Analysis of coarse sediment connectivity in semiarid river channels

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Abstract Coarse sediment in river channels influences the channel morphology but channel morphology also influences the supply, sediment transfer and sedimentation. Coarse sediment is mainly stored on bars: lack of bars in a reach may reflect lack of supply, lack of storage availability, or high competence. A conceptual model of sediment connectivity has been developed and is applied to two channel systems in the semiarid area of southeast Arizona, USA. Detailed evidence of sediment sources was collected from field mapping and aerial photographs. Sediment size was sampled at intervals down the channel and competence was calculated from surveyed cross-sections and hydraulic data. The spatial patterns of sediment transfer and storage were shown to be related to a complex combination of sediment supply, valley morphology and channel gradient. Deposits and sediment segregation in such systems can reflect recessional flows. The implications of spatial variability in coarse sediment transfer and storage are discussed.

Key words channel bars; channel morphology; connectivity; flow competence; fluvial deposits; sediment

INTRODUCTION

Understanding of coarse sediment transport in fluvial systems is important because of its influence upon morphology through deposition in channels, mainly as bars. Morphology itself influences the transport and deposition of coarse material. There is increased emphasis in the literature on identification of sediment sources, transfers and sinks/stores and on the use of sediment budgets as a framework for analysis. However, it is important to identify whether there is direct connectivity of the coarse sediment. Inferences can be made from the geomorphological and sedimentological evidence.

CONCEPTUAL MODEL

Conventional theory assumes that there is sediment connectivity down through a channel system. i.e. that sediment has the potential to move through the system. If sediment is too coarse to be moved then it is assumed that accumulation takes place such that channel hydraulics are altered to accommodate that movement over time. Situations where this connectivity of transport of particular sizes of sediment do not apply have been recognized, e.g. in studies by Ferguson & Ashworth (1991) and others of Allt Dubhaig in which a fining downstream is seen to be the result of selective transport due to a marked decrease in valley slope. Much debate has taken place on the role of selective transport and abrasion in downstream fining of sediment. Newson (1992) long ago recognized that fluvial systems may function as a series of individual systems in sequence downstream with discontinuities between. Barriers obviously act as discontinuities, but in other cases the connectivity may not be obvious. Coarse sediment moves in steps through systems, during high flows and much research has been undertaken into lengths of steps or distances of travel, e.g. Hassan *et al.* (1991).

The major storage locations in channels are bars. Reaches with channel bars are therefore indicative of a sediment flux, though only from the nearest upstream source (within or out of channel). Reaches which lack bars are not necessarily indicative of a lack of coarse sediment transport but may arise from several different causes or situations (Fig. 1):

(a) A lack of supply of sediment to be transported and stored, (due to lack of sources, deposition upstream or absorption of load by lateral movement);
(b) A lack of competence to transport sediment through the reach;
(c) High competence such that coarse sediment is flushed through the reach and not stored.

Inferences about the status or functioning of such reaches can be made from the morphological and sedimentological evidence in the sequence of reaches upstream and downstream. For example, lack of coarse sediment supply would generally be indicated by erosion and lack of bed sediment upstream. A lack of competence would result in a storage zone of coarse sediment upstream of the incompetent reach. A highly competent reach would result in coarse deposition downstream where competence decreases but could only be demonstrated if there were no new sources in between. The competence of a reach can be calculated using various published formulae and relationships.

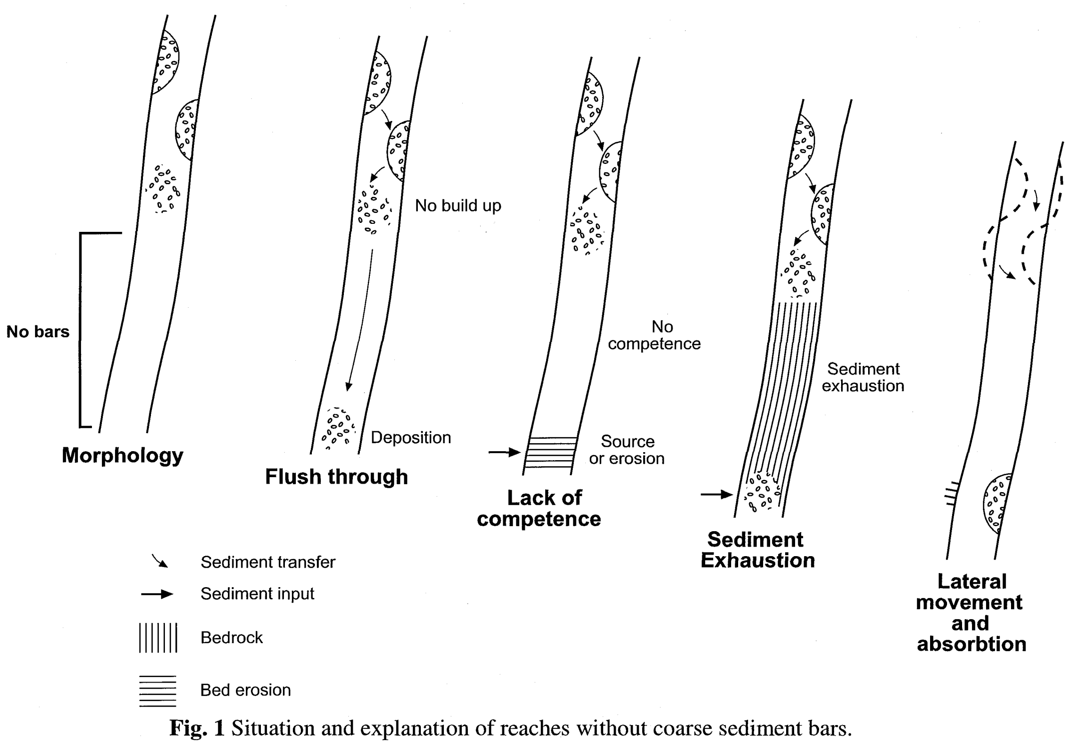

Fig. 1 Situation and explanation of reaches without coarse sediment bars.

METHOD

It is suggested that inferences can be made about the functioning of a reach by careful mapping and measurement of morphological features and sediment characteristics in reaches and analysis of the spatial patterns and sequences. These methods have been applied to several channel systems in contrasting environments. Hooke (2003) showed that an active meandering system, with perennial flow, such as the River Dane in northwest England, may be functioning as a disconnected system, with deposition close to sources of sediment.

In this paper two channel systems from a dryland area, differing in size and hydrological regime, are examined. In each case, long sections of channel incorporating reaches of differing characteristics have been mapped morphologically and sediment has been sampled. Competence has been calculated for representative cross-sections in each reach.

RESULTS

Case Study 1: River Gila in Safford Valley, Arizona

The Gila River in Safford valley in southeast Arizona is a large river, flowing through an arid area, with a highly variable but perennial discharge. Though much of the sediment is very coarse and appears abundant, morphological mapping of the sources from very large-scale aerial photographs and field verification indicate a wide range of sources, including gullies and arroyos, valley wall, channel banks and bars, and high spatial variability in their occurrence (Fig. 2). There is evidence of high mobility of sediment in floods from other published studies (e.g. Huckleberry, 1994) and by direct observation of deposits. Detailed cross sectional and sediment size measurements have been made at 1-km intervals through the valley (Fig. 3) (Hooke, 2000). Competence calculations have been made using various methods and various discharges. The values from Graf's (1983) equation are plotted in Fig. 4

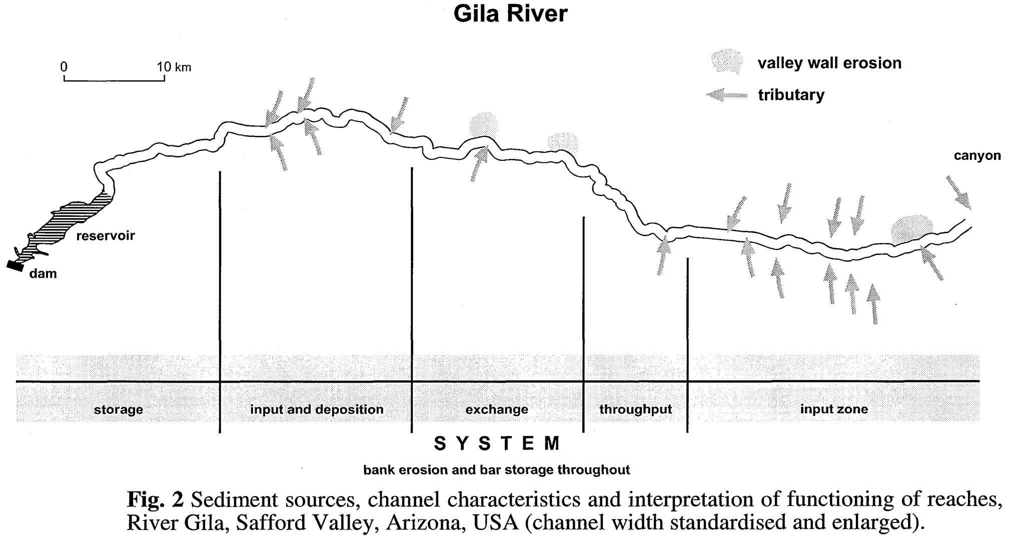

Fig. 2 Sediment sources, channel characteristics and interpretation of functioning of reaches, River Gila, Safford Valley, Arizona, USA (channel width standardised and enlarged).

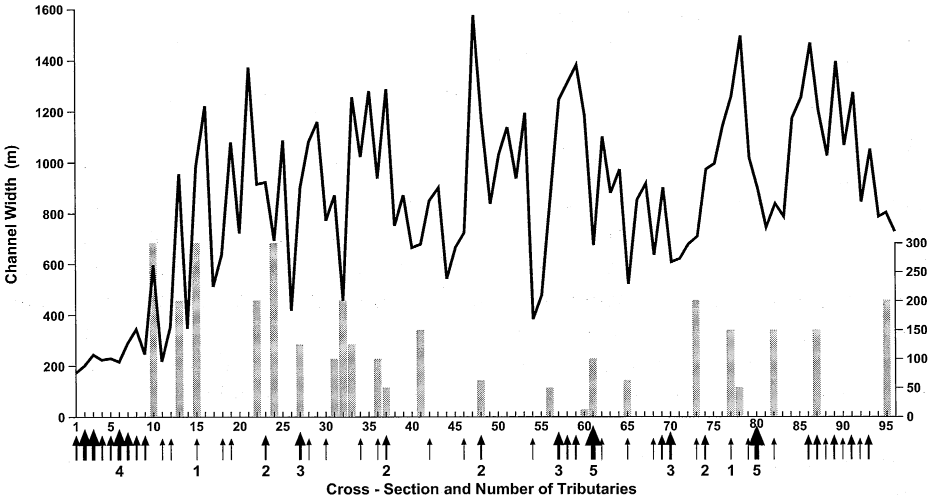

Fig. 3 Spatial pattern of channel width, maximum sediment size and tributaries, River Gila.

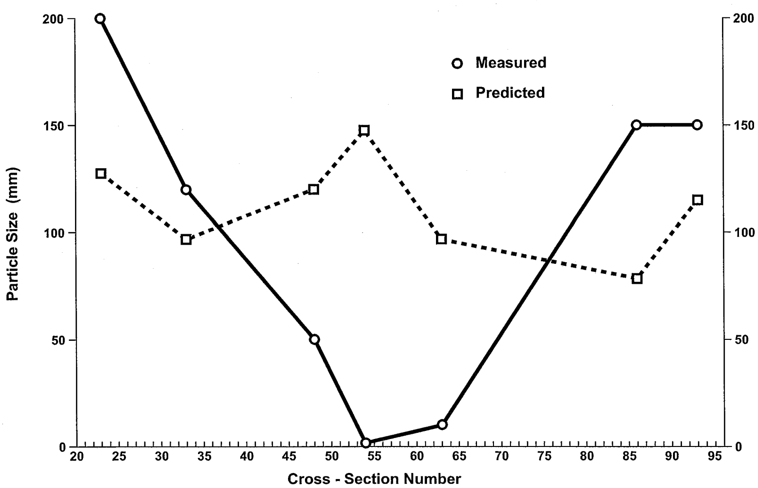

Fig. 4 Competence of flow and variation in sediment size in River Gila, Safford Valley, Arizona, USA.

for sample sections and compared with maximum sediment sizes measured in the channel. The size of material deposited does vary through the valley. In particular, in one reach around cross-section 54 the deposited material is much finer. This is a steep and narrow reach and competence calculations indicate that coarse material could be carried through here in moderate flows (Fig. 4) (Hooke, 2000). There are two possible interpretations of this narrow, fine sediment reach, lacking coarse bars. One is that the decline in sediment size downstream implies an exhaustion or lack of supply of coarse sediment. Alternatively, the coarse sediment may be flushed through on high flows and only fine material is deposited at low flow. It would appear that in highly competent reaches the deposits represent the residual flow rather than the maximum competence. There is some evidence from the upstream values of sediment size to suggest sediment exhaustion in this case.

Case Study 2: Walnut Gulch, Arizona

Walnut Gulch is an ephemerally flowing channel in southeast Arizona, USA. It is an instrumented catchment that has been run by the US Agricultural Research Service since the 1950s. In this study the channel of one sub-catchment has been intensively mapped and cross-sections and sediment sampled at intervals through the catchment. Fig. 5 indicates that there is a range of hillslope and channel sources, though many of the hillslope channels do not connect with the main channel. Overland flow from the hillslopes is unlikely to transport coarse material. Some coarse material is derived from valleyside erosion of older deposits. The channel material is dominantly gravel, with some sand and a few cobbles, but most of the coarse material is found on the bars. The channel material is mostly rather homogenous, d_{50} of channel samples at most sections being in the range 1–4 mm diameter. There are some zones of bars and braiding but their density varies and they are more common in the uppermost and lowermost reaches.

Calculations of the hydraulic competence of flows indicate that even a flood of 5-year recurrence interval could transport very coarse material. This is confirmed by measurements made after such a flood in 1993 when there was evidence of cobbles up to 160 mm diameter having been transported and evidence from bulldozed trenches across the channel that the whole channel bed to a depth of about 20 cm had been mobile. The question is whether the coarse material was actually moved through the reaches lacking bars. Hydraulic calculations indicate that it could have been moved. Some ancillary evidence indicates that in these narrower parts the coarse sediment may be flushed through because a few cobbles were found trapped in vegetation in the middle of the channel. Elsewhere, the coarse sediment is deposited on the tops of bars and edges of the channel, indicating deposition during high flow. Finer material is deposited in the channels, indicating continued transport in deeper

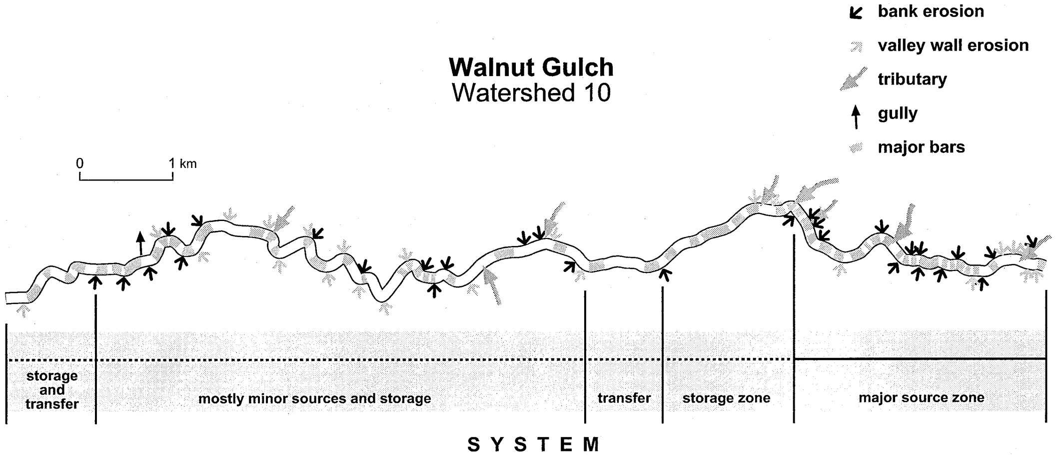

Fig. 5 Sediment sources, channel characteristics and interpretation of functioning of reaches, Walnut Gulch, Arizona, USA.

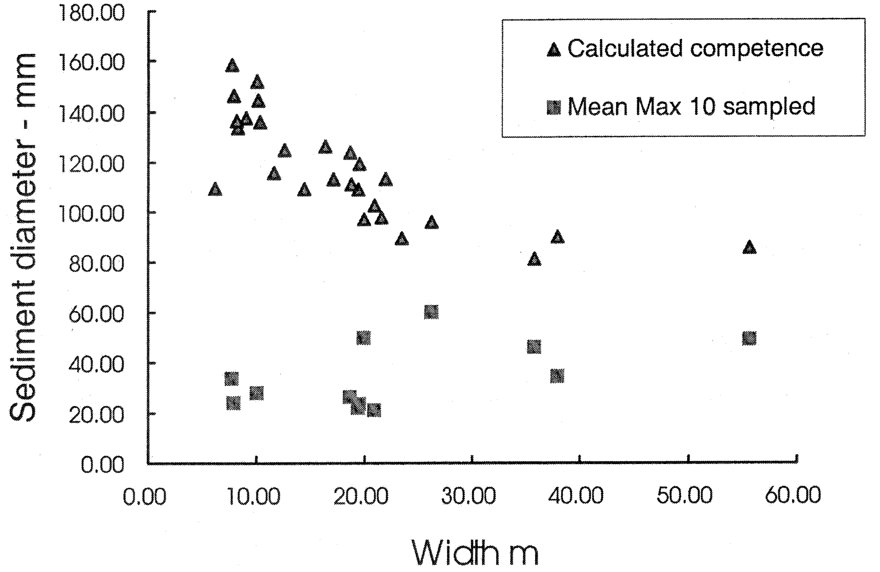

Fig. 6 Flow competence calculated for 5-year recurrence interval flow, and mean sizes of largest 10 particles sampled.

flow until the highly mobile, fine gravel and sand sediment is deposited in the late stages of flow recession. An analysis of the competence of the cross sections in relation to width indicates a non-linear inverse relation. However, measurements of coarsest material deposited show a positive relation to width (Fig. 6).

DISCUSSION AND CONCLUSIONS

Both of these channel systems appear to be highly connected, or potentially highly connected if sediment is available, for coarse sediment, though their morphological and sedimentological characteristics vary down through the system and they have reaches lacking bars that are of greater length than commonly quoted step lengths of coarse particle transport. High flows in dryland systems are generally highly competent and transport large loads. In both these channel systems it would appear that the steep narrow reaches without bars have the potential to flush coarse material through. However, there is some question of the availability of coarse material, particularly in the case of the Gila.

Comparison of competence calculations with actual maximum sizes deposited (with evidence of transport) shows an inverse relation, indicating deposition of coarse material at lowest competences. Under the conditions of transport in such channels, with a wide range of sizes of material, then the material deposited is related to loss of competence and recession of flows so that coarse material is deposited at the upper and outer edges of flow, on bars, and finer material continues to be carried until low flow in the most competent reaches, producing fine channel deposits. In the short term the wide shallow sections, with bars, having low competence, will tend to be perpetuated and the steep narrow sections will tend to flush material through and offer no opportunities for storage.

The interpretation of functioning of reaches is important for understanding the actual and potential for coarse sediment transport through reaches. Direct measurements of flux also need to be carefully interpreted in relation to sources and stores and their connectivity, because measurements in one reach may not be representative of what is moving though the whole channel system or even through adjacent reaches. Geomorphological analysis of the spatial relations and functioning of channel reaches, based on morphological and sedimentological evidence, can provide useful insights into the connectivity of the system and a framework for interpretation of any direct measurements.

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