Field Measurements And Characterization Of A Sand Bed Stream For Riparian Rehabilitation And Modeling

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EXTENDED ABSTRACT

This paper reports on the initial phase of a linked ARC research project supported by the University of Newcastle and the NSW Department of Natural Resources. The project aims to advance the understanding of interactions between flow, sediment, vegetation and channel morphology in natural open channels. The first objective of the project is to characterise geomorphic, flow and sediment transport processes at a selected field site with sparse vegetation. The field site will be the subject of a future riparian rehabilitation trial. Later objectives focus on the modelling of stream processes in experimental and computational settings. Like all models of natural systems, these will rely on adequate data provision and an understanding of field processes, in particular the nature of channel forming events.

Laboratory experiments will be conducted in reduced scale (1:10) flume model, incorporating the most important processes of the field site. Here a range of rehabilitation alternatives will be tested using simulated vegetation under different flow conditions. These experiments will be used to develop, adapt and test quantitative models of flow dynamics, sediment transport and channel morphology incorporating vegetation.

A semi degraded sand bed stream situated in the Hunter Valley has been chosen for intensive study. The results of the first research objective; to assess its geomorphic character are presented in this paper. The findings relate to the effects of a recent flood event that peaked on 30 June 2005. The results include reach scale patterns of scour and fill mapped from topographic surveys. Secondly, flow structure has been evaluated from two and three dimensional flow velocities measured by an Acoustic Doppler Velocimeter (ADV) during the falling limb of the flood. Considerable agreement was found between flow velocity measurements and reach scale patterns of scour and fill.

As a result of the flood event large amounts of sediment stored within the streambed were mobilized and deposited in the reach. Scour occurred in pools and along the outside bend. Fill along the inside bank and bar.

Flow measurements were able to identify high and low zones of velocity and turbulence. Spanwise velocity vectors were unambiguous in identifying the deflection of flow as influenced by channel planform. In addition, secondary circulation patterns in two of three measured sections were found. Discussion focuses on the relationship between measured flow structure and channel change. It was concluded that the flood event, was an effective channel forming agent, resulting in no new geomorphic features but rather reinforcing existing channel morphology.

The nature of this channel forming discharge has a number of implications for future modeling, in both experimental and computational settings. Like field research, modeling is primarily concerned with high flow events therefore the present study will provide an important validation of high flow simulations in the flume. This study has also been able to identify important aspects of channel morphology which influence flow structure during bankfull events. In addition patterns of sediment movement were identified which will inform the position and density of planting both in the field and experimental channel. Lastly it is concluded that as a result of field measurements the selected field site is ideal for investigating the interactions between flow, sediment, channel morphology and riparian vegetation.

1. INTRODUCTION

Riparian vegetation has a profound influence on the hydraulics of open channel flows by reducing flow velocities and near-bed shear stresses. For this reason it can control local erosion and sediment transport patterns and has the ability to affect the entire channel morphology (Bennett et al., 2002; Thorne, 1990). These interactions have been the subject of recent research in ecohydraulics and fluvial geomorphology. It has been found that fluid forces driving sediment transport and morphological change are modulated by riparian vegetation (Bennett et al., 2002; Lopez and Garcia, 1998; Nepf, 1999). Research also shows that such interaction is dependent upon the density of vegetation, its position and arrangement within the stream and the degree of submergence. A challenge for future research involves integration of the idealized experimental and modeling settings with actual field conditions. From a management perspective, a second challenge involves applying this scientific understanding to the rehabilitation of degraded streams.

This paper reports on the initial phase of an ARC Linkage research project supported by the University of Newcastle and the NSW Department of Natural Resources. The project aims to advance the understanding of links between flow, sediment, vegetation and channel morphology in natural open channels. This will enable the scientific design of plantings for riparian rehabilitation using longstem tubestock. Unlike standard tubestock, these plants are grown up to 1m allowing deep planting into the stream bank. Appropriate methods will also be developed to predict in-stream sediment transport and bank erosion in the presence of riparian vegetation. Lastly new practical guidelines for rehabilitation works using longstem tubestock will be established.

The first objective of the project is to characterise geomorphic, flow and sediment transport processes at a selected field site. These findings will inform the direction of subsequent field and experimental research. In particular a unique experimental channel based on field characteristics will be constructed in a flume for detailed study. Fixed bed experiments will be carried out to investigate interactions between flow, channel boundaries and vegetation. Mobile bed experiments will examine interaction between sediment transport and vegetation. Both experiments will trial a number of different discharges and configurations of vegetation used in riparian rehabilitation strategies. These findings will be used to develop a model of flow dynamics, sediment transport and channel morphology that incorporates riparian vegetation. The model will be used to evaluate the performance of various riparian rehabilitation alternatives and identify strategies that are hydraulically efficient and ecologically sustainable.

The primary aim of this paper is to address the first objective; to assess the geomorphic character of a selected reach along the Widden Brook. As most geomorphic work is generally completed with a bankfull flow it is particularly important to understand the effects of such events. A recent flow event exceeding bankfull capacity occurred on 31 June 2005. Two surveys completed before and after the flood event illustrate the response of the streambed and banks. In addition two and three dimensional flow velocities were measured during the falling limb of the flood event. Discussion will focus on the relationship between measured channel change and flow structure, and finish with implications and significance for future modeling. Concluding comments will be made concerning the suitability of the field site for the research objectives. In addition future directions of field research will be mentioned.

2. SITE DESCRIPTION

The Widden Brook is located in the Goulburn River drainage basin, situated in the Hunter Valley, New South Wales (Fig 1). It has a total catchment area of 700 km^2 consisting of a long and relatively narrow Triassic sandstone valley. At the vicinity of the field site the valley setting is laterally unconfined with an upstream catchment area of 392 km^2. The Widden Brook itself is a sand bed stream with moderately cohesive banks. The 100m field site is contained within an almost straight reach, 1 km long (Fig 2). The bed slope is 2.2 m km^{-1} while bed material comprises mainly sand and some gravel with mean grain sizes of 0.5mm and 3mm respectively.

The Widden Brook has an over-widened channel formed by large flood events. Excessive amounts of sand-sized sediment stored within the stream bed are periodically reworked by smaller flood events, and subsequently incised to form a new low flow channel. It is likely that the Widden Brook responds to a similar range of channel forming discharges as identified by Erskine (1994) along the Goulburn River.

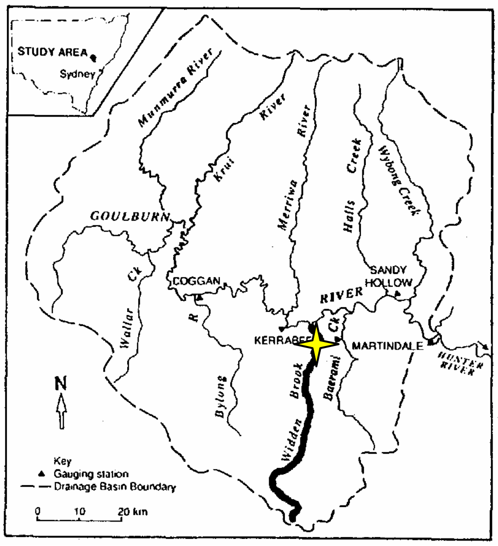


Figure 1. Goulburn River Drainage Basin showing the Widden Brook. (Source: (Erskine, 1994))

Figure 2. Aerial Photo of the Widden Brook and the field site

A partial series flood frequency analysis of a historic streamflow record near the field site indicates the 1 year ARI (Average Recurrence Interval) flood is $120m^3/s$. This compared to a bankfull discharge of $52.9m^3/s$ approximated from cross sectional surveys and using a Manning n roughness coefficient of 0.035. Both calculations followed the methodology set out by the Australian Institute of Engineers (Pilgrim and Doran, 1987). Further analysis of rainfall and streamflow records in other areas of Widden Valley and neighbouring catchments is necessary to confirm and extend the present record. The flood in question was recorded along the Goulburn River at Sandy Hollow, downstream of its junction with the Widden Brook (Fig. 1). The rising limb was relatively short with the falling stage lasting a full 10 days. The headwater received 160mm of rainfall in the 48 hr period prior to flooding.

3. METHODOLOGY

The field site was surveyed at 29 cross sections spaced approximately at 10 metre intervals and oriented orthogonally to the bankfull channel direction. The initial survey was completed on 31 May 2005. An additional survey was taken on 13 July following a flood event that peaked on 30 June. Both surveys used differential GPS equipment to within 20 mm vertical accuracy. In addition sediment mobility was estimated using the Shield's Criterion, which indicates the critical bed shear stress required for motion and suspension of sediment.

Three-dimensional and two-dimensional flow velocities were measured at cross sections (XS) 9, 4 and 1 on 5 July (Fig. 6 and 7). Steady flow conditions occurred throughout the period of measurement. Data collection occurred five days after the peak flow event in conditions that were hydraulically rough. The discharge was $17m^3/s$, which is equivalent to a third of bankfull capacity.

Flow properties were measured using two Acoustic Doppler Velocimeter (ADV) probes. One was capable of measuring flow velocity in three dimensions, the other in two dimensions. The advantages of using two probes simultaneously and gaining more information outweighed the disadvantage of losing the vertical velocity component in profiles using the 2D probe. The ADVs were set to record at a sampling rate of 25 Hz over a $70mm^3$ sampling volume. A minimum of 3000 samples were recorded at each point in the flow. The 2 minute sampling length was necessary to obtain a reasonably constant time averaged reading.

The instruments were orientated so that the x-coordinate measured streamwise velocity (u), the y-coordinate spanwise velocity (v) and where applicable the z-coordinate measured in the vertical direction (w). Both instruments were secured to wading rods with a scale to record the depth of measurement. The water surface level was surveyed to link depth of measurement to same coordinate system as the corresponding cross section. Four vertical profiles containing 8 points were recorded in each cross section.

4. NET SEDIMENT MOVEMENT

Before describing net sediment movement in response to the flood event some attention will be given to initial geomorphology and sediment mobility. Several important geomorphic units of the reach can be observed in Figure 3. Beginning upstream, the flow merges in a constriction before the active streambed widens and a bar diverts flow towards the left bank. This lateral bar (Brierley and Fryirs, 2005) is attached to the right bank and is a semi-permanent feature of the reach. In comparison, the bed configuration which includes the thalweg, dunes and other streambed features change periodically with flooding. The bar is positioned on the inside of a mild inflection while the outside bank exhibits a corresponding bend. A deep pool has formed where flow diverts from the bar to the left bank. Further downstream, flow converges into another deep pool before leaving the reach.

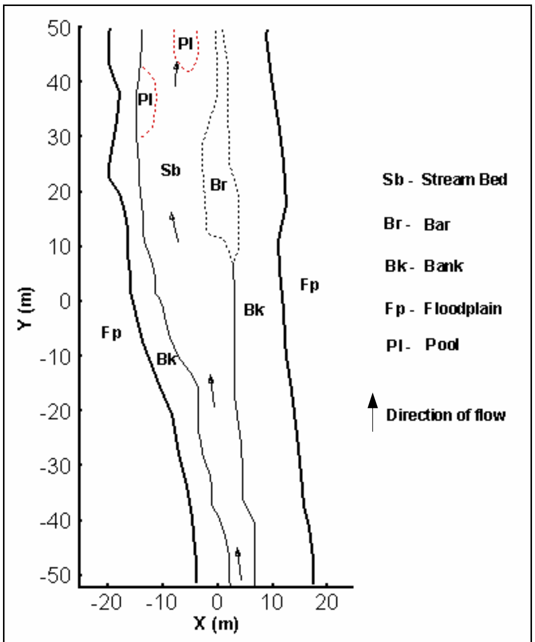


Figure 3. A reach scale planform map of important geomorphic units.

Existing riparian vegetation is quite sparse. In the middle ground of Plate 1 *Phragmites* a riparian reed, grows on the right bank. However these plants are seasonal and not flood resistant. Longstem tubestocks will be planted mainly along the bare left bank for rehabilitation and ongoing monitoring.

Plate 1. Field reach looking downstream. (Source: Gorrick, S).

Sediment mobility was computed for two grain sizes representative of sand and gravel portions comprising the stream bed. The effective bed shear stress for a plane bed was calculated. The result, 1.73×10^{-2} kN m^{-2} exceeded the threshold of motion for sand and gravel (2×10^{-5} kN m^{-2} and 1.02×10^{-2} kN m^{-2}). Shear velocities were calculated from field measurements of velocity using the law of the wall. Resultant bed shear stress varied between 0 to 9.2×10^{-3} kN m^{-2}. Therefore flows during field measurement were still above the threshold of motion for sand, but marginal for gravel portions.

As a result of the flood event large amounts of sediment stored within the streambed were mobilized and deposited in the reach increasing the thalweg height by as much as 0.4 m (Fig. 4). Only at the downstream end did any bed lowering occur.

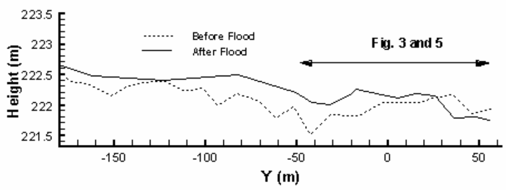


Figure 4. Thalweg profile of the field site and upstream reach before and after the flood event.

Reach scale patterns of scour and fill are mapped in Figure 5. It represents the net movement of sediment in response to the entire flood hydrograph. The terms scour and fill are used loosely to describe the local depletion and accumulation of sediment.

The upstream section of stream bed has responded by extensive fill. Downstream there is a smaller area of deposition positioned on the leeward side of the bank attached bar. The bar itself has also aggraded between 0.1 and 0.2 m. Therefore the bar has experienced longitudinal and vertical growth. In addition the left bank has experienced some accretion.

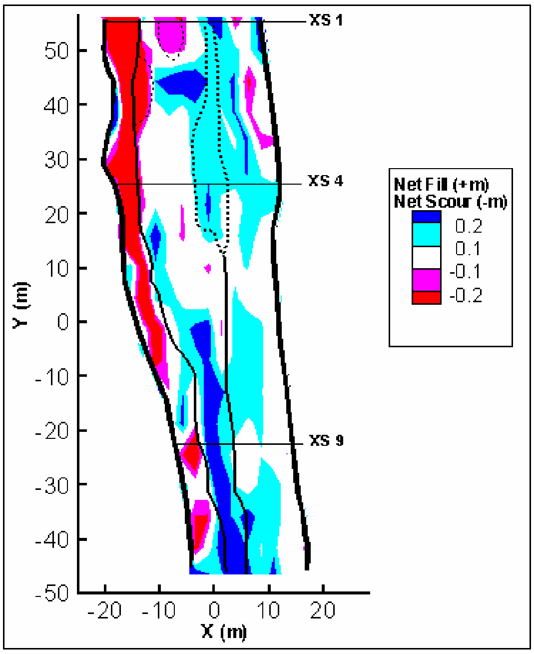


Figure 5. Reach scale patterns of net scour and fill after the flood event.

In comparison to extensive areas of streambed which filled, only the existing pools underwent net scour. The first occurred adjacent to an area of fill, the second in the vicinity of XS 1. Also of note the left bank has experienced extensive scour, receding more than 0.2 m. Field observation also noted the removal of vegetation and the presence of slumped material.

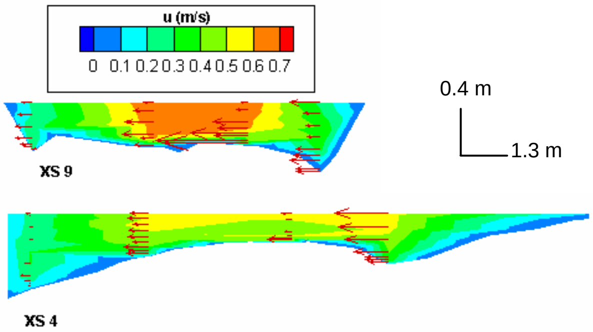
On inspection of Figure 5 scour tends to concentrate along the outside bend, fill along the inside while upstream has experienced extensive fill covering the entire streambed. The longitudinal connectivity of fill depicted in the thalweg profile means it is probably more accurately described as a migration of sand bars and dunes from further upstream.

5. FLOW STRUCTURE

Flow velocity data was processed using the commercial WinADV software. Flow parameters including streamwise velocity (u), spanwise velocity vectors and turbulent kinetic energy (TKE) were extracted. TKE represents the energy extracted from the flow by turbulent eddies. Together the parameters form a representation of the flow structure. Velocity results are presented in Figure 6, were contours represent streamwise velocity, and vectors represent spanwise velocity.

A smaller channel at XS 9 constricts flow resulting in higher streamwise velocity (Fig. 6). XS 4 has greater channel capacity and streamwise velocity is slower (Fig. 7). XS 1 contains a zone of high streamwise velocity in the central region of the channel bounded by two slow moving zones (Fig. 6). Turbulence at XS 9 is also high with maximum values of TKE twice that of XS 1 and 4 (Fig. 7). Unusually high TKE exists near the left bank (Fig. 7). A weak secondary circulation cell may partly explain the high turbulence. In XS 1 spanwise velocity vectors show a secondary circulation cell moving toward the left bank near the bed. The zone of maximum TKE occurs near the channel thalweg but is not particularly high (Fig. 7).

ADV measurements were quite unambiguous in identifying the direction of flow. At XS 9 and 4 spanwise velocity vectors are directed towards the left bank as controlled by channel curvature. At an inflection point between XS 4 and 1 the channel redirects flow towards the right bank. Further downstream at XS 1, the spanwise velocity component is directed towards the right bank.



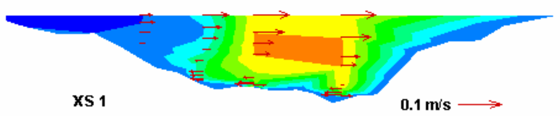


Figure 6. Streamwise flow velocity and spanwise velocity vectors in XS 1, 4 and 9.

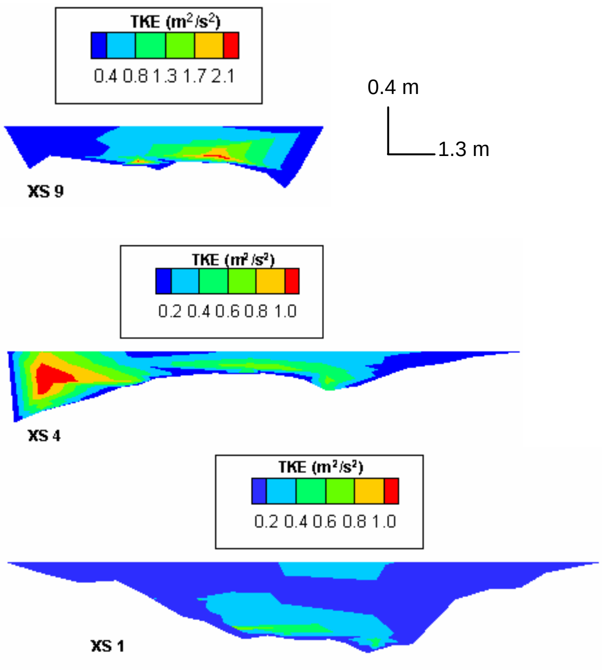


Figure 7. Turbulent Kinetic Energy (TKE) at XS 1, 4 and 9, note different scales.

6. DISCUSSION

Some important inferences can be made on the relationship between geomorphic changes, flow structure and channel morphology at each cross section. Beginning upstream, XS 9 transects an area of extensive fill with relatively high velocity and turbulence fields. There is no doubt that extensive fill has occurred through large sediment influxes originating further upstream. High values of TKE, streamwise velocity, and strong spanwise velocity may indicate ongoing migration of bedload downstream. In addition the highest level of bed shear stress was recorded at XS 9 (9.2 Pa). Richards (1982) comments on short term adjustments made during flood events. He infers that incoming sediment cannot be carried through a reach all at once, instead it is deposited. In so doing channel capacity is reduced, increasing velocity and allowing more sediment to be carried through. Put another way high velocities would indicate a positive feedback to maintain sediment transport through the reach in response to a large influx of sediment from upstream.

Further downstream, scour and fill occur along the outside and inside bend respectively. At XS 4 flow goes around the lateral bar consistent with measurements showing small velocities, low turbulence and deposition. The streambed remains unchanged but this does not exclude mutual scour and fill processes associated with rising and falling stages of a flood event. Continuing downstream, flow is forced over the bar toward the opposite bank at all points in the flow. At bankfull discharge it is hypothesized that topographic steering of flow creates enough shear force to scour the opposite bank.

Between XS 1 and 4, at the inflection point of the outside bend a pool creates a zone of flow convergence. This pool has scoured while an adjacent area has filled, perhaps indicating a lateral flux of sediment into the wake of the upstream bar, which affects its longitudinal growth. Again continuing downstream, flow has redirected toward the right bank, and enters another pool at XS 1. The scouring of existing pools is consistent with velocity reversal at high flows which results in greater increases of bed shear stress with increasing discharge in pools (Richards, 1982). In summary the flood event has created no new geomorphic features. Rather it has reinforced existing channel morphology, through a longitudinal and perhaps lateral redistribution of sediment. This is consistent with the work of Erskine (1994) along the Goulburn River. He concluded that large amounts of sand stored within the bed are periodically reworked by small flood events which determine the form of the bed.

The initial phase of research was able to describe the nature of a channel forming event. In particular, those aspects of channel morphology which influence flow structure during bankfull conditions. Fixed bed experiments will incorporate these morphologic features to investigate the interaction between vegetation, flow and channel morphology. Inferences made between flow structure and channel morphology will also inform the position density and of simulated vegetation within the channel for a number of experiments. The data presented can be used to calculate net sediment flux over the entire reach for comparison with mobile bed experiments.

For both fixed and mobile bed experiments, the validity of results depends upon simulating field like conditions for high flow events. Likewise, increasing sophistication in numerical models of open channel flow means they are no longer a limiting factor, and their ultimate success is determined by a sufficient understanding of relevant field processes and adequate data provision. For numerical modeling, field measurement is essential for calibration, delineation of boundary conditions and the identification of relevant stream processes. Ongoing characterization and monitoring of the reach will ensure field processes are adequately represented in experimental and computational settings.

7. CONCLUSIONS

This paper has presented important baseline findings regarding the impact of flooding on the stream bed and banks. The flow structure was also presented with flow velocity measurements measured during the falling limb. It is anticipated that these measurements will present even greater significance when subsequent experimental and computer models require calibration and testing.

So far the findings illustrate the selected reach is ideal for investigating the effects of longstem tubestock plantings on flow and sediment transport processes for a number of reasons. Firstly, the reach is devoid of any permanent riparian vegetation. Thus longstem tubestocks will be planted and allowed to establish from September 2005. Secondly, the streambed is quite dynamic and mobile under a range of large flow conditions. Bankfull flows are even capable of scouring the left bank. Hence strategically placed, the longstem tubestock plantings can potentially affect the readjustment of the streambed and banks during large flows. Therefore plantings should affect some morphological change within the research period and provide a longer term state from which experimental and modeling outcomes can be measured. Finally although the reach is relatively straight, initial flow measurements show meandering flow patterns which can be simulated in a reduced scale (1:10) model while remaining within the physical limits of the experimental flume.

Further reconnaissance in the field will continue to characterize and monitor geomorphic, sediment and hydraulic processes. Measurement of flow velocities, suspended load using an OBS (Optical Backscatter Sensor) and bedload sediment using a Helley-Smith sampler will continue subject to flow conditions. Ongoing monitoring of the site will include continuous water surface data, routine discharge and sediment measurements and periodic resurveys.

8. ACKNOWLEDGEMENTS

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