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Bed morphology and sedimentology at the confluence of unequal depth channels

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ABSTRACT

Spatial and temporal variations in the bed geometry and bed material size of a sand-bed river confluence with unequal-depth channels were monitored during a sequence of floods Additionally, two other sand-bed confluences were surveyed to test the replicability of these observations The confluences studied here have only one avalanche face, which corresponds to the front of a tributary mouth bar in the shallower channel, and do not exhibit a marked scour zone Three distinct morpho-sedimentological zones are present (1) an area around the upstream corner of the junction where the sediments are generally finer than the mean, (2) a maximum depth zone with coarser than average particles and (3) a bar at the downstream junction corner where grain size is finer than the mean and decreases slightly downstream Changes in relative discharge between the two channels had little effect on the grain size of the downstream junction corner bar, but exerted a strong influence on the position of the maximum depth zone and the front of the tributary mouth bar The downstream junction corner bar showed little evidence of the separation zone which is commonly observed at the confluences of laboratory channels The contrasting depths of the approach channels at the sites studied here may be partly responsible for the absence of the separation zone

Introduction

The recent increase in the number of studies of river channel confluences has yielded a better, yet still incomplete, understanding of the links between flow dynamics, sediment transport and bed morphology at these sites (Mosley, 1976, 1982; Ashmore, 1982; Ashmore and Parker, 1983, Gippel, 1985; Best, 1985, 1986, 1987, 1988; Roy et al , 1988, Roy and De Serres, 1989; Roy and Bergeron, 1990; Ashmore et al , 1992) These studies have shown that many junctions consist of two avalanche faces dipping into a scour zone, together with a bar at one or both of the downstream corners of the junction (Mosley, 1976, Best, 1986) However, the relations between bed morphology, grain size distribution and bedform type and orientation have not been investigated systematically. A better understanding of these relationships is an essential step in deriving a general model of confluence dynamics since bed morphology and bed material characteristics are closely linked to the flow dynamics of channel confluences. A thorough understanding of the variations in bed morphology and grain size distribution is also important for prediction of the transport and deposition of sediment-borne pollutants

The effect of tributary channels on longstream variations in grain size and sorting of the bed material has been shown to be of great importance (Miller, 1958; Lodina and Chalov, 1971; Livesey, 1976; Knighton, 1980; Troutman, 1980; Rhoads, 1987) At the scale of the confluence itself, Best (1988) published detailed maps of the bed morphology and grain size distribution He observed three main features in the distribution of sediments. (1) a decrease of the particle size at the upstream corner of the junction, corresponding to a zone of flow stagnation; (2) relatively coarse particles in the scour zone, (3) a rapid downstream decrease followed by a gradual increase of the grain size on the bar deposited downstream of the lower junction corner in a zone of flow separation Recently, Ashworth et al. (1992) examined the grain size distributions of bed material, bed load and bar head deposition in a braided river chute and lobe and observed some important spatial and temporal variations within a confluence–diffluence reach. In a more limited study, Petts and Thoms (1987) concentrated their sampling on the downstream corner bar and noticed a marked lateral coarsening of the grain size towards the main channel

There is a lack of data on the sedimentary facies preserved at channel confluences, which hinders the testing of hypothetical models such as those proposed by Bristow et al (1993) These models suggest the presence of large scale cross-stratification filling the scour zone formed by progradation of the mouth bars of each confluent channel Bristow et al. (1993) also anticipated that, based on Best's (1985, 1987, 1988) flow dynamics model, upstream dipping cross-stratification in deposits formed below the downstream junction corner as a result of recirculating flow in the separation zone Reverse flows have also been observed due to the partial diversion of flow from the main channel upstream along the tributary channel (Alam et al , 1985, Kochel and Ritter, 1986).

Until recently, laboratory studies on the morphology and fluid dynamics at confluences were only concerned with equal depth channels junctions However, Kennedy (1984), based on a data set from over 100 confluences, concluded that a high proportion of the junctions are discordant, i e. the tributary bed is higher than that of the main channel. This is mainly due to differences in channel-forming discharges and varying rock type and sediment calibre of the bed and banks (Kennedy, 1984) Best and Roy (1991) conducted simple laboratory experiments on confluences of unequal depth channels and observed the deformation of vortices generated along the mixing layer between the two flows. They postulated that these vortices may affect the sediment transport and bed morphology and that, consequently, the sedimentological characteristics of river channel confluences having unequal depth would differ significantly from those of equal depth

The field study reported here had two objectives (1) to describe the bed geometry at confluences of unequal depth channels and (2) to examine the relationships between bed morphology, surface sediments properties and flow dynamics as discharge varied at a given junction

Experimental design

The morphology and grain size distribution were surveyed at a sand-bedded confluence (Bayonne-Berthier, 90 km NNE of Montréal, Québec, Fig. 1a) during a period when flow conditions were changing rapidly. At this site, both rivers upstream of the junction have similar widths (~8 m) and the junction angle is 65° The tributary and main channels were determined according to the respective drainage area of the two rivers. The tributary (Berthier) comes from a wooded drainage basin whereas the main channel (Bayonne) drains an agricultural basin. Because of this, visualization of the mixing layer is enhanced by a difference in turbidity between the two rivers (Fig 1b) There is an elevation difference of approximately 0 60 m between the tributary and the main channel beds and the tributary has a mouth bar

A moveable bridge was installed to avoid disturbing either the flow or the bed during the measurement period and to improve the precision of measurement The bridge is 24 m long and rolls on two 30 m long rails, thereby allow-

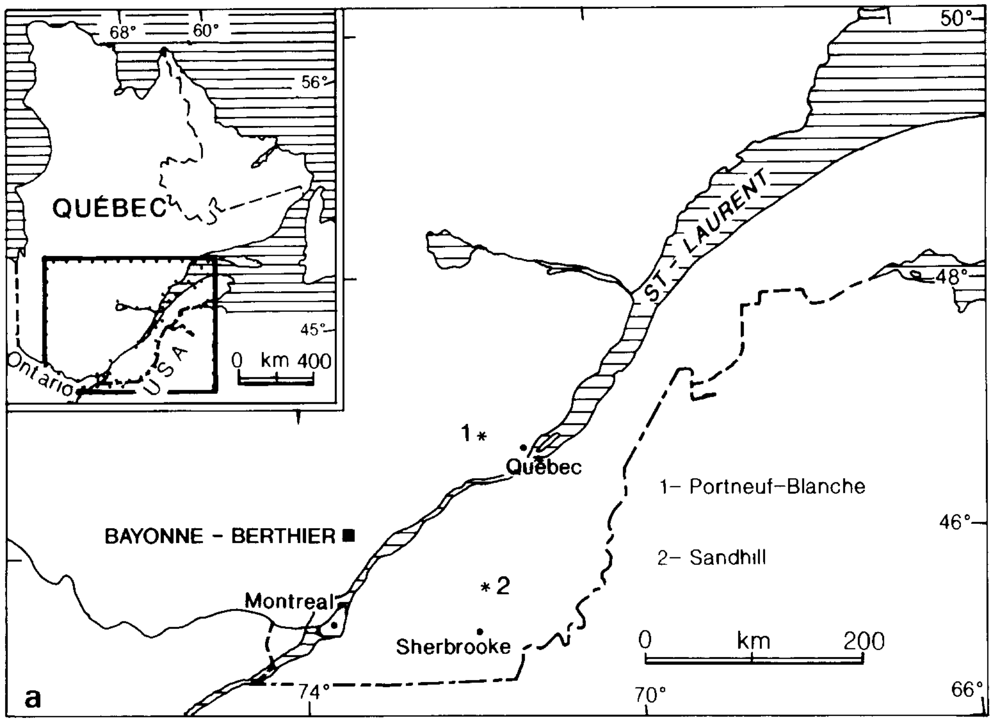

Fig 1 (a) Location of the study sites (b) Bayonne–Berthier confluence with the moveable bridge Flow is from right to left and the post-confluence channel is approximately 12 m wide Note the turbidity difference between the two streams ing sampling at any point within the confluence (Fig. 1b). Bathymetrical surveys were done on nine occasions during a sequence of floods (from October 1st to October 31st, 1990) using a gauging rod from the bridge which corresponds to the datum for all the maps The datum is located at the top of the metallic bridge structure, approximately 1 8 m above bankfull level, and is constant as the bridge moves on horizontal and levelled rails. The mixing layer limits (see Figs. 4 and 8) were taken from visual observations from the bridge at different longitudinal positions on each survey Twenty samples of bed material (equal to the top 5 cm of the superficial sediments) were also taken from the bridge on each of these nine occasions using a 4 m metre long rod with a 0 25 m long cylindrical collector which had a diameter of 0 07 m The spatial distribution of the sampling points was guided by preliminary morphological and granulometric survey, which indicated the zones with different characteristics, and was kept constant throughout the sampling period (Fig 2) Grain size distributions of the sediment samples were obtained solely by dry sieving as the proportion of particles finer than 63 μm was insignificant (<1%) Mean velocities were measured with Marsh–McBirney electromagnetic current meters in the tributary and main channel upstream of the junction in order to calculate the momentum flux ratio, M_r, which is defined as:

$$M_r = Q_2 v_2 \rho_2 / Q_1 v_1 \rho_1$$

where Q is the discharge (m^3/s), v is the mean velocity (m/s) of the cross-section and ρ is the water density (kg/m^3). The use of the momentum flux ratio is preferable to that of the discharge ratio since the depth and the width of the wetted perimeter are not constant (Best and Reid, 1984) On two occasions (October 16th and October 31st), velocity measurements could not be obtained and M_r was estimated from the flow stage (low flow stage usually corresponded to high momentum flux ratio and vice versa)

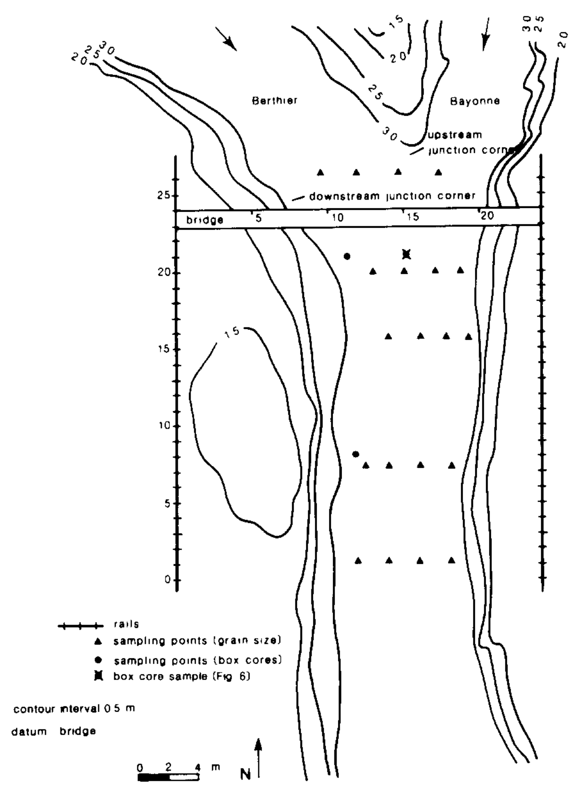

Fig 2 Topographic map of the Bayonne–Berthier confluence showing location of sampling points and moveable bridge All distances in metres

The vertical structure of sediments deposited at the Bayonne–Berthier confluence was sampled on two occasions using a Senckenberg-type corer with a closing arm and box cores 0.20 m deep, 0.15 m wide and 0.08 m thick. In this study, box cores were taken from the tributary mouth bar and the bar at the downstream corner of the junction (see Fig 2 for the position of the cores). Epoxy resin peels were made from the box cores in order to study the sedimentary structures (see Bridge et al , 1986 for a previous use of this technique). Photographs taken from the bridge allowed mapping of the bedform pattern, although this could only be done when the water was clear during low flows.

To test if the observations and results obtained at the Bayonne–Berthier junction could be generalized to other sites with similar grain

TABLE 1

Hydraulic conditions during the sampling period at the Bayonne-Berthier confluence

Date	Water level[a] (cm)	Maximum depth[a] (cm)	Mean flow depth (cm)	Mean flow velocities (cm/s)	M_r	Q_r	Sediment transport
October 1st	−277	−409	1 99	1 22	1 61	1 33	1 yes
			2 65	2 32			2 yes
October 4th	−315	−419	1 83	1 13	2 02	1 01	1 no
			2 32	2 30			2 yes
October 5th	−288	−415	1 100	1 23	1 22	0 71	1 no
			2 55	2 26			2 yes
October 9th	−318	−414	1 70	1 24	0 65	0 57	1 no
			2 25	2 33			2 yes
October 10th	−286	−414	1 100	1 28	0 46	0 55	1 yes
			2 56	2 24			2 yes
October 12th	−250	−414	1 124	1 48	0 18	0 38	1 yes
			2 81	2 22			2 yes
October 13th	−255	−409	1 114	1 37	0 49	0 67	1 yes
			2 73	2 28			2 yes
October 16th	−287	−418	1 92	1 22*	1 20*	0 70*	1 no
			2 56	2 26*			2 yes
October 31st	−322	−420	1 65	1 13*	2 00*	1 00*	1 no
			2 17	2 26*			2 yes

[a]Datum = bridge
*Approximative values
1 Main channel (Bayonne), 2 Tributary (Berthier)
M_r Momentum flux ratio, Q_r Discharge ratio

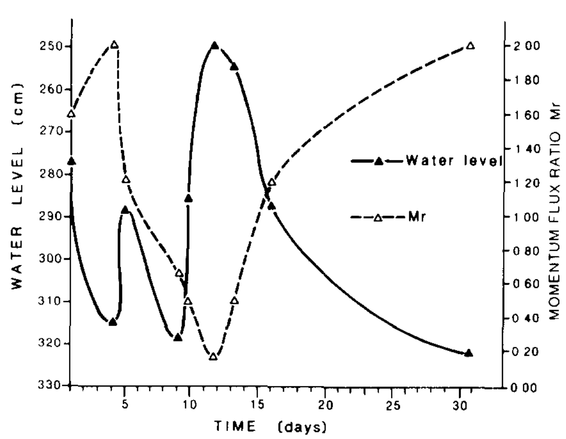

Fig 3 Water level and momentum flux ratio (M_r) variation at the Bayonne–Berthier confluence during the sampling period (October 1st to October 31st) Bankfull level is at −180 cm

sizes and planform geometries, two other sand-bedded confluences (Portneuf–Blanche, 200 km NE of Montréal and Sandhill, 150 km E of Montréal, Fig 1a) were surveyed during low flow conditions. Similarity in junction angle to the Bayonne–Berthier confluence was the main criterion for the selection of these sites. The size of the Portneuf–Blanche confluence (~12 m wide immediately downstream from the junction) is similar to that of the Bayonne–Berthier but the width is less at Sandhill (~2 m). A difference in bed elevation between the confluent channels was also present at both sites but was particularly marked at the Portneuf–Blanche confluence (1 40 m) Twenty bed material samples were taken at the Portneuf–Blanche confluence and 45 at Sandhill. Bed-form distributions were also examined at these

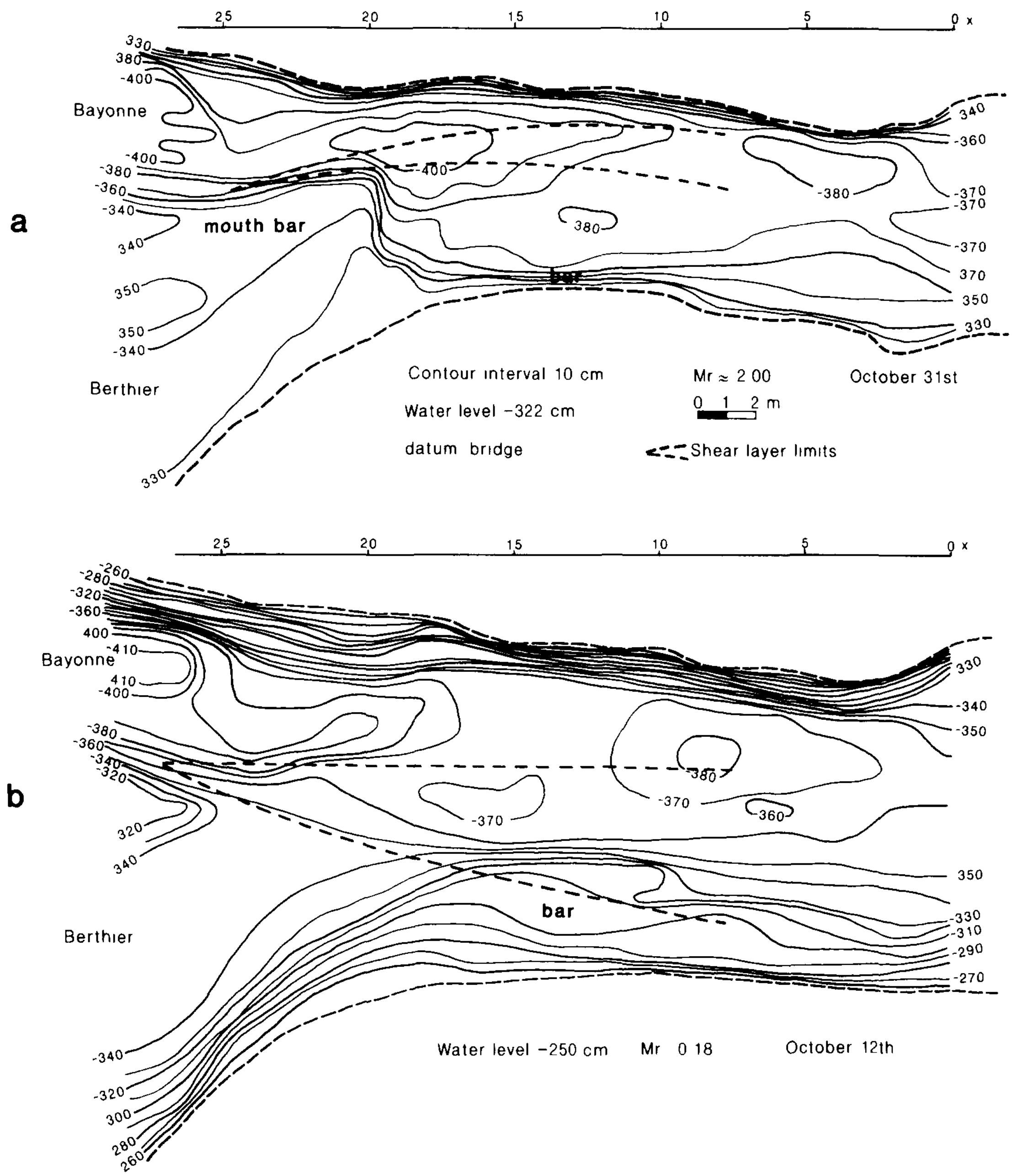

Fig 4 Bed topography of the Bayonne–Berthier confluence on (a) October 31st (low flow stage) and (b) October 12th (high flow stage) Shear layer limits were taken from visual inspection from the bridge

sites, but the Senckenberg-type corer could only be used at the Portneuf–Blanche confluence.

Results

During the sampling period at the Bayonne–Berthier confluence, the water level varied by 120 cm, i.e. from approximately 1/4 to 2/3 bankfull (Fig. 3) The momentum flux ratio also fluctuated rapidly since the two incoming streams do not necessarily have similar flood hydrographs during a flood (Fig 3). Table 1

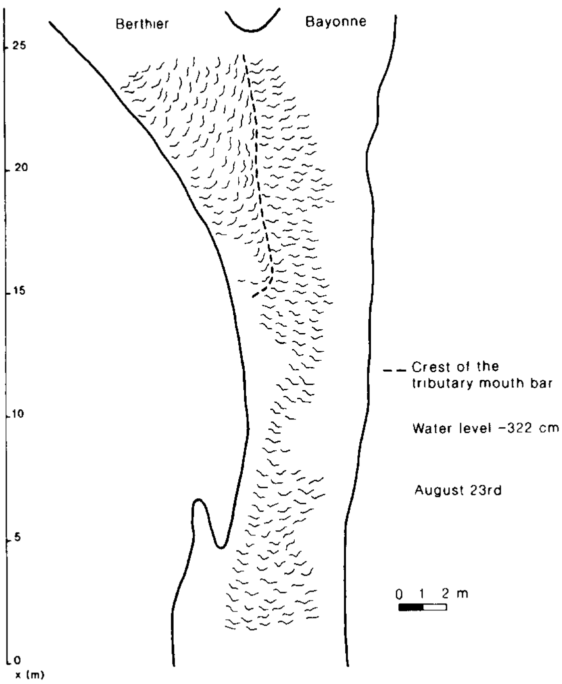

Fig 5 Map of the ripple crestline orientation during low flow conditions at the Bayonne–Berthier confluence The bedforms on the Bayonne side of the confluence were not detectable because of the water turbidity

summarizes the hydraulic conditions for the nine surveys.

The difference in depth between the two confluent channels can be represented by a depth ratio (D_r), defined as:

$$D_r = D_2 / D_1$$

where D is the mean flow depth and the subscripts 1 and 2 correspond to the main (Bayonne) and tributary (Berthier) channels, respectively. This ratio changes with flow stage since the relative depth difference decreases as the water level increases. For the flows monitored at the Bayonne–Berthier confluence, D_r varied from 0.26 to 0.66 (mean: 0.52).

Bed morphology

The morphology at the Bayonne–Berthier confluence varied considerably during the sampling period but at all times we observed: (1) a single tributary mouth bar, (2) the absence of a marked scour zone and (3) a bar on the tributary bank downstream from the junction (Fig 4)

The tributary mouth bar prograded into the main channel when the momentum flux ratio was high, a situation which usually occurred at low flow (Fig. 4a) This migration produced a steeper face than that observed at higher flow where the momentum flux of the main channel was usually greater than that of the tributary (Fig. 4b) The presence of a tributary mouth bar created a marked flow deflection at the entry of the confluence and this was particularly apparent in the ripple pattern at low flow where the change in orientation between ripples on the tributary mouth bar and in the main channel could be as much as 90° (Fig. 5) The progradation of the avalanche face produced large cross-sets (height 8 cm) which are visible in the bottom of a box core sample (Fig. 6) Smaller scale cross-laminae within some of these sets record the occasional presence of ripples migrating sub-parallel to the avalanche face. The avalanche face cross-sets are erosively overlain by ripple laminated sands which fine upwards; these may indicate reworking of the top of the mouth bar during a flood event.

A striking feature of the Bayonne–Berthier morphology is the absence of a marked scour zone, which is commonly seen as a major morphological characteristic of river channel confluences (Mosley, 1976, Ashmore and Parker, 1983, Best, 1986) The maximum depth downstream of the confluence was generally less than the maximum depth of the main channel upstream of the confluence (Fig 4) The apparent scouring observed at low flow stage (Fig 4a) is likely the result of local erosion due to the bank protrusion which constricts the flow in that zone. In any case, these zones of local scouring cannot be compared with typical confluence scours (e g Mosley, 1976, Best, 1986) which are always deeper than both tributary beds Moreover, Table 1 shows the lack of a relation between maximum bed

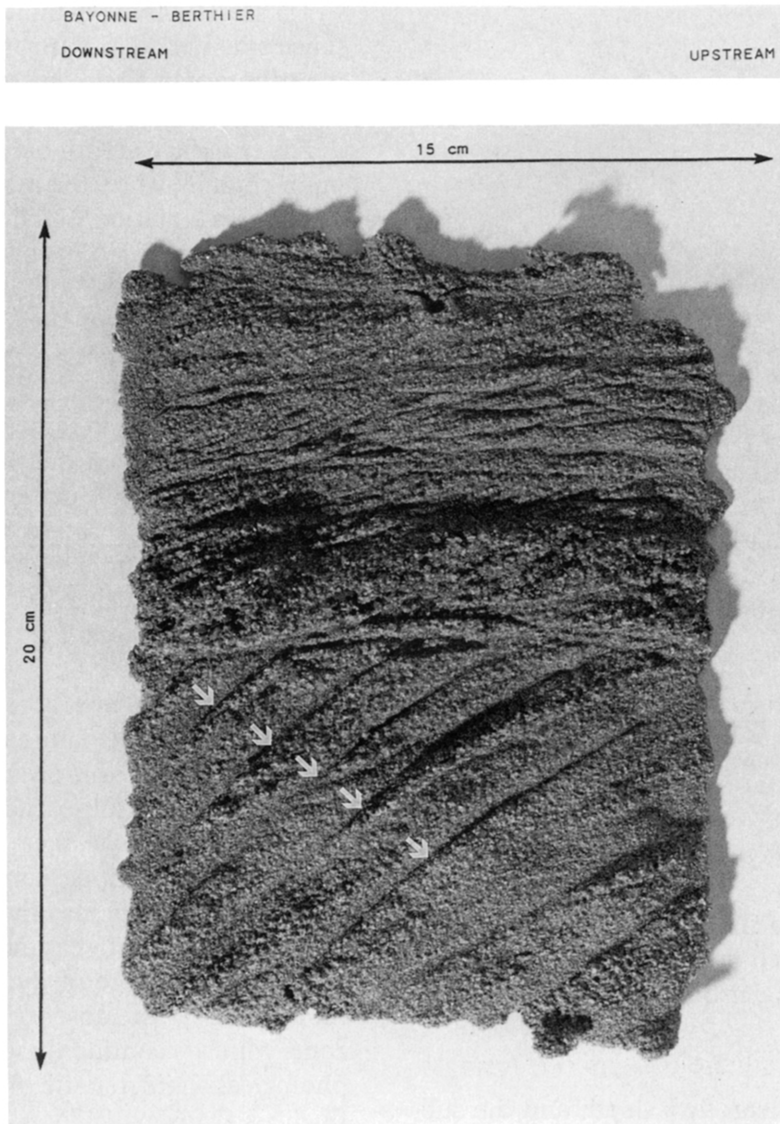

Fig 6 Box core sample taken near the avalanche face on the tributary mouth bar at the Bayonne–Berthier confluence (see precise location on Fig 2) Note the large scale cross-sets in the bottom of the sample (indicated by the arrows)

elevation and the discharge ratio ($r = -0.006$) This is inconsistent with the results of Mosley (1976) and Best (1985, 1987, 1988) which indicated a direct relation between scour depth (i e. maximum depth) and discharge ratio and may show that the scouring processes at an unequal depth channels confluence are different from those at a confluence with concordant beds. Indeed, our observations at other unequal depth confluences (e.g. Portneuf–Blanche, Fig 7a) show that the morphology is generally characterized by an absence of scour and by only one true avalanche face which corresponds to the front of the tributary mouth bar. This morphology, however, is not solely the result of bed discordance and can be affected by other factors such as junction angle, plan symmetry or discharge ratio. The area at the base

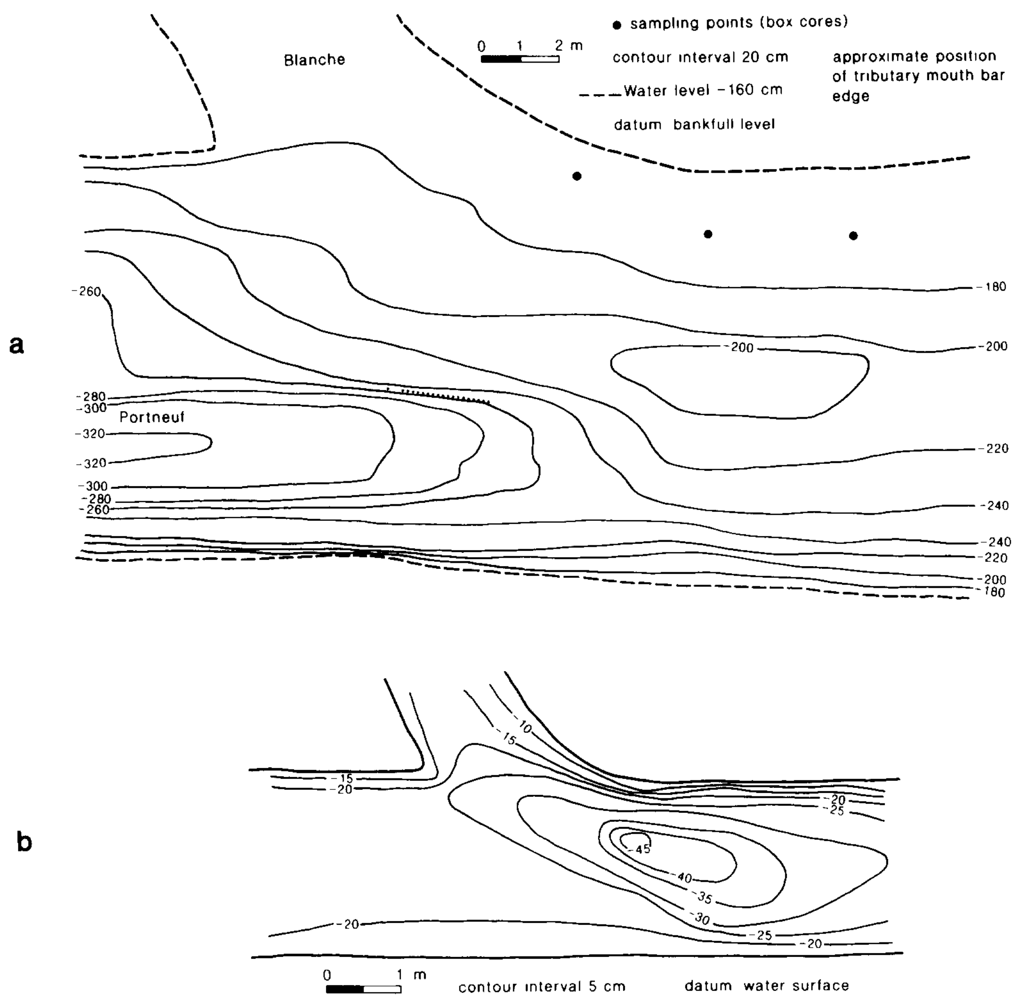

Fig 7 Bed topography of sand-bedded confluences at low flow stage (a) Portneuf–Blanche and (b) Sandhill

of the mouth bar is therefore described as the maximum depth zone rather than a scour zone since it corresponds to the main channel thalweg. At the Sandhill confluence, the depth ratio was greater than those at the Bayonne–Berthier and Portneuf–Blanche confluences; its lowest value (i e at low flow) was 0.66 and would be near unity at high flow. The bed morphology at this site is therefore different from that at marked unequal depth channel confluences and is characterized by the "classical bed morphology" of a confluence consisting of a scour zone with two avalanche faces (Fig. 7b).

A bar at the downstream junction corner was observed at all times at the Bayonne–Berthier confluence and at the two other sites even though it is less apparent at low flows because it is exposed (Figs. 4a and 7b). The presence of this bar is consistent with previous observations on other rivers (Mosley, 1976; Best, 1985, 1987, 1988). However, at the Bayonne–Berthier confluence, no evidence was found for a flow separation zone (Best, 1987); for the monitored flows, the ripples were always oriented downstream (Fig 5)

Grain size distribution

At the Bayonne–Berthier confluence, the median particle diameters of bed material of

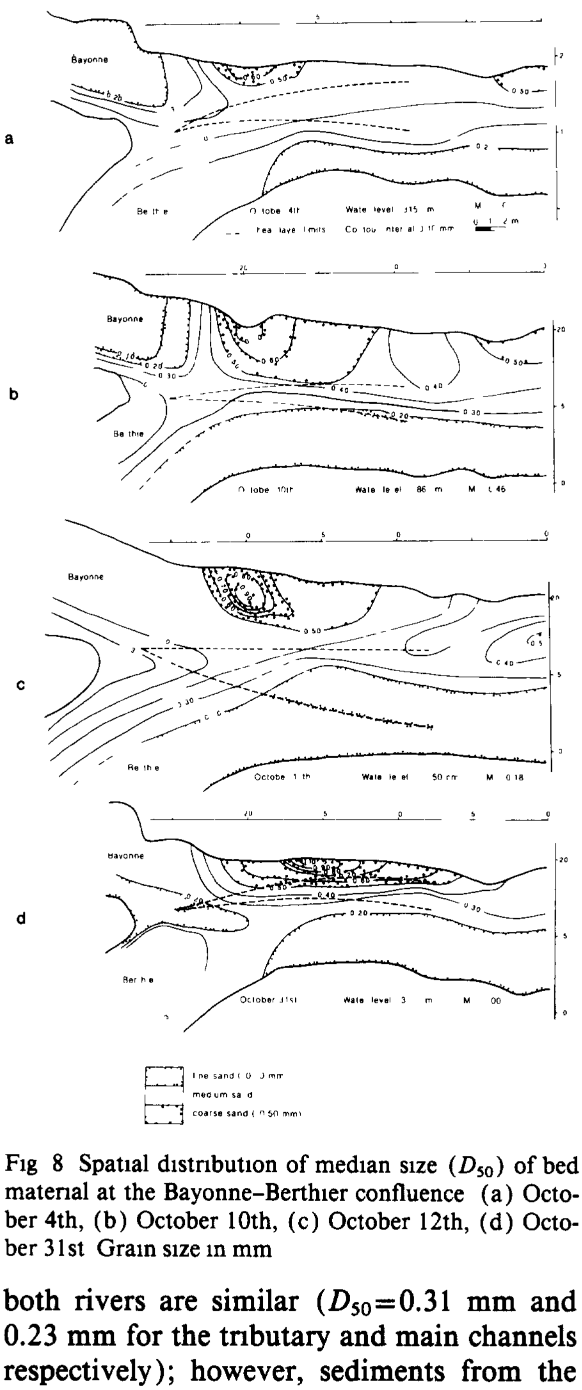

Fig 8 Spatial distribution of median size (D_{50}) of bed material at the Bayonne–Berthier confluence (a) October 4th, (b) October 10th, (c) October 12th, (d) October 31st Grain size in mm

both rivers are similar (D_{50}=0.31 mm and 0.23 mm for the tributary and main channels respectively); however, sediments from the Berthier are moderately sorted medium sands (mean sorting coefficient, σ=0.86) whereas the grain size distribution of the Bayonne is bimodal with peaks in coarse silts and coarse sands (σ=1.98). The bed sediments of the Berthier and Bayonne rivers were easily detectable by their different colour (ochre and grey respectively) At all times, the spatial distribution in bed material grain size was characterized by three distinct zones which corresponded roughly to the three morphological zones previously identified: (1) the upstream corner of the junction which has generally a finer grain size (Fig. 8c, d); (2) the maximum depth zone where the sediments are relatively coarse and (3) the bar at the downstream corner of the junction where the particles are finer (Fig. 8). Similar zones were also observed at the Portneuf–Blanche and Sandhill confluences (Fig. 9). Although this general spatial pattern in grain size was observed for each survey at the Bayonne–Berthier confluence, there were important variations related to stage

At the apex of the junction, when the momentum flux ratio is high (M_r> 1), the tributary flow penetrates slightly into the main channel, allowing the Berthier sediments to be deposited on the Bayonne side (Fig. 8a). As the momentum flux ratio decreases, finer particles from the Bayonne are found on the Berthier bed (Fig 8c) However, the response of the sediments to changing momentum flux ratio is not instantaneous and there may be a lag between a given flow condition and the resulting grain size. For example, fine sediments with a peak in coarse silts characteristic of the Bayonne sediments are found on the Berthier side despite the high momentum flux ratio in Fig. 8d.

In the maximum depth zone, the median grain size varied from 0.66 mm (October 4th) to 1 15 mm (October 31st). The increase in the median grain size appears to be the result of the increasing bed shear stress as flow stage rises However, the coarsest particles are observed on October 31st (Fig. 8d) where flow stage is lowest; this grain size distribution is likely inherited from previous flow conditions. An interesting feature in Fig. 8 is the lateral displacement of the coarse particles, illustrated by the position of the limit of the 0.50 mm curve moving from the left bank (y=19

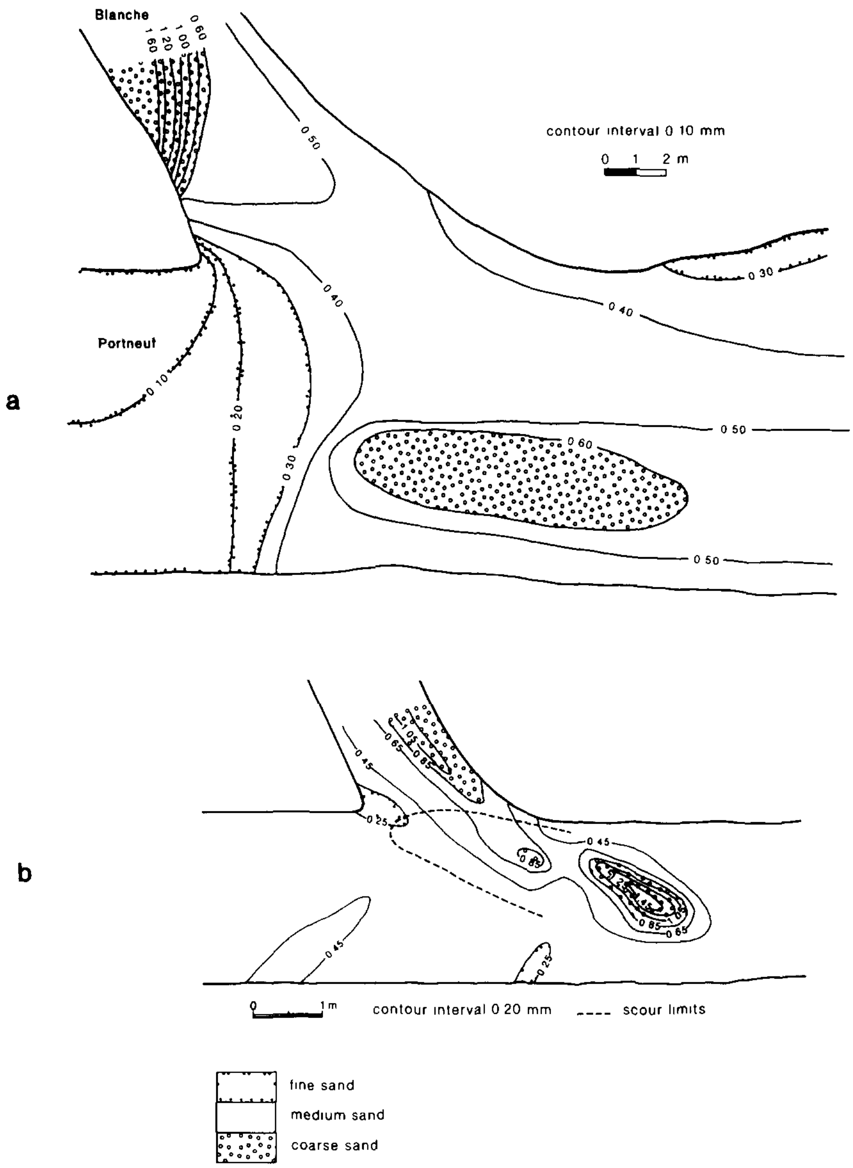

Fig 9 Spatial distribution of median size (D_{50}) of bed material at two sand-bedded confluences (a) Portneuf–Blanche and (b) Sandhill

m, Fig 8a) towards the centre of the junction (y=16.5 m, Fig. 8b). This lateral displacement of the coarser particles seems to be related to the position of the mixing layer which is itself controlled by the momentum flux ratio For a high momentum flux ratio, the coarser sediments are located close to the left bank (Fig 8a) while the opposite occurs for a low ratio (Fig. 8c)

The grain size distribution on the bar at the downstream junction corner was remarkably constant compared to that of the two previous zones. For the nine surveys, the particle size was significantly finer than the average median grain size of the post-confluence channel (Fig. 8). However, the particle size in the upstream part of the bar (x=13 m to x=23 m) is more affected by the changes in flow conditions (0.13 mm < D_{50} < 0.39 mm) than the downstream end (x=0 m to x=13 m) where the median diameters only varied from 0.12 to 0.14 mm during the sampling period. The box cores also revealed a clear distinction between the upstream and downstream part of the bar there were virtually no variations within a box core in the downstream zone whereas upstream zone box cores exhibited some grain size vertical variations. At all times, we noted a slight streamwise reduction of the grain size, contrary to the decrease followed by an increase in grain size that Best (1988) observed at a gravel bedded confluence

Discussion

Upstream junction corner

Best (1985, 1987, 1988) described the upstream junction corner as a flow stagnation zone where the two incoming flows diverge towards the outer banks and, therefore, the velocities are significantly reduced. As a consequence, Best (1988) observed at a gravel-bedded confluence a decrease in the grain size which was explained by the low bed shear stresses in the stagnation zone. Although the results in this study confirm this tendency, considerable temporal variations in particle size are present at the upstream junction corner. These variations are consistent with the existence of a stagnation zone near the upstream junction corner, but additionally indicate that the location of the stagnation zone fluctuates on both sides of the confluence apex as the momentum flux ratio varies. Turbidity differences between the two confluent flows allowed observation of the penetration of the flow from the Bayonne into the Berthier channel at the upstream junction corner when the momentum flux ratio was low and the opposite for a high momentum flux ratio. Best (1985, 1987, 1988) noted the penetration of main channel flow into the tributary channel but only for very high junction angles (105°) which are uncommon in natural environments but our results indicate that this situation may occur at lower junction angles. Particles which are deposited for a given hydraulic condition can therefore be re-entrained when variation in the momentum flux ratio generates a lateral displacement of the stagnation zone.

Maximum depth zone

According to Best (1985), the increase of the grain size in the maximum depth zone is explained by a combination of factors including flow acceleration due to the reduced area of the cross-section caused by separation of flow at the lower junction corner, the reattachment of the secondary flows downstream of the avalanche faces and the influence of the mixing layer. As was shown earlier, changes in the position of the coarser particles in the maximum depth zone are related to changes in the position of the mixing layer

The effect of the mixing layer on bed geometry and grain size distribution is not yet fully understood. Mosley (1976) did not consider the mixing layer as a primary factor in the formation of the scour zone, rather that curvature-related helicoidal cells were mainly responsible for scouring at confluences. According to Ashmore et al (1992) who described secondary flow in two braided confluences, these cells would principally be caused by stream line curvature and would be bigger where the scour depth is greater. Observations by De Serres (1989) and Roy and De Serres (1989) suggest that turbulence generated in the mixing layer is more important than the secondary flows for the formation and the maintenance of the scour zone, particularly at non-concordant beds confluences. In fact, De Serres (1989) noted that the lateral extension of the scour zone at Sandhill corresponded to the mean amplitude of the shear layer oscillations. He did not consider helical cells as the cause but as the consequence of the scour, i.e. created by the vertical separation in the lee of the avalanche faces, a feature also documented in flume studies (Best, 1985, 1988). This could then explain the reduced cell size and strength which Ashmore et al. (1992) observed at a low scour depth confluence.

Bar at the downstream junction corner

Our results clearly indicate the presence of finer sediments on the bar near the downstream junction corner, but neither the spatial grain size distribution nor the bedforms present convincing evidence of a recirculating motion in that zone, such as that observed by Best (1985, 1987, 1988). The laboratory experiments of Best (1985) showed that the absence of recirculation may occur when the bar is filled with sediments and steady state conditions are achieved Steady state conditions are not likely to be reached in natural confluences but the influence of bed morphology upon flow separation remains important even in non-equilibrium conditions (Best, 1985). The present observations, even though they cover a range of hydraulic conditions and different confluences, do not prove that recirculation never occurs but highlight the fact that recirculation is not necessarily present at natural confluences

The absence of flow reversal indicators in bars at the downstream junction corner can be partially explained by erosion of the downstream bank of the tributary which lowers the actual merging angle of the tributary flow and limits flow detachment (Roy et al., 1988). It is also possible that the recirculation cells are not detectable in the deposits since the size of the recirculation zone decreases with the distance from the water surface towards the bed (Weerakoon, 1990). Furthermore, the difference in bed elevation between the tributary and the main channel may be an important element in explaining the discrepancies between laboratory and natural environment results. The basal part of the deeper flow coming from the main channel, instead of deviating towards the mainstream bank, appears to pass underneath the shallower tributary flow and resurges at the downstream junction corner This has been observed at the Sandhill confluence by De Serres (1989) and reported by Roy and De Serres (1989). The turbidity difference between the Berthier and Bayonne allowed visualization of upwelling of fluid near the downstream junction corner which indicated that some of the main channel flow passed underneath the Berthier flow in a manner similar to the observations of De Serres (1989). The implications of this inequality in channel depth may also affect the mixing layer which becomes distorted towards the tributary bank (Best and Roy, 1991) It is possible therefore that due to complex three-dimensional flow distortion, the separation zone at the downstream junction corner of confluences of unequal depth channels does not exist, or at least has a much more limited extent than at confluences with equal depth channels

Conclusions

The morphology and sedimentology of sand-bedded river channel confluences are complex and subject to important temporal variations caused by the different hydrological responses of the two incoming rivers. Despite these variations, it is possible to identify three morpho-sedimentological zones with distinct grain size, sediment structure and bedform characteristics, namely the upstream junction corner, the maximum depth zone and the bar at the downstream junction corner. The typical morphology of river channel confluences which is described in the literature, i.e. a scour zone with two steep avalanche faces, appears only appropriate for junctions where the depth ratio is near unity. The evidence presented here suggests a different morphology for unequal depth channel confluences consisting of a mouth bar with an avalanche face on the tributary side and the absence of a marked scour zone.

The morphological and sedimentological features are indicators of the flow dynamics and the present results show some consistencies with existing hydrodynamic models of river channel confluences. However, the importance of the separation zone and particularly the presence of a recirculatory motion at the downstream junction corner appeared to be less than that observed in laboratory studies. This is due to factors such as the lower merging angle of the tributary flow at natural river confluences, the influence of bed morphology upon flow separation and the non-concordance of the beds which results in a very different flow behaviour in the separation zone area. The true implications of unequal channels depth, however, have just begun to be documented (Best and Roy, 1991) and, for the moment, these effects can only be described in qualitative terms. The situation can be quite complex since the variation of relative bed height differences with flow stage implies that the flow dynamics can be very different at low and high flow conditions This demands that future research concentrates on the dynamical picture of river channel confluences. Laboratory studies combined with field observations are needed to develop a global quantitative model of river channel confluences.

Acknowledgements

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