

# Smart rocks and sand slugs: innovative methods for modelling sediment transport in rivers

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## Key Points

- Stream sediment erosion and transport processes are essential for structuring physical habitats that support biodiversity, but developing techniques to predict how, when and where that material will move has proved difficult.
- We successfully demonstrated the use of geochemical fingerprinting as a technique for tracing fine sediments creating sand slugs in the lower Pages River, coastal NSW. Importantly, using multiple lines of evidence from slope, geological and radiometric mapping to corroborate and verify the results of geochemical studies substantially improves confidence in identifying sources and sinks of fine sediments in streams.
- The development and testing of 'Smart Rocks': artificial rocks that house internal loggers to track fine- and large-scale rock movement represent significant methodological and conceptual advancements in river sediment modelling.
- Innovative techniques developed in this study will contribute to successful river restoration by better understanding the processes that create and maintain physical stream habitats.

## Abstract

Sediment erosion and transport are essential processes for structuring physical habitats in fluvial systems, but developing techniques to predict where that material will end up has proved difficult. That poses problems for engineers and communities trying to protect bridges, dams, levees and pumps from shifting sediment, and for ecologists trying to plan river successful restoration projects or understand patterns in biodiversity. We have developed two new techniques for better understanding processes that regulate the erosion, transport and deposition of fine sediments (<2mm) and cobbles (>128mm) in rivers. A digital elevation model, radiometric map and multiple geochemical tracers including physical characteristics, major and trace elements, and stable isotopes combined in a mixing model were successfully used to identify the sources of fine sediments dominating a large sediment slug in the lowland reaches of the Pages River. For large sediment, we have developed and validated 'Smart Rocks' fitted with a GPS and triaxial accelerometer that allow the mapping of the specific path travelled by individual rocks during high flow events. When combined, these methods represent a significant advancement in fine- and large-scale sediment modelling in river systems, and substantially improve our current conceptual basis of sediment dynamics in rivers.

## Keywords

Coastal rivers, erosion, sand slug, cobble, geochemical tracers, digital elevation model, restoration.

## Introduction

Worldwide, rivers transport an estimated 13 gigatons of sediment each year (Milliman & Farnsworth 2011). Sediment transport and deposition are essential processes in fluvial systems, facilitating the dynamic erosion and deposition of physical habitats that help maintain a diversity of ecological functions and biotic assemblages (Owens et al. 2005). The creation and persistence of these geomorphic habitats are influenced

by the interaction among riverbed morphology, sediment supply, stream discharge and flow velocity (De Almeida & Rodríguez, 2011). Overlying these processes are anthropogenic activities such as riparian and catchment clearing associated with land-use change, channelization, damming and gravel extraction that can alter the spatial and temporal patterns of hydrology and sediment supply and transport (Fryirs et al. 2007). Existing sedimentation methods do not provide the spatial resolution for hydrologists to model shear stresses that instigate sediment movement, for ecologists to quantify sediment movements that maintain habitats for biodiversity, or for geomorphologists to develop river-scale sediment budgets that document the origin and transport processes of fine and bedload sediments.

Fine sediments are defined as less than 2mm in diameter and play an essential role in fluvial environments; facilitating significant transfers of carbon and nutrients throughout the system (Wood & Armitage, 1997). Elevated levels of fine sediments arising from erosion, transport and deposition processes have physical, chemical and biological implications for fluvial environments (Evrard et al. 2011). An increase in fine sediment suspended within the water column can reduce water quality through increased nutrient transport and deposition, and reduced light penetration for photosynthesis, with deposition of fine sediments altering channel morphology and smothering benthic habitats and biota (Haddadchi et al. 2013). Site-based techniques such as the Universal Soil Loss Equation, erosion plots, pins and surveying methods, and larger scale GIS-based techniques have been applied to sedimentation studies (Walling 2005). The large scale and highly variable nature of sedimentation processes, and the need to identify priority sites for erosion mitigation requires more innovative techniques.

Similarly, researchers have struggled with the difficult and dangerous task of quantifying sediment movement during floods when rivers move most of the coarse-grained (>128mm) bedload material. In the 1960s, the influential geomorphologist Gordon Wolman dropped marked marbles into a stream and noted how far they moved. Today, our understanding of sediment movement is still based on the deployment of tracer particles (generally painted or numbered rocks) with a range of sizes that are tracked following discrete flow events (Black et al. 2007). However, this technique only provides information on the end point for deposition and not the process and path of movement. Understanding the flow conditions necessary to roll or saltate coarse sediments, the path they take during movement, and the spatial scale of movement (meters to kms) under non-flood flows are essential processes to quantify for understanding sediment dynamics in rivers.

Sediment transport is an intrinsically stochastic process. Although large spatial variations in sediment flux have been documented in flume experiments, relatively few field observations of sediment movement at reach or individual riffle (m) scale exist (Haddadchi et al. 2013). This study aims to explore the application of geochemical fingerprinting of fine sediment in the Pages River and the development and testing of 'Smart Rocks' in the Bellinger River that house a logging tri-axial accelerometer and GPS embedded in artificial river stones. Our aim is to improve our understanding of sedimentation processes and the flow conditions regulating movement, representing significant methodological and conceptual advancements in river sediment modelling.

## **Methods**

### *Geochemical fingerprinting of fine sediment*

Fine sediments were collected from 15 source (catchment geologies and active in-channel erosion) and 8 sink (deposited instream fine sediments along the length of the river) locations in the Pages River, a tributary of the Hunter River in coastal NSW. Agriculture is the dominant land use within the Pages River catchment and led to substantial areas of catchment and channel erosion (Hoyle et al. 2007). The result is an 8km long fine sediment slug in the lower Pages River, reaching almost to the confluence with the Hunter River (Figure 1).

## 8ASM Full Paper

Ryder & Mika - Smart rocks and sand slugs: modelling sediment transport in rivers

Fine sediments were analysed for multiple tracers including; physical characteristics (colour, particle size and organic matter), major and trace elements (XRF - X-Ray Fluorescence, Inductively Coupled Plasma Mass Spectrometer - ICPMS), and stable carbon and nitrogen isotopes. Spatial data were used to construct a digital elevation model (DEM – 30m resolution), flow accumulation models of catchment boundaries and drainage lines, slope and erodibility maps, and a radiometric map of the distribution of different geologies and the movement of sediment within the Pages River trunk based on levels of potassium, thorium and uranium.



**Figure 1. The main channel of the lower Pages River showing the fine sediment filling over 1.5m of channel depth for many kilometers upstream.**

A modified Hughes mixing model using all physical and chemical fine sediment attributes was used to maximise the potential for discriminating sediment sources and improving accuracy in identifying sediment source contributions (Haddadchi et al. 2013). The source sites were split into the four main geologies; basalt, carboniferous conglomerate, triassic conglomerate and sandstone. A Kruskal-Wallis H-test and a stepwise multivariate Discriminant Function Analysis (DFA) were used to isolate the optimal combination of sediment fingerprint properties to define the four geological sources. The modified Hughes mixing model (Haddadchi et al. 2013) was used to define the percentage contribution the four geologies made to each sink site in the main trunk of the Pages River. The modified Hughes mixing model was used to determine the sediment contribution to sink sites of the Pages River, run on those geochemical tracers that were significantly different ( $P < 0.05$ ) using the Kruskal-Wallis H-test, and ultimately based on seven geochemical tracers (Ga, Sb, Ba, Th, Rb, Cs and Ag) that explained 100% of the variance in source geologies.

### *Modelling bedload movement using Smart Rocks*

A DEM was constructed for a 150m reach of the Bellinger River in coastal NSW based on high-resolution, quantitative topographic data acquired using a (TOPCON GTS701, TOPCON Positioning Services, USA) total station and reflector-prism. Flow velocity was measured simultaneously with topographic data by attaching a Marsh McBirney FlowMate (Hach Industries, USA) to the end of the reflector-prism pole. Water depth was also recorded for all data points. Surveys exceeded densities  $>1 \text{ point m}^{-2}$  and were feature-based with point densities increasing ( $>1 \text{ point m}^{-2}$ ) around topographic breaks in slope (e.g. thalweg, and bedrock) (Wheaton et al., 2010) and abrupt changes in flow velocities (e.g.  $> 0.20 \text{ msec}^{-1}$ ). Extra data points were collected on bank and bars where possible to provide context for the wetted channel.



**Figure 2. Surveying the location of the 1290 painted tracer rocks and Smart Rocks in the Bellinger River.**

A total of 1290 painted and numbered tracer rocks from four clast sizes (600 @ 16-32mm; 300 @ 32-64mm; 300 @ 64-128mm; and 90 @ 128-256mm) were placed at the top of the study reach in October 2015, and their precise location within the DEM recorded (Figure 2).

Five identical Smart Rocks (130mm a-axis, 92mm b-axis, 65mm c-axis) were designed and built from weighted resin using a cast of a river stone from the study site and contained specialised electronics sourced from a range of suppliers: Onset triaxial logging accelerometer, G10 Ultralite GPS logger and radiotracker in a waterproof housing (Figure 3). Smart Rocks were placed at the top of the study reach in October 2015, and their precise location within the DEM recorded.



**Figure 3. Smart Rocks design housing a triaxial logging accelerometer to record rock movement, GPS logger to record the travel path, and a radiotracker to locate rocks after movement.**

Following a 3,500 ML day<sup>-1</sup> (60<sup>th</sup> percentile) flow event in December 2015, the location of each numbered painted tracer rock that could be recovered in the study reach and the final location of the Smart Rocks were resurveyed. The Smart Rocks were returned to the laboratory and accelerometer and GPS data were downloaded. The GPS-based travel path of the Smart Rocks was recorded on the DEM, and the distance travelled by individual rocks calculated and recorded as minimum, maximum and average distance travelled per size clast.

## **Results and Discussion**

### *Geochemical fingerprinting of fine sediment*

The aim of this study was to use geochemical fingerprinting techniques to identify the sediment sources providing high volumes of fine sediment to the Pages River (Figure 4a). Sites 1 to 5 are located in the lower catchment and cover two major geologies, sandstone and carboniferous conglomerate, and cover a large longitudinal distance (approximately 60km) of the Pages River channel (Figure 4b), and sites 6 to 8 are in the upper basalt dominated catchment. The DEM (Figure 4c) and slope (Figure 4d) identify the basalt and carboniferous conglomerate geologies occur in parts of the catchment with the highest slopes and erosion potential.

In the upper reaches of the Pages River catchment, over 90% of the sediment source contribution was from basalt and aligns with basalt as the dominant geology (Figure 4f). The contribution of carboniferous conglomerate increased markedly (to over 40%) after the confluence with Warlands Creek (site 5) and remained dominant through to the lower reaches of the Pages River. The erodibility of conglomerate is generally higher than that of basalt, as conglomerate has a higher portion of sand and silt (Ashman and Puri, 2002) and we would therefore predict a higher contribution of fine sediment from this geology. The radiometric map concurs with the geological and geochemical data as it shows a change in the dominant geology within the Pages River trunk, from basalt in the upper catchment to conglomerate downstream of the confluence with Warlands Creek (Figure 4e). It is well known that rates of erosion depend on factors including, land-use, soil type, slope, ground and vegetation cover (Gordon et al. 2008). Warlands Creek is dominated by cleared cattle grazing land as the main land-use, which increases the sediment erosion potential on an already erodible geology (Gordon et al. 2008).

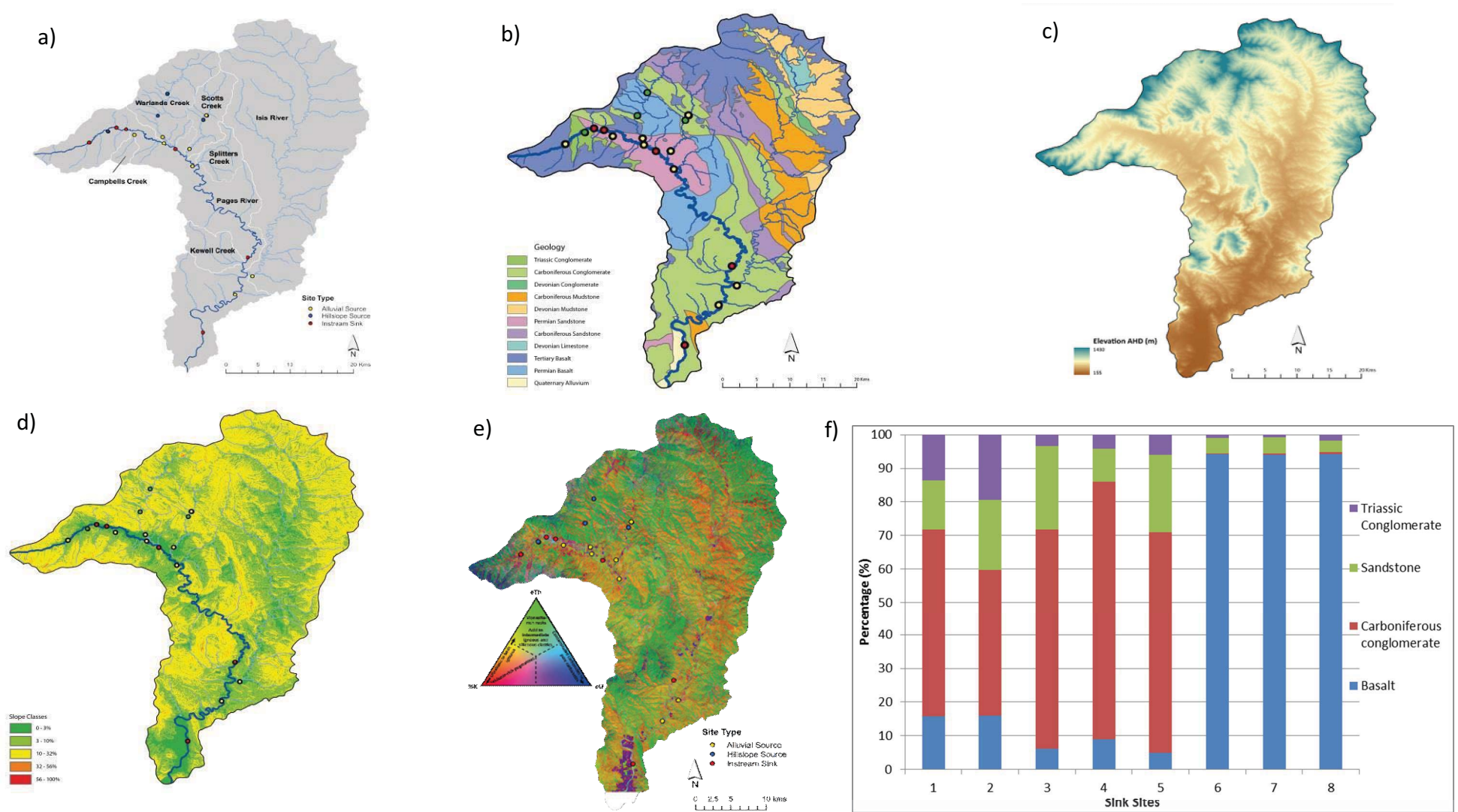


Figure 4. Maps of a) Pages River catchment, subcatchments and locations of sites for sediment sources (yellow dots) and sinks (red dots), b) geology, c) DEM, d) slope, e) radiometric data and f) percent relative contribution of each geological sediment source to deposited fine river sediments from site 1 in the lower reaches site 8 in the headwaters of the Pages River.

Only seven tracers were significant from the Kruskal-Wallis test to proceed to the modified Hughes mixing model and used for discriminating between source sites. The radiometric map clearly shows basalt erosion and deposition in the upper reaches of the Pages River catchment and the movement of basalt along the Pages River main trunk. The radiometric map also shows a change in sediment distribution within the Pages River directly downstream of the confluence with Warlands Creek and the Isis River, concurring with the seven tracer output from the modified Hughes mixing model.

Fine sediment accumulation occurred throughout the channels of the Pages River, however the sediment slug in the Lower Pages River downstream of Gundy is of major environmental concern. The sediment slug occurs where the catchment slope is below 3%. The sediment slug contains over 50% carboniferous conglomerate and 15% basalt, which has been transported from the upper Pages River catchment and Warlands Creek. Many lines of evidence confirmed this large fine sediment contribution from Warlands Creek. The use of geochemical fingerprints combined with GIS spatial data to produce a digital elevation model, and geological, radiometric and land-use maps all contributed to confirming the high sediment erosion and transport from the Warlands Creek sub-catchment.

### Modelling bedload movement using Smart Rocks

The recovery of painted rocks following the 3500 ML d<sup>-1</sup> peak flow ranged from 36% for the smallest rock clast (16-32mm) to 99% for the largest rocks (Figure 5). The largest rock clast (128-256mm) travelled the least average distance at 49.4m and the 32-64mm size clast had the furthest average distance travelled at 69.8m. However, as reported throughout the literature there is substantial variation in the distance travelled in all size clasts (Black et al. 2007).

Interestingly, hotspots of higher velocity (up to 1m sec<sup>-1</sup>) are both sites for sediment deposition and transport. The Smart Rocks clearly demonstrate the path for sediment transport is neither linear nor consistent among replicate rocks, with one travelling 18m and deposited in a high flow velocity patch. Other Smart Rocks travelled up to 49m distance through patch, with one deposited in a high velocity patch while two others were deposited in low velocity patches of the stream bed.

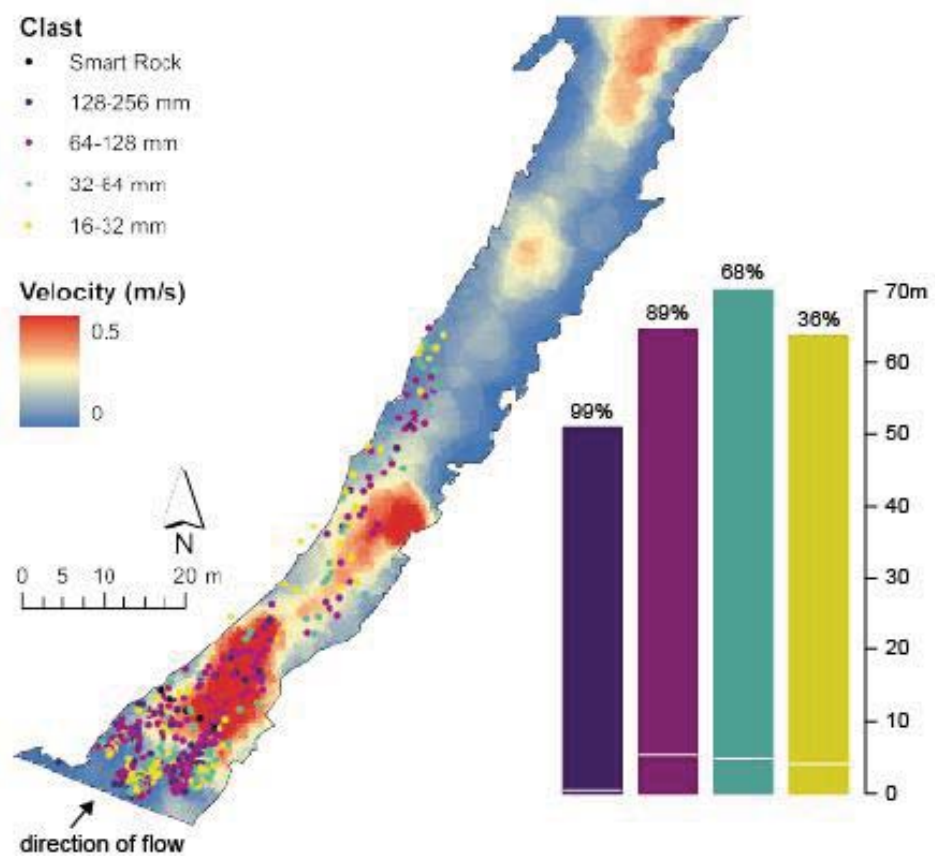


Figure 5. DEM of study reach showing the post-flood location of each painted-numbered rock for each of the four size clasts, the transport path and end location of Smart Rocks (dashed lines), and the recovery success (%) and average distance (m) travelled by each size class .

## Conclusions

Successful river restoration relies on understanding the processes that create and maintain physical habitats. Geochemical fingerprinting techniques successfully identified catchment locations that were contributing a disproportionate volume of fine sediment to the Pages River. Importantly, we have shown that radiometric, slope and geology mapping can be used to corroborate and verify the results of geochemical studies, and is an important process to include in sediment fingerprinting studies. These techniques are initially costly, but once the key geochemical tracers are identified sampling is targeted and efficient. The comparison of painted rock sediment tracing techniques with the development and field deployment of Smart Rocks identified the potential for the Smart Rocks to provide key information on the stability, movement path and deposition of cobble sediments. Smart Rocks are a new technology and as such are relatively expensive (~\$2500/rock), but reveal information impossible to gather using any other techniques. Like all technology these costs will be reduced over time. When combined, these methods represent significant advancements in fine- and large-scale sediment modelling, and substantially improve our understanding of sediment dynamics in rivers.

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## References

- Ashman, M. R., & Puri, G. (2002). *Essential Soil Science: A Clear and Concise Introduction to Soil Science*. Blackwell Publishing.
- Black, K. S., Athey, S., Wilson, P., & Evans, D. (2007). The use of particle tracking in sediment transport studies: a review. *Geological Society, London, Special Publications*, 274: 73-91.
- De Almeida, G., & Rodríguez, J. F. (2011). Understanding pool-riffle dynamics through continuous morphological simulations. *Water Resources Research* 47. doi: 10.1029/2010WR009170
- Evrard, O., Navratil, O., Ayrault, S., Ahmadi, M., Némery, J., Legout, C., ... & Esteves, M. (2011). Combining suspended sediment monitoring and fingerprinting to determine the spatial origin of fine sediment in a mountainous river catchment. *Earth Surface Processes and Landforms*, 36(8), 1072-1089.
- Fryirs, K. A., Brierley, G. J., Preston, N. J., & Kasai, M. (2007). Buffers, barriers and blankets: the (dis) connectivity of catchment-scale sediment cascades. *Catena*, 70(1), 49-67.
- Gordon, D. N., McMahon, T. A., Finlayson, B. L., Gippel, C. J., & Nathan, R. J. (2008). *Stream Hydrology, An Introduction for Ecologists*, Second Edition. John Wiley & Sons, Ltd. ISBN: 978-0-470-84358-1
- Haddadchi, A., Ryder, D., Evrard, O., & Olley, J. (2013). Sediment fingerprinting in fluvial systems: review of tracers, sediment sources and mixing models. *Int Journal of Sediment Research*, 28 (4), 560-578.
- Hoyle, J., Brierley, G., Brooks, A., & Fryirs, K. (2007). 16 Sediment organisation along the upper Hunter River, Australia: a multivariate statistical approach. *Develop in Earth Surface Processes*, 11, 409-441.
- Milliman, J. D., & K. L. Farnsworth. (2011) River discharge to the coastal ocean: a global synthesis. Cambridge University Press.
- Owens, P. N., Batalla, R. J., Collins, A. J., Gomez, B., Hicks, D. M., Horowitz, A. J. & Trustrum, N. A. (2005). Sediment in river systems: Environmental significance and management issues. *River Research and Applications*, 21, 693-717.
- Walling, D. E. (2005). Tracing suspended sediment sources in catchments and river systems. *Science of the Total Environment*. 344, 159-184.
- Wheaton, J. M., Brasington, J., Darby, S. E., & Sear, D. A. (2010). Accounting for uncertainty in DEMs from repeat surveys: improved sediment budgets. *Earth Surface Processes & Landforms*, 35, 136-156.
- Wood, P. J & Armitage, P. D. (1997). Biological Effects of Fine Sediment in the Lotic Environment. *Environmental Management*. 21, 203-217.