and the confined flow helps to increase depths. At the end of the FDR regime in 1900, the Nepean was very wide and shallow. By 1949 most widths had decreased, some by up to 70m.

The surveys

It is evident from frequent surveys that there are fluctuations in dimensions rather than single trends, for example, recent surveys at Penrith and bridge-profile data at Windsor (Table 4). Here widths were increasing, while depths decreased and then increased by 1891. Data for that date may be anomalous because an 1891 hydrographic survey shows very shallow depths in that area.

Table 4 Cross section dimension data for the Windsor bridge

Date	Ref level	w	A	d_m	d	Remarks
<1872?	LWM	94	388	6.4	4.1	CS4 undated survey
<1872?	mid tide	96	450	7.1	4.7	CS4 undated survey
1872	AHD	98	375	4.9	3.8	(if deck = 4.3m)
1875?	AHD	107	230	3.8	2.2	
1891	AHD	128	350	4.7	2.7	

LWM low water mark; AHD Australian Height Datum; w width; A cross-section area; d_m maximum depth and d mean depth; CS cross section.

Source: N.S.W. Department of Main Roads maps and plans.

For the low flood stage (6m) only the data shown in Table 5 are available. All these changes were in a FDR (1864-1900). The date of the first map is unknown; it may have predated the 1867 flood. The 1872 survey was 9 years into the regime after seven 10m and eight 6m floods. The post-1875 survey is also undated but it shows the 1875 flood level (11.8m) but not the 1879 (13.1m). Thus it is assumed to predate the latter event. In the 7 year interval, there were ten 6m and only two 10m floods. Prior to 1891, the final survey in Tables 4 and 5, there were another thirteen 6m and six 10m floods.

This evidence shows that in-channel changes did occur within this regime. Changes above 6m are unknown but may be inferred from land

Table 5 Windsor bridge dimensions at 6m stage

Date	w	A	d_m	d	Remarks
1872	183	1130	10.9	6.2	some extrapolation of left bank data
>1875	181	1040	9.8	5.2	-8% area
1891	181	1217	10.7	6.7	+ 17% area

Source: N.S.W. Department of Main Roads plans.

clearance of flood-plain levels. Thus variations in stage have not only involved discharge, as suggested by Riley (1980), but also channel and flood-plain changes.

At Penrith, in the 5.5 km reach from weir to delta, many more surveys are available for comparison (Table 6). Originally this reach had a fairly flat gradient below the Warragamba-Nepean confluence, now enhanced even more by the weir. Deep holes in the sandstone gorge gave way to a more uniform bed downstream. Overlaps in surveys provide the best data on time-based changes but these are not common except at the two bridge sites (Tables 7 and 8).

Table 6 Penrith surveys (Figure 1b for locations)

Location	FDR	DDR	FDR	DDR	FDR		
Rail br = 14 = gauge	-	1863	-	-	1976	1980	1985
46 cross sections	-	-	1900	1949(w)	1982/3		
Cross Sections 1-6	-	-	-	1938(4)	1964	1984	1986
Cross Sections 14-16 20-22		-	-	-	1980	1985	

1900 cross sections not shown on Figure 1b

Sources: State Government plans from Public Works Department, Metropolitan Water, Sewerage and Drainage Board and Water Resources Commission. Sydney University Geography Department: 1949 and 1970 (Widths only), 1982/83, 1984, 1985 and 1986.

Table 7 Victoria bridge - channel changes

	At CTF				At BF (24.7m)				Cross section
Date	w	A	d_m	d	w	A	d_m	d	
1863	156	183	2.7	1.2	239	1971	12.3	8.3	Rail Survey
1900	201				-				Map 1900
1949	160								Air Photo
1976	201	586	4.6	2.9	242	2708	14.2	11.2	Gauge
1980	205	665	5.2	3.2	250	2666	14.8	10.7	14 WC+IC
1985	191	723	5.5	3.7	249	2832	15.2	11.4	14 SUGD

CTF cease to flow at the weir; BF near bankfull at 24.7 m AHD. WC + IC Water Conservation and Irrigation Commission.

Source: State Authorities, air photo analysis and survey.

Table 8 F4 freeway bridge - channel changes

	at CTF				BF				
Date	w	A	d_m	d	w	A	d_m	d	Cross Section
1900	173	348	3.5	2.0					42
1949	122	-	-	-					42
1964	144	476	3.8	3.5	244	2278	13.4	9.3	5 at 24.7m
1980	146	675	6.6	4.6	290	2808	17.5	9.7	20 at 26.0m
1984	146	733	6.0	5.0					5 at 24.7m
1985	143	743	7.0	5.2	245	2710	17.9	11.1	20 at 26.0m
1986	146	727	6.0	5.0	241	2462	15.6	10.2	5 at 24.7m

The first survey for the Victoria Bridge was at the end of a DDR in 1863. By the end of the following FDR, the width had been increased by 45m (1900) and then reduced by about 40m in the next DDR (Table 7). By 1976 in the present FDR, this loss had been recovered. Between 1863 and 1976, there had been an increase in capacity of 220% to weir crest level and of 37% to bankfull. Thereafter increases in capacity probably reflect the sediment deficiencies imposed by Warragamba Dam. Recent width reduction is due to bank-protection works.

Cross sections from 1900 (42), 1964 (20) and 1980 (5) are within 80m of each other and near the F4 bridge, built in the early 1970's (Table 8). In 1900 the channel was wide and shallow but at the end of the last DDR (1949), the width had been reduced by about 50m. In the present regime it has been stabilized at 144-146 m by bank works. The big increase in capacity after 1964 is probably due to sediment deficiencies imposed by the dam and delta (Table 9: Figure 1).

The other cross sections are of limited value with only 4 extending back to 1938. They tend to indicate "noise" induced by other factors, as is shown by width and mean depth changes in Table 9.

Table 9 Changes in width and mean depth

Cross Section	1938-1964	1964-1984	1984-1986
1	-	w-(14) d-(0.4)	w-(9) d+(0.1)
2	w+(5) d+(0.7)	w-(6) d-(0.1)	w-(4) d+(0.1)
3	w-(5) d+(0.6)	w+(8) d-(0.3)	w-(1) d+(0.2)
4	w-(5) d+(0.2)	w-(2) d+(0.6)	w-(1) d-(0.1)
6	w-(5) d+(0.2)	w-(26) d+(1.0)	w-(1) d-(0.2)
	1980-1985		
15	w-(10) d+(0.2)		
16	w+(3) d+(0.2)		
21	w+(13) d+(0.4)		
22	w-(3) d-(0.2)		

w width; d mean depth. (4) (0.2) width and depth changes in m.

Between 1938 and 1964, width should have been increasing and depths decreasing. The reverse indicates that sediment deficiencies were already apparent. In the next 21 years widths continued mainly to decrease with depths nearest the weir decreasing and those upstream increasing greatly (1.0m at C.S.6). After the 1986 flood, changes were minor except near the weir, where widths decreased. In the period 1980 to 1985, width changes were variable, while depths increased downstream from the delta accretion (C.S.22). These changes indicate that general tendencies are masked by other impacts, like closeness to weir (1), bank protection works (2, 4 and 6), scour below the delta (6 and 21), and accretion near delta (22), as well as the general effects of the dam.

Discussion

The secular change in climate in the late 1940's has been well documented (Pittock 1975; Cornish 1977), and the geomorphic effects of this change to a FDR were initially studied in the Upper Nepean by Pickup (1976a and 1976b). Its impacts elsewhere have received much attention (Henry 1977; Bell and Erskine 1981; Erskine and Bell 1982; Erskine and Melville 1983; Riley 1981; Warner 1983 and 1985; Warner and Paterson 1985).

The longer records have only been used more recently to define variable regimes and their consequences (Warner 1984 and 1986). These have imposed longer-term adjustments, which have been superimposed on the effects of short-term variations. Built into these longer changes are lagged responses based on variable thresholds in both bed and bank materials.

Where rivers are in gorges or source zones (Pickup 1984 and 1980), adjustments are minimal. Where they flow in armoured bed zones, major responses are infrequent even in FDRs, if thresholds for movement are related to low frequency events (Graf 1983). However, in transition and mobile zones, some or much of the bed load is moved more frequently and bed adjustments may be rapid. In backwater zones or sediment sinks (Pickup 1984 and 1986), low gradients and more cohesive perimeters again slow down changes (Warner 1986; Warner and Paterson 1985). Where beds are armoured and banks cohesive or well protected by vegetation, dimensional changes may also be slow, or in some cases they may occur overbank, involving flood-plain stripping (Nanson 1985). Then there is essentially a two-stage channel: an inner, smaller form conforming to lower flows (possibly the $Q_{2.33}$ of a DDR), and a larger channel flanked by high eroded alluvial banks, relating to lower frequency flows of the FDR. Where bank vegetation fails, there are rapid increases in width, especially where much of the energy is confined to the channel. This is in marked contrast to the smaller cohesive channels flanked by wide flood plains in backwater zones. Here flood-water ponding is common in low energy environments and there is no stripping in FDRs, only a greater incidence of flooding and slow adjustments in the main channel (Nanson and Young 1981; Warner and Paterson 1985).

In the study reach, the banks are fairly cohesive while the bed varies from armoured to mobile. At the end of the FDR in 1900 the channel was wide, shallow with numerous sand shoals and mobile. By 1949, after a DDR, it was much narrower. When surveys began in 1982, it was evident that a boulder bed existed in several parts, especially approaching the weir. Armouring continues below the weir where large volumes of sand and gravel have been removed.

The banks are a combination of several types of alluvium. There is even sandstone in the bed and left bank upstream of the F4 bridge. Well weathered Pleistocene gravels outcrop on the right bank near the Victoria bridge. In general the banks are fairly cohesive, with failure in amphitheatre-like scars, seemingly related to basal weakness in layers of wet, sandy alluvium. Benches often occur below these forms. Water level erosion involves tree falls and sandy bench trimming. Dense native riparian and exotic vegetation offers some protection to banks which extend up to 15m above low-water stage. Some bench surfaces equate to Q_{2-3} levels and might be viewed as incipient flood plains; others "relate" to less frequent flow stages, while the bank tops are at or above Q_{100} levels. Banks are being progressively engineered with grassed, graded slopes, rock-fill bases and gabions. This is to provide protection for residential areas on the bank tops, safer viewing areas for spectators at rowing competitions, and recreational parklands.

Conclusions

One hundred and eighty years of flood stage records at Windsor and 90 years of discharge data at Penrith have allowed alternating FDRs and DDRs to be defined. Two to fourfold shifts in the magnitude of assumed channel-forming discharges have great potential impacts on channel perimeters.

Differences in $Q_{2.33}$ stages at Windsor involve about 3m between FDRs and DDRs. However, frequencies and therefore energy to affect changes are much higher in FDRs. For instance, 6m floods occur 0.7 to 1.6 times per year and 10m floods every 2 to 3 years. In DDRs, their incidence is 2 to 3 years and 5 to 10 years respectively.

Their impacts on channels can be confirmed in part by surveys and air photograph analysis, particularly in the Penrith reach where there are several former surveys. In FDRs channels adjust normally by increasing widths and decreasing depths, while in DDRs, these trends are reversed. However, added complications can occur. These are due to drainage-basin modification, like land-use changes and urbanization, and to the effects of dams, weirs, bank-protection works, sand and gravel extraction, and the Glenbrook delta.

Recognition of these changes, their relations to alternating regimes, and the role of banks (even flood-plain surfaces in some instances) as dynamic buffer zones are important in the management of this river, particularly when contemplating future sand and gravel extraction and costly bank rehabilitation and stabilization works.

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