Exploring the relationship between channel bed control structures and stream power in low-gradient floodplain wetlands

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Key Points

- Excessive erosion in channels of floodplain wetlands threaten inundation and aquatic ecosystem processes.
- Peaks in stream power tend to occur where channel bed slope increases, often at bed control structures.
- Local over-steepening of bed slope increases erosion risk in these parts of the channels.
- Stream power modelling can guide erosion risk assessment to support water and wetland management.

Abstract

Floodplain wetlands are complex fluvial systems that provide critical ecosystem services. Some floodplain wetlands suffer from erosion that threatens to create and enlarge channels and potentially disconnect wetlands from vital overbank flows. Excessive channel erosion can have dramatic effects on flow routing, inundation patterns and aquatic ecosystem dynamics. Channel erosion is sometimes mitigated by the use of bed control structures to arrest bed lowering and associated channel enlargement. Stream power modelling techniques based on Digital Elevation Models (DEMs) have rarely been used in low-gradient rivers and wetlands. A modified stream power modelling method was used to identify hotspots of enhanced stream power, and therefore potential erosion risk, in the Ramsar-listed Macquarie Marshes, NSW. Peaks in stream power occur where pronounced steps exist in channel longitudinal profiles, most notably at rock bed control structures. In low-gradient floodplain wetlands, local over-steepening within the channel is associated with increased stream power and erosion potential. Stream power modelling provides an important screening tool to prioritise sites for detailed investigation and erosion assessment. Ultimately, such modelling can guide further monitoring and/or interventions to reduce the risk of erosion and ecological deteriorations.

Keywords

Channel erosion, discharge, hydrology, geomorphology, stream power

Introduction

Stream power is an important metric that is widely used to understand the energy of a river, or a river reach, used to transport sediment and undergo geomorphological adjustment (Bizzi and Lerner, 2015). Stream power is a measure of the rate of energy dissipation of water flowing against channel bed and banks, and is essentially calculated as a function of river discharge and slope (together with the specific weight of water). Remote sensing techniques have allowed investigations of stream power for a range of environments over large spatial scales without the need for extensive field data (Reinfelds et al., 2004; Bizzi and Lerner, 2015;

Gartner, 2016). Digital Elevation Model (DEM) data allow delineation of channels, estimation of longitudinal profile elevation and channel slope, and calculation of catchment area using flow accumulation tools in a Geographic Information System (GIS) environment. In small- to medium-sized catchments with well-established relationships between channel discharge and catchment area, this allows calculation of downstream trends and patterns in total and unit stream power (Brierley and Fryirs, 2005; Bizzi and Lerner, 2015; Gartner, 2016). However, in complex, low-gradient, multi-channelled systems where discharge declines downstream (as commonly found in dryland regions), using catchment area as a proxy for bankfull discharge is not accurate or meaningful. Therefore, other methods are required to provide an estimate of discharge to allow calculation of stream power when flow velocity and discharge cannot be directly measured. In this study we employed a stream power modelling technique in the Macquarie Marshes (Figure 1), that uses 1 m resolution Light Detection and Ranging (LiDAR) derived DEM data to estimate channel slope, while discharge was estimated using a regional empirical regime equation, and bankfull width was measured manually. Identification and assessment of patterns of stream power provide a better understanding of the causes of higher stream power, and therefore likely causes of erosion hotspots, in the system.
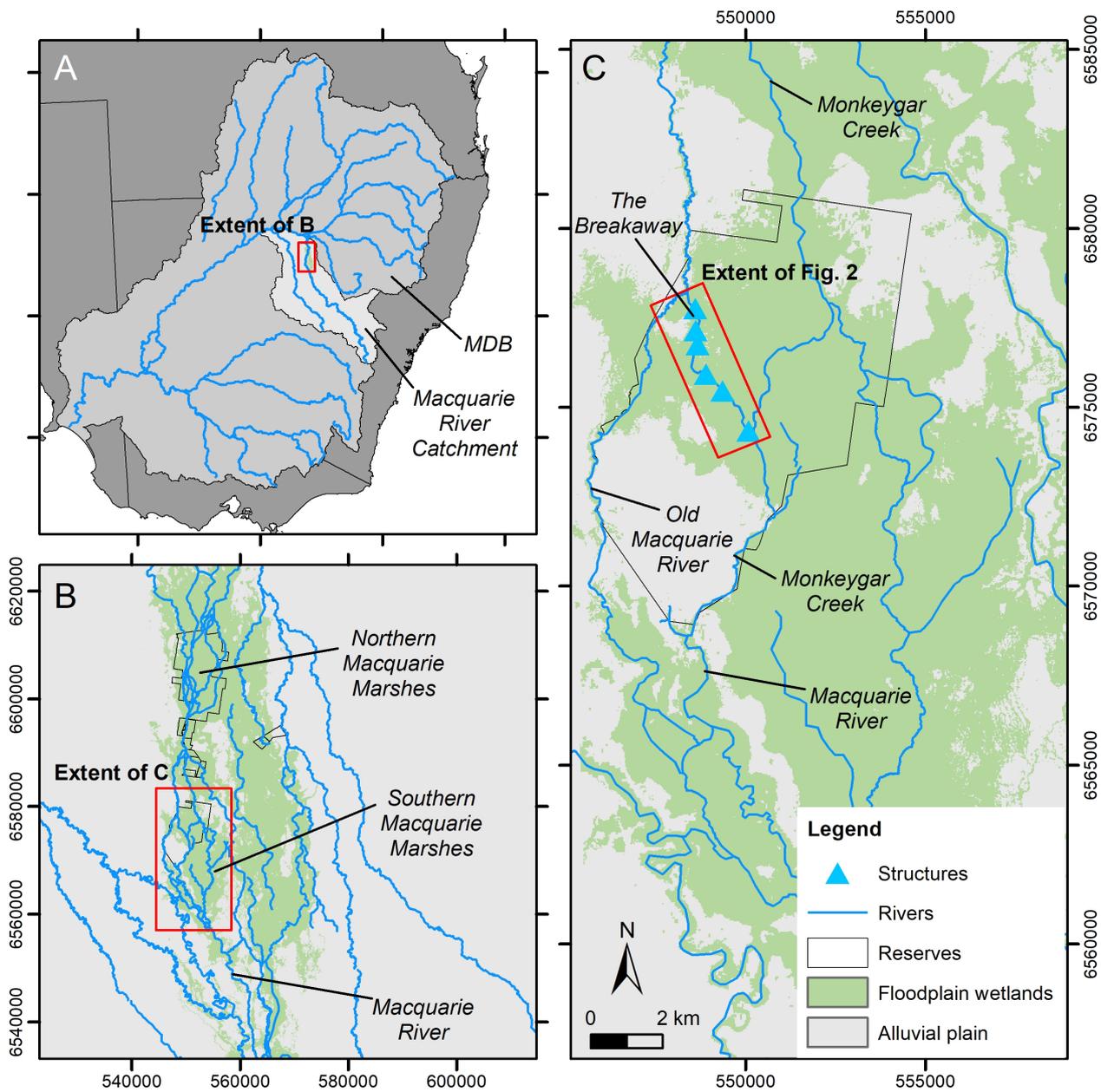

Figure 1. (A) The Macquarie River catchment in the Murray-Darling Basin; (B) The Macquarie Marshes on the lower Macquarie River; (C) The Breakaway channel and structures in the Macquarie Marshes.

Study Site and Methods

The Macquarie Marshes

The Macquarie Marshes have formed on the lower reaches of the Macquarie River in the Murray-Darling Basin due to persistent downstream declines in discharge and stream power, leading to anastomosing channels and the disintegration of channelised flow in extensive floodplain wetlands (Ralph and Hesse, 2010). In the southern Macquarie Marshes, channels are quite dynamic over decades to hundreds of years, with sedimentation and erosion driving constant channel adjustment and even new channel formation through avulsion (Ralph et al., 2011; Ralph et al., 2016). Some channels suffer from rapid erosion due to knickpoint retreat (i.e. head-cutting gullies), while others have bed incision and/or bank erosion and slumping (Oyston et al., 2014). The Breakaway is one such channel that has experienced channel enlargement due to both bed and bank erosion and has, as a result, several erosion control structures in place (Figure 1).

Methods

Stream power was modelled in 100 m segments over the 6 km length of The Breakaway channel to help identify and assess potential hotspots of erosion. Channel slope (s) is a critical component of the calculation of total and unit stream power, and was estimated by extracting channel bed elevation and distance data from a 1 m LiDAR-derived DEM (DECC, 2009). This LiDAR-derived DEM has ±15 cm vertical accuracy and ±45 cm horizontal accuracy, and has been used previously for channel change assessments in the Macquarie Marshes (Yousefi et al., 2018). In order to account for inherent fine-scale errors in the DEM caused by the presence of water and/or vegetation, we calculated the raw slope for each segment by dividing the total change in elevation by the change in distance downstream between points. We also calculated an overall slope value for the whole channel using linear regression of the elevation and distance data.

Bankfull discharge (Q_{bf}) was estimated using a regional hydrological regime equation developed by Hesse et al. (2018), who found that bankfull channel width (w_{bf}) is the best predictor of bankfull discharge for low-energy, sinuous rivers of the Murray-Darling Basin. Although this method introduces some uncertainty for small channels like The Breakaway, limited spatial and temporal flow gauge records in the Macquarie Marshes means that this is the best method to apply widely and consistently in order to assess patterns of stream power and potential erosion hotspots in the system. Bankfull channel width was measured manually in GIS for each 100 m segment using aerial imagery and DEM datasets.

Total stream power and unit stream power were calculated using the following equations:

$$\Omega = \gamma \cdot Q_{bf} \cdot s$$

where Ω = total stream power (W/m), γ = specific weight of water (9800 N/m^3), Q_{bf} = bankfull discharge (m^3/s), s = channel slope (m/m)

$$\omega = \Omega\ /\ w$$

where ω = unit stream power (W/m^2), Ω = total stream power (W/m), w_{bf} = bankfull width (m).

Results and Discussion

Stream power trends

Stream power was highly variable along The Breakaway, but hotspots of unit stream power did occur near bed control structures S1, S2, S3, S4 and S6, and in the last reach of the channel before it enters the Old Macquarie River (Figures 2 and 3). The position of the hotspots on the map just upstream of these structures are an artefact of the 100 m long slope segments used, which span the structures and therefore incorporate their changes in elevation (Figure 2A). Based on an overall slope, stream power was less variable (Figure 2B).
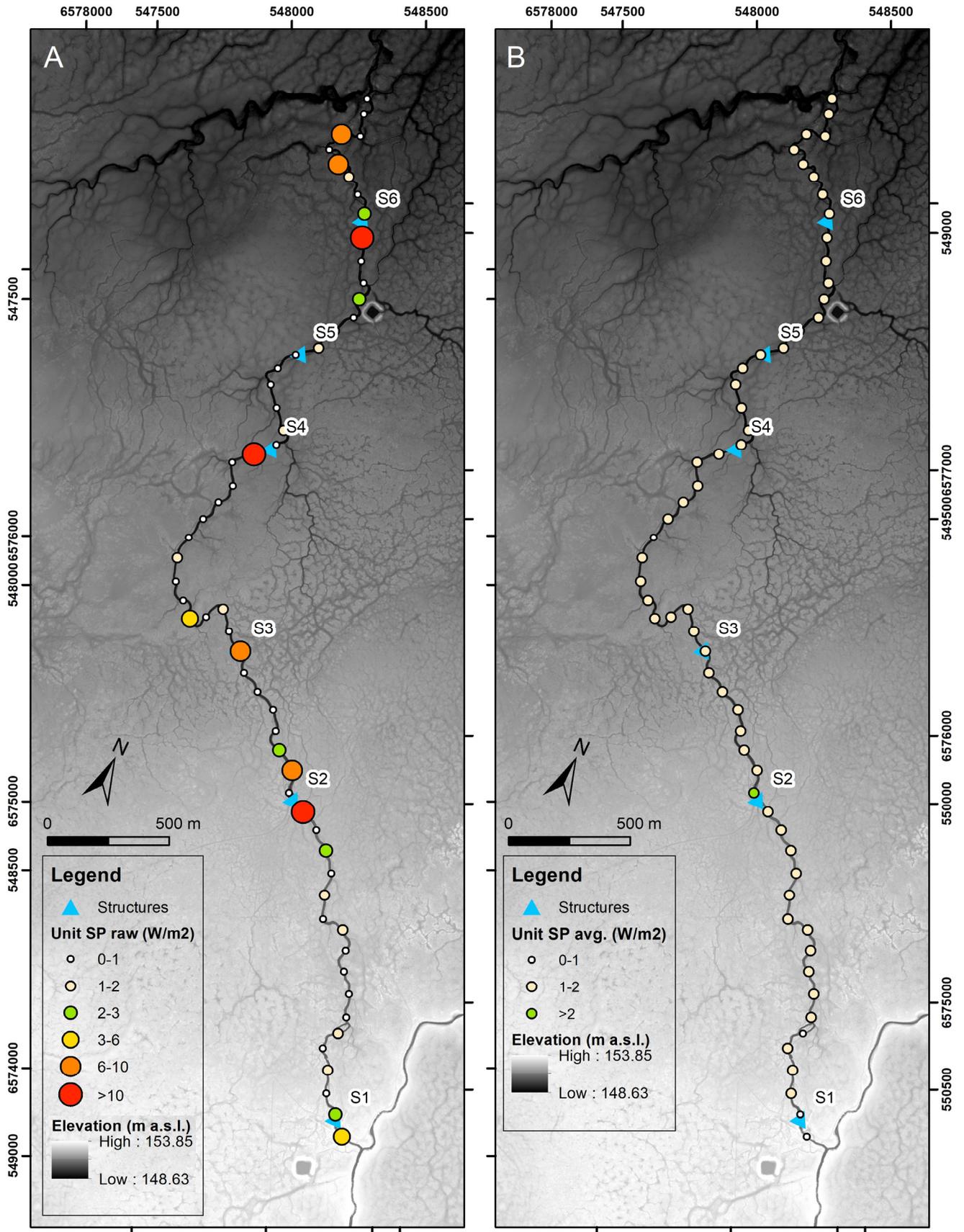
Figure 2. (A) Unit stream power along The Breakaway, calculated for 100 m segments using raw slope values; (B) Unit stream power calculated for 100 m segments using an overall slope value derived from linear regression; see Figure 3A.
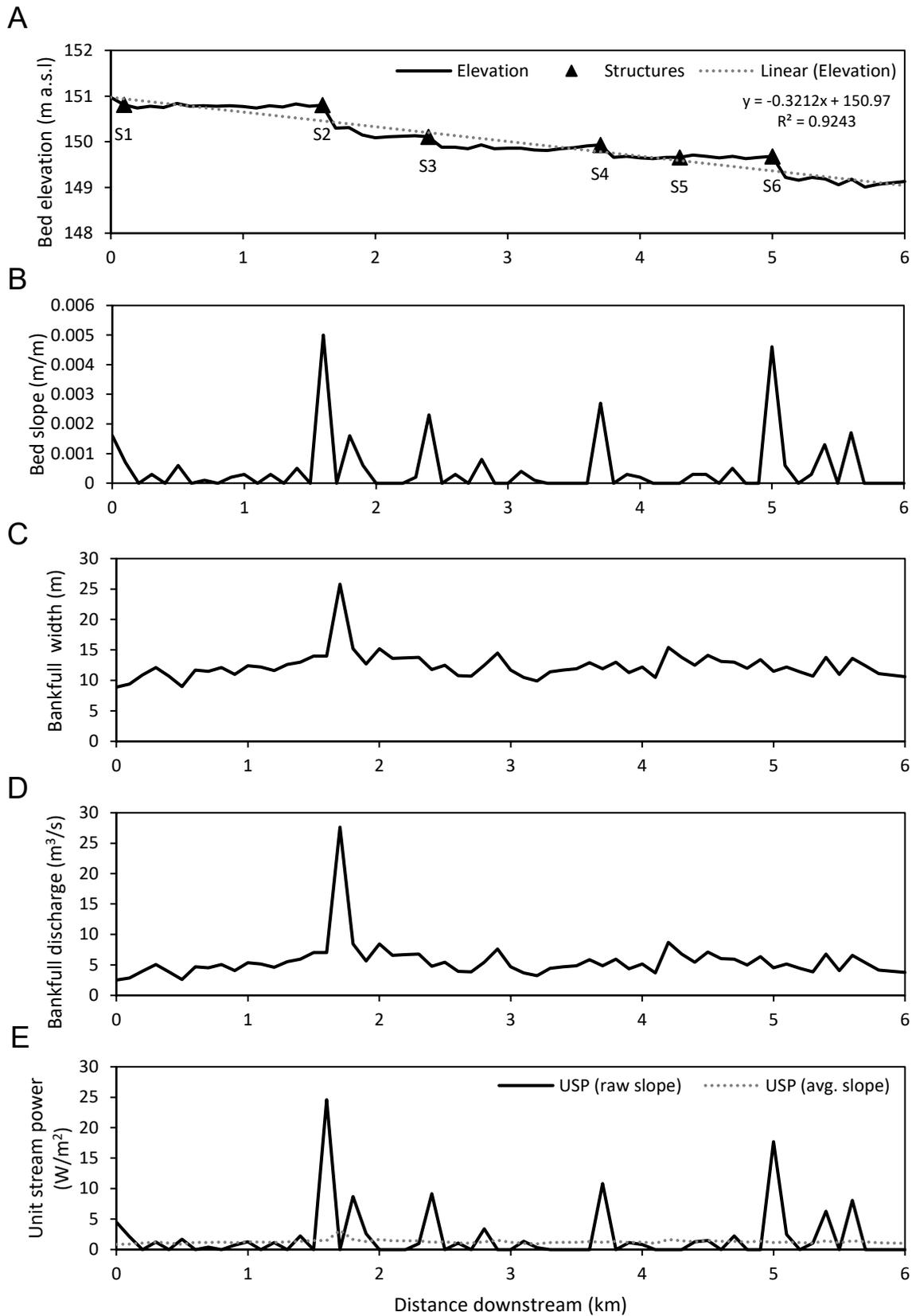
Figure 3. (A) Longitudinal profile of The Breakaway with bed control structures, and linear regression used to estimate overall slope (note y-axis units are m, x-axis units are km); (B) Channel bed slope raw values for 100 m segments; (C) Channel bankfull width; (D) Estimated channel bankfull discharge; (E) Modelled unit stream power using raw slope values for 100 m segments and an overall slope for the whole channel.

Marked changes in channel gradient clearly play a critical role in the stream power hotspots and trends, since bed slope at the structures (except for S5) was greater than elsewhere along the channel (Figures 3A and 3B). The greatest changes in bed elevation occurred around structures S2 and S6, which also had the greatest predicted unit stream power. Coupled with this, S2 had the greatest channel bankfull width and estimated bankfull discharge (Figures 3C and 3D). At this site, erosion has caused a very large scour hole to form just downstream of the structure itself. Overall, stream power was greatest along The Breakaway where both channel bed slope and width were greatest, particularly around the bed control structures (Figure 3E). Since active erosion has been observed at all the structures, based on this data, a unit stream power threshold for significant erosion is likely to be around 5 W/m^2.

Since the bed slopes used in this analysis are partly a result of the bed control structures themselves, which have been in place since the 1990s, it is useful to compare the overall slope-derived unit stream power estimates which indicate that should bed slope equilibrate, then stream power hotspots would be much less pronounced (Figures 2B and 3E). Using an overall slope of 0.0003 m/m, unit stream power does not exceed 2 W/m^2 except for at the very head of the channel where it is ~3 W/m^2. Predicting the slope of the channel of The Breakaway under scenarios where either 1) the structures were never put in place and erosion had continued unchecked since the 1990s, or 2) the structures were to be removed or modified in the future, is very difficult due to variable rates and intermittent behaviour of incisional erosion and knickpoint retreat (i.e. flood-driven erosion of head-cutting channels) and the irregular (or patchy) patterns of bank erosion in the system due to animal trails and (de)vegetation of the banks. Nevertheless, our findings demonstrate that should channel bed slope become reduced and stabilized along The Breakaway, stream power and therefore erosion potential would likely be mitigated or reduced.

Implications for management

Although it seems obvious that stream power would be highest in the steepest parts of the channel, the fact that changes in bed slope in discrete sections of The Breakaway appear to be exacerbated by bed control structures poses some key questions for management. For example, do the existing structures adequately reduce or even contribute to erosion risk in the channel? What overall bed slope is desirable to minimize erosion and how can this be achieved? What cost effective options are suitable to mitigate erosion without causing major changes in flow distribution in connected channels? Further research is required to address these questions, but clearly stream power is a critical hydro-geomorphic factor that should be considered together with other water and wetland monitoring options.

Although erosion is a natural process in rivers, we must understand and monitor stream power and other factors that contribute to erosion potential at locations that are highly susceptible to change, or that have less resilience to change, in order to assist river, wetland and water management. In some cases, accelerated rates of erosion can have negative impacts including loss of land and associated resources, as well as damage to property and infrastructure (Piegay et al., 2005). In the Macquarie Marshes, which have historically had a reduction in the extent and duration of wetland inundation (Kingsford, 2000), excessive channel erosion and enlargement poses a significant threat to floodplain wetland inundation and therefore to aquatic processes and ecological values (e.g. Kobayashi et al., 2011; 2015).

Conclusions

Sites of enhanced stream power were identified using a modified stream power modelling method in the Macquarie Marshes. Peaks in stream power were coincident with steps in channel slope at bed control structures. In low-gradient floodplain wetlands such as these, erosion potential may be exacerbated where peaks in stream power occur. Ultimately, modelling such as this with associated geomorphological interpretations can guide further monitoring and/or interventions to reduce erosion risk and enhance wetland ecosystem health.

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