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The use of stream power as an indicator of channel sensitivity to erosion and deposition processes

S. Bizzi[1, 2*], David N. Lerner[1]

[1] Dipartimento di Elettronica e Informazione, Politecnico di Milano, Milan, Italy

[2] Catchment Science Centre, Kroto Research Institute, The University of Sheffield, Broad Lane, Sheffield, S3 7HQ, UK

* corresponding author: Dipartimento di Elettronica e Informazione, Politecnico di Milano, Milan, Italy; Tel: 0039 0223999616; E-mail: bizzi@elet.polimi.it

Abstract

Stream power is a measure of the main driving forces acting in a channel and determines a river's capacity to transport sediment and perform geomorphic work. Recent digital elevation models allow the calculation of channel gradient and consequently stream power at unprecedented spatial resolution, opening promising and novel opportunities to investigate river geomorphic processes and forms. The present paper investigates the suitability of map-derived information on total and specific stream power (TSP and SSP) to identify dominant processes within the channel (i.e. erosion, transport or deposition). SSP has been already used to identify a threshold for channel stability. This paper tests this knowledge and investigates whether or not attributes of stream power profiles are statistically correlated with distinctive field morphological forms. Two gravel bed single-thread English rivers are used as case studies, the Lune and the Wye. Available deposition and erosion features surveyed in the field from 124 different locations are used to classify channel reaches as erosion, transport or deposition dominated. Meaningful patterns emerge between the stream power attributes and the field-based channel classification. An SSP threshold above which erosion is triggered compares favourably with ones in the literature. Information about upstream stream power profiles helps to determine the dominant processes.

The joint configuration of local and upstream stream power information uniquely classifies reaches into four classes of different sensitivity to erosion and deposition.

Introduction

An understanding of sediment transport and channel sensitivity to erosion or deposition processes is essential for river management. For instance, deposition dominated reaches may have reduced channel conveyance, making overtopping more likely. Erosion dominated reaches have increased risk of infrastructure failure or instability. Recent flood management schemes have used assessments of channel geomorphic processes in order to design suitable and effective solutions (Wallerstein *et al.* 2006; Rinaldi*et al*. 2009). The influence of channel geomorphic processes and forms on freshwater biotic communities is also well recognised (Poff & Ward 1990; Lorenz *et al.* 2004; Jahnig *et al.* 2009) and the focus of research (Vaughan *et al.* 2007; Palmer *et al.* 2010; Vaughan & Ormerod 2010). A recent EU directive requires the evaluation of hydro-morphological quality for all the river networks in order to assess river ecological status and to deliver catchment management plans (EC 2000).

Channel geomorphic behaviours are usually investigated by field-based fluvial audits (e.g. Harvey 2001; Surian & Rinaldi 2003; Rinaldi *et al.* 2009) and by sophisticated hydrodynamic models (e.g. HEC 1976; Olsen 2003; ISIS 2006; Langendoen 2008). These approaches require very detailed inputs on channel discharges, cross sections and grain size distributions. This information is normally provided through intensive fieldwork and uses experienced staff for interpretation. Methods which require fewer resources would be of great value for regional or national assessments (Newson *et al.* 1998; Newson & Large 2006; Wallerstein *et al.* 2006).

River geomorphic processes and the resulting morphological forms are driven by a balance of driving (e.g. channel gradient and discharge) and resisting (e.g. bed and bank resistance to transport) forces. The various equilibria which can be established between these contrasting forces are functions of the geological setting, catchment hydrology and the geomorphic history of the catchment and create the variety of river styles present in nature (Knighton 1998; Nanson & Huang 2008). The ability to perform geomorphic work, commonly expressed as stream power, is a measure of the main driving forces acting in the channel, i.e. the joint effect of channel gradient and discharge. Stream power has been widely used to assess sediment transport and channel geomorphic patterns in general (e.g. Bagnold 1977; Chang 1979; Nanson & Croke 1992; Ferguson 2005). Modern digital elevation models (DEMs) allow the quantification of channel slope at high resolution, exploration of stream power variability along the full length of a river (Barker *et al.* 2009), and offer the potential to use stream power as a stream assessment tool (Vocal Ferencevic & Ashmore 2012).

Our objective is to demonstrate, using existing data, that significant relationships exist between total and specific stream power (respectively TSP and SSP) and distinctive features of erosion and deposition. Such relationships could be used for initial categorisation of all the reaches of a river for their likelihood of being dominated by erosion or deposition. Our underlying hypothesis is that the dominant process is determined by both the local and the upstream stream power (SP), the latter being an indicator of the river's ability to provide sediment. The argument is that deposition is likely to be dominant when local SP is notably lower than upstream one and conversely for erosion. Readily available datasets are used to provide a proof of the concept for two gravel-bed rivers in England and Wales, the rivers Wye and Lune.

Method

Stream power

Total stream power (TSP, W m^{-1}) is defined as*:*

$$TSP = \gamma QS \tag{1}$$

Specific stream power (SSP, W m^{-2}) is defined as*:*

$$SSP = \frac{TSP}{w} \tag{2}$$

where γ is the unit weight of water (=9800 N/m^3), Q is discharge (m^3/s), and S is energy slope (m/m) which is often approximated by bed slope, and w is the channel bankful width (m) (Bagnold 1966, 1977).

Field observations

The dominant process acting within the channel can be qualitatively evaluated by interpretation of field observations (Sear *et al.* 2003; Rinaldi *et al.* 2010). For instance, for single channel gravel bed rivers, the extended presence of unvegetated gravel bars indicates a rich sediment supply from upstream which is partially stored in the reach and constantly re-worked by periodic floods. In contrast, vegetated bars indicate a channel which is rarely mobilized and so is colonized by vegetation; the upstream sediment supply does not frequently overtop the bars. Conversely the limited occurrence or absence of unvegetated bars within a channel type where they are expected is a sign of limited sediment supply. It might also indicate processes of river bed incision or armouring, i.e. the selection of grains on a river bed of sufficient coarseness that they protect the finer material below from erosion and thus stabilize the bed (Simon & Rinaldi 2006). Erosion features such as eroding cliffs and vertical or undercut banks indicate processes of bank erosion and are an indication of the degree of lateral mobility and of the amount of sediment mobilized towards downstream. Bed incision might destabilize bank toes and trigger bank failures (Little *et al.* 1982). However, the interpretation of field observations must be contextualised in relation to the river type because differences in river styles correspond to differences in geomorphic forms and processes (Schumm 1985; Church 1992).

Case studies and datasets

The rivers Wye and Lune have been chosen as case studies because both are characterized by sinuous single-thread channels with predominantly boulder, cobble and gravel beds and because a good number of field observations are available. The Lune catchment has an area of 1223 km^2 and the river is more than 90 km long (see Figure 1). The geomorphology of the area has been strongly influenced by glaciation. The upper reaches of the Lune and its tributaries flow through a limestone landscape, which provides a significant, albeit flashy, contribution to surface waters, whereas the lower part is dominated by Millstone Grit. The river Wye is the fifth longest river in the UK and flows between England and Wales (see Figure 1). This catchment is 4136 km^2 and the river is 215 km long. The geology includes limestone, mudstone and sandstone rocks. The information that was available for both the catchments include flow discharges at monitored stations, river network maps and DEMs at 50 m grid resolution. Higher resolution DEMs became available after the project, and their potential impact is discussed later.

Field observations are provided by the River Habitat Survey (RHS) which is a well established protocol to survey physical and habitat features of a river reach (Raven *et al.* 1998; Environment Agency 2003). Data is collected by a field survey along a standard 500 m river reach. Morphological and physical habitat features within the channel and the adjacent river corridor are recorded at 10 spot checks at 50 m intervals, while other features are qualitative described for the entire 500 m reach.

124 sites surveyed between 1996 and 2000 were judged suitable for the present analysis (22 along the river Lune and 102 along the river Wye, see Figure 1). Sites which are strongly affected by artificial infrastructures or altered conditions were omitted because the interpretation of morphological forms is affected: for instance, bank protection prevents erosion, conversely livestock damage increases it. The survey dates are close to the DEM which was updated in 2004. Configurations of geomorphological controls along the river course and associable morphological forms do not normally change significantly over a few years.

Calculating TSP and SSP

Traditionally the median flood (two year return period) is used in the calculation of stream power (Jain *et al.* 2006; Barker *et al.* 2009). For some cases, this discharge is comparable with the 'effective discharge', which is defined as the discharge that transports the largest proportion of the annual sediment load (Wharton 1995). In other cases, effective discharge has been proved to differ from the median flood (Ma *et al.* 2010). However, the median annual maximum flood (Q_{MED}) is considered a suitable discharge to characterize stream energy for rivers in England and Wales (Barker *et al.* 2009; Bizzi & Lerner 2012). Therefore in this study we have used Q_{MED} as the reference discharge. It is available as the Flood Estimation Handbook index flood for the network of flow gauging stations in England and Wales (Robson & Reed 1999). These indexes are available for all gauging stations in the two catchments: 15 stations for the Wye catchment and 11 for the Lune catchment. Power regressions were established between Q_{MED} and Shreve's (1966) index of river link magnitude (m) as suggested by Knighton (1999) for the Lune (Q_{MED}=8.5 $m^{0.58}$, R^2 = 0.93), and the Wye (Q_{MED}=2.90 $m^{0.67}$, R^2 = 0.95). These relationships take account of the non-linear relations between flow and distance downstream due to the tributaries. Relating Q_{MED} directly to catchment area gave similar results with a slightly lower R^2.

The channel gradient was obtained from a DEM using the altitude difference between a cell and a cell 4 km upstream; see Bizzi & Lerner (2012) for a more detailed description of the procedure. Bankful width (w) is also required for the continuum of the river course in order to calculate SSP. It was estimated using the empirical relation of Hey and Thorne (1986) between Q_{MED} and width ($w=3.42\ Q_{MED}^{0.46}$) for gravel-bed rivers in Britain, also as suggested by Knighton (1999). Values of slope, Q and w were associated with each 50m DEM cell along the river course (a total of 7465 cells for the two rivers).

In order to investigate the hypothesis linking morphological forms within an RHS site and TSP and SSP, we need to identify local and upstream contributions. The local TSP and SSP are averages of the ten stream power values, one for each 50 m of the DEM grid within the 500 m RHS reach. The upstream SP values (SP_{up}) aims to represent the river capacity to transport sediment into the reach of interest and is defined as the average over a specified upstream length of channel. The difference between local and upstream SP ($\Delta SSP = SSP_{local} - SSP_{up}$, $\Delta TSP = TSP_{local} - TSP_{up}$) indicates the potential of the reach to transport the sediment entering from upstream: if positive, erosion should dominate and conversely deposition should dominate if ΔSSP is negative. Figure 2 shows three versions of SSP_{up} for lengths of 3, 5 and 10 km and compares them with a longitudinal profile of SSP, for the River Lune. SSP_{up} at 3 km more closely follows SSP patterns whereas SSP_{up} at 10 km average out most of peaks present in the SSP trajectory. SSP_{up} at 5 km behaves between these two. An analysis of TSP for the Lune and of SSP and TSP on the Wye produced similar patterns (not shown). ΔSSP and ΔTSP were calculated using SSP_{up} at 3, 5 and 10 km to identify the most suitable predictors of the channel classes studied.

Channel classification

Geomorphological processes and forms vary, for instance from an unconfined alluvial reach to a confined stable bed reach and, consequently, the interpretation of process dominance needs to take river type into account (Schumm 1985; Nanson & Croke 1992). For this reason the entire dataset is subdivided by expert judgment into confined and unconfined channels. The information to classify qualitatively the two channel classes includes the bed and the bank material at the site (as recorded by the RHS), valley setting, and the extent of the floodplain. This latter is taken as the width of the zone with an altitude ≤2 m above the channel (Bizzi & Lerner 2012).

Confined channels are indicated by bedrock or boulders and cobbles as the predominant bank material, and by a partly stable bed with sporadic or extensive occurrence of bedrock and boulders. Unconfined channels have earth, gravels and sand as bank material, and have unstable beds characterized by gravels, cobbles and sand. Confined channels are partly inhibited in their lateral migration and the vertical accumulation of relatively coarse sands and gravels is likely to be the dominant process of floodplain formation. Unconfined channels have higher lateral mobility which supports the creation of meandering rivers, the main mechanism of floodplain formation is lateral point-bar or braid-channel accretion (Nanson & Croke 1992).

Table 1 presents criteria which define two categories, namely extended and limited, that describe the occurrence of deposition and erosion features. These criteria are based on previous research (Newson *et al.* 1998, Bizzi *et al.* 2009) that identified these RHS variables and associated categories, and on specific analysis of the distribution of these features within the datasets used. The morphological forms and the criteria differ slightly between confined and unconfined channels because the two channel types present distinctive geomorphic characters, as stated earlier. These lead to two classes of confined and four classes of unconfined channels based on different configurations of deposition and erosion features (Table 2). ‘Deposition dominated’ is characterized by extended deposition features and the absence or limited occurrence of erosion features. Such a reach is primarily a sink of sediment, possibly associated with moderate or severe aggradation. ’Erosion dominated’ and ‘unstable equilibrium’ classes do not occur for confined channels because the resistance of bank and bed material inhibits the formation of extensive erosion features. ‘Stable equilibrium’ for confined channels describes reaches with extended presence of exposed bedrocks and boulders and limited occurrence of erosion features and unvegetated bars. The ‘erosion dominated’ class for unconfined channels describes a reach which works mainly as a source of sediment, and is characterized by bank instability and possibly by channel bed incision. Both the equilibrium classes for unconfined channels show equilibrium between erosion and deposition, but of different natures. Unstable equilibrium is associated with channel dynamism where extended erosion features are present as well as deposition ones. These channels are characterized by the higher lateral mobility typical of unconfined meandering rivers.

Stable equilibrium conversely is characterized by the absence of extended deposition or erosion features, but signs of lateral mobility and unvegetated bars are scarce.

Results

Stream power and channel classes relationships

Plot boxes in Figures 3, 4 and 5 report lower quartile, median and upper quartile values of TSP, SSP, ΔSSP and ΔTSP for each channel class. Whiskers from each end of the box show the data range or, if smaller, the most extreme values within 1.5 times the inter quartile range from the ends of the box. Outliers beyond the ends of the whiskers are marked with a ‘+’.

The upper part of Figure 3 shows SSP and TSP distributions for confined channels. The stable equilibrium class does not occur for SSP lower than 60 W m^{-2} and it is separated from deposition dominated, whereas TSP has a wider range for the equilibrium class and the two classes overlap. Figure 4 presents the distributions of ΔSSP and ΔTSP for the two classes (ΔSSP and ΔTSP at 10 km is not shown because does not add any relevant information). The central quartiles of the two classes are clearly separated for both ΔSSP and ΔTSP, except for ΔTSP at 3 km. The bottom part of Figure 3 shows SSP and TSP distributions for unconfined channels. Here the separation between the classes is less evident. Erosion dominated and unstable equilibrium classes have similar distributions well separated from the stable equilibrium class for both SSP and TSP. SSP values between 30 and 40 W m^{-2} or TSP around 2000 W m^{-1} provide a transition zone between erosion or unstable and deposition or stable classes. Figure 5 shows the distributions of ΔSSP and ΔTSP at 3 and 5 km for unconfined channels. The central quartiles of erosion dominated are characterized by positive ΔSSP and ΔTSP especially if taken over 5 km, whereas all the other classes have negatives ones. Stable equilibrium has values closer to zero, whereas deposition and unstable equilibrium have more negative ΔSP.

The results confirm some hypotheses stated above: i) a decrease in both SSP and TSP from upstream to downstream leads to deposition dominance, and ii) local stream power (SSP and TSP) drives local erosion processes. Indeed unstable equilibrium and deposition dominated classes have extensive deposition features (see Table 2) and both these classes are characterized by negative ΔSSP (see Figure 4 and 5), whereas erosion features are extensive for erosion dominated and unstable equilibrium classes, both characterized by SSP higher than 40 W m^{-2} or TSP above 2000 W (see Figure 3).

Each channel class seems to be characterized by unique combinations of predictors, i.e. SSP, TSP, ΔSSP, ΔTSP and channel type. These relationships are formalized using a classification tree. The regression tree, reported in Figure 6, correctly classifies 90% of the dataset. The tree firstly divides by channel type, supporting the idea of significantly different geomorphic processes characterizing the two types. For confined channels, deposition dominated and equilibrium classes are separated through ΔTSP at 3 km.

For unconfined channels, deposition dominated and unstable equilibrium have ΔTSP at 5 km lower than -46 W m^{-1}. Both the classes are characterized by the extensive presence of sediment bars (see Table 2) indicating that a decrease in TSP from upstream to downstream (i.e. a negative ΔTSP) creates some of the conditions necessary to deposit part of the entering sediment from upstream within the reach. Unstable equilibrium reaches are divided by deposition dominated ones by a TSP > 1648 W m^{-1}, which could be seen as the threshold necessary to trigger the formation of some erosion features within the this type of reach. The concurrent presence of extensive erosion and deposition features which characterizes this channel class (see Table 2) is the result of the concurrent ability of the reach to develop erosion process (TSP > 1648 W m^{-1}) and to deposit part of the entering sediment from upstream (negative ΔTSP).

For unconfined channels, ΔTSP at 5 km > -46 W m^{-1} indicates a limited ability of the river to deposit the entering sediment within the reach; if this condition is coupled with SSP higher than 34 W m^{-2} erosion dominated is the most likely class. An SSP of 34 W m^{-2} can also be seen as a threshold necessary to trigger erosion features within such reaches.

Extending the results to the whole river course

The decision tree can be applied to the whole river course. Map derived information on valley settings and the extent of the floodplain for the entire river courses were used to extend the channel confinement classification to those river stretches where RHS sites are scarce or absent. The results are reported in Figure 7 for the river Lune and Figure 8 for the river Wye.

The River Lune has two major stream power peaks at 20 and 35 km. The River Wye has an upstream peak and a wide mid-catchment one (at approximately 50 km). The two rivers have created distinctive sequences of erosion-transport-deposition reaches. Stream power profiles on the Wye oscillate around the erosion and deposition conditions defined by the tree (Figure 6). The river Lune has the higher stream energy with TSP higher than the threshold of 1648 W m^{-1} for most of its course. Where river transport capacity decreases downstream (negative ΔSP), this situation produces unstable equilibrium in unconfined channels. However, erosion dominates each time ΔSP is positive, i.e. each time the river creates the condition to transport downstream more sediment than it is able to supply from upstream. Deposition dominated reaches are mostly located in the lower catchment.

Discussion

Relationships between channel classes and stream power

The results show that there are significant relationships between the channel classes and stream power profiles. A TSP of 1648 W m^{-1} and an SSP of 34 W m^{-2} emerge as the minimum energy necessary to trigger erosion processes, i.e. to mobilize sediment, and to activate bank erosion and lateral channel migration. In a situation of a sediment supply deficit, this energy condition can trigger incision of the river bed. Reaches with SSP or TSP lower than these thresholds tend to be stable and have limited ability to activate those geomorphic processes.

Newson *et al.* (1998) used the RHS database to carry out a similar research experiment. A dataset of 484 sites across England and Wales was used to investigate the relationships between channel instability classes and a list of catchment geomorphic drivers (such as SSP, channel gradient, catchment physical settings etc.). SSP was identified as the most important parameter. However the study obtained few results about SSP's ability to discern channel classes, in contrast to our study. There are various potential reasons for this difference. Newson's dataset covers a variety of river types which were not analysed separately. Moreover Q_{MED} were determined by empirical relationships and not from monitored gauging stations. Channel gradient was determined from maps and not from a DEM. Future research is encouraged to test if, how and why the thresholds identified here might vary in relation to river types and regional settings.

Similar patterns emerge for SSP and TSP in Figures 3, 4 and 5. TSP represents the total energy available to the river channel to perform geomorphic work, create river dimensions (e.g. width, channel pattern) and to determine reach-scale sediment budgets (deposition or erosion oriented). SSP is related to TSP (eq. 2) but is more concerned with processes such local entrainment and unit bed load flux. TSP should be better able to predict larger scale channel classes. The regression tree identified ΔTSP as more useful than ΔSSP. However both TSP and SSP can be used to discern channel classes with similar accuracy (results not shown).

Analysis of profiles of upstream stream power at 3, 5 and 10 km showed that confined channel classes are mores strongly defined by SP at 3 km (although the relationship is relatively weak as the dataset includes only two deposition dominated sites in confined channels); unconfined ones are better defined by SP at 5 km upstream. This result suggests that the stream power drivers of the geomorphic processes shaping the channel are dissimilar between the two channel types. Confined channels in the case study show high energy and are characterized by the presence of boulders and exposed bedrock (see Table 1). Here bed sediment sizes are bigger than in lower energy reaches, valleys are steeper, channel and hillslope processes are strongly coupled and tributary density is higher. In this context, reach morphology is characterized by nearby upstream stream power, and *vice-versa* for unconfined ones.

Current limitations and future agenda

The framework provides a characterization of the river driving forces, i.e. the potential ability to transport, erode and store sediment within its course. However the present analysis does not properly assess sediment availability and connectivity as these would require large datasets. Instead, it uses averaged stream power over 3, 5 and 10 km upstream to assess the river potential to supply sediment from upstream reaches. This approach could be a notable limitation when analysing rivers where a recent severe imbalance has occurred and the river is still recovering by changing its slope, width and depth (Simon & Rinaldi 2006). In this situation, a negative ΔSP would not guarantee the necessary input of sediment from upstream to balance the river transport capacity in the reach. However, since continuous stream power profiles are available for the river, statistics can be extracted and compared with available field data. This paper found strong correlations between specific patterns of upstream stream power and channel features for confined and unconfined channel types. Similar results were recently found by Vocal Ferencevic and Ashmore (2012) who successfully used stream power as an assessment tool to understand river processes on Highland Creek in Canada. Further research in this direction promises to enrich our understanding of the role of stream power in driving river processes.

The RHS is primarily a protocol to survey physical habitats and not a proper geomorphological assessment (Newson *et al.* 1998). It has a limited capability to detect erosion and deposition processes. For example, the occurrence but not the extent of gravel bars and erosion features is recorded. There are no evaluations of sediment longitudinal continuity, channel-floodplain connectivity or bed armouring which might provide relevant information to interpret the current geomorphological behaviour of the river reach. This makes quantitative comparisons of erosion and deposition features difficult. However, small changes to the RHS protocols would greatly enhance, delivering more quantitative geomorphological data to complement the habitat data it already provides. Various field survey protocols already exist which would cost-effectively improve its capabilities (Sear *et al.* 2003; Rinaldi *et al.* 2010).

There are a number of uncertainties in the calculation of SP. Channel gradient requires caution in its calculation from a DEM especially for shallow slopes (Lane & Chandler 2003). Differences have been noticed between field and map derived values, especially for incised river reaches, and field confirmation may be necessary (Barker *et al.* 2009). New DEMs, with a 5 m horizontal grid and a vertical accuracy of 0.5 m, give slope estimates which correlate well with field measurements (Barker *et al.* 2009) and have the potential to improve the precision of future stream power calculations. For SSP, this paper uses an estimate of bankful width from an empirical relationship. Better results might be provided by interpolating field observations, however bankful estimates from field data show high variability (Orr & Walsh 2007).

Given these uncertainties, we tested the robustness of our findings by adding random errors to the estimates of slope, Q and w for each 50m DEM cell along the rivers. For simplicity, the error was sampled from an uniform distribution ranging 30% either side of the original value. The values of SSP, TSP, ΔSSP and ΔTSP for 3, 5 and 10 km were then recalculated from the slope, Q and w of the 7465 cells that now embed the error measurements. The resulting regression tree had only a moderate loss in the performance still being able to correctly classify 85% of the dataset.

Interpretation of the tree gave similar conclusions to the tree in Figure 6; the only difference was to use TSP instead of SSP to discern between erosion and stable in the furthest right branch. This confirms the robustness of the approach and, although error measurements in the calculation of stream power need to be addressed in future applications, the potential to use stream power profiles as predictors of fluvial processes of deposition and incision is promising.

Stream power as an indicator of channel sensitivity to erosion and deposition processes

The erosion threshold provided by this paper recalls Brookes' 'stability point' (Brookes 1987). He concluded, from studying incising channels in Denmark, England and Wales that, when a stream has enlarged to the point that it has a SSP below 35 W m^{-2}, the major phase of erosion is over. Similarly we obtained a threshold of 34 W m^{-2} SSP to discern between erosion dominated and equilibrium stable. The value also compares favourably with the erosion and deposition transition threshold between 30 and 35 W m^{-2} reported by Orr *et al.* (2008). Given the difficulties of rehabilitating incising channels, it is very important to identify conditions under which they cease actively deepening and attain a state of relative stability. This 35 W m^{-2} threshold has been already widely applied in stream rehabilitation work as it provides a neat target for waterway design and assessment (Brookes & Shields 1996; Erskine & White 1996; Urban & Rhoads 2003).

The risk of erosion for the river Lune is particularly elevated where the uplands join the lowland area (around the 40th km, Figure 6) and upstream within the first 15 km (Figure 6). Orr and Carling (2006) reported evidence of extensive bank erosion particularly in the piedmont area (over 40% of the bank length). They also found evidence of adjustment to channelization in the upper Lune where erosion and incision have increased in rate during the last 30 years. The proposed framework correctly identifies erosion domination for unconfined channels in upstream reaches (within the first 15 km), whereas further downstream the channel becomes confined and is classified as stable equilibrium. Our current ability to detect possible incision for this class is limited due to the deficiencies of RHS features surveyed.

Along the river Wye there are some reaches within the first 90 km where stream power drops rapidly creating conditions for severe deposition. Rowan and Walling (1992) analysed the transport and fluvial redistribution of Chernobyl-derived radiocaesium within the river Wye basin. Interestingly, they identified that the ^{134}Cs maxima in the upper 15 cm of floodplain sediment occurred between 50 and 90 km downstream; specifically, maxima occurred at the 60th and 80th km and match the deposition zones identified by Figure 7.

Thus the stream power analysis has the ability to identify channel sensitivity to erosion-deposition processes and so support management decision making. Indeed the concept of 'stability points' or thresholds have already been proposed by Brookes (1987, 1988), and used widely in river rehabilitation and management projects. However, the threshold idea, although very attractive, needs to be used with caution given the complexity of fluvial geomorphic processes. As noted previously, stream power mainly characterizes the river driving forces, and does not include information on resisting forces (such as sediment size distribution) or on limiting factors in general (such as sediment availability and connectivity). The approach proposed in this paper opens a different perspective on this issue. Nowadays, coupling high resolution information on stream power with more comprehensive fluvial geomorphic assessments, it is possible to build non-trivial relationships between stream power and reach conditions , thereby enhancing fluvial process understanding and promising effective management tools.

Our method contributes towards the goal of developing automated GIS and statistical procedures able to provide regional or even national assessment of river geomorphic characteristics. These tools are urgently required in the context of modern catchment management (Alber & Piégay 2011; Bizzi & Lerner 2012; Vocal Ferencevic & Ashmore 2012). They will have inherent limitations for assessments of large areas but are needed for strategic planning (Schmitt *et al.* 2007; Alber & Piégay 2011). In the future, large area assessments will help to plan more detailed smaller scale fluvial geomorphic assessments, with the latter enriching the former in a virtuous circle.

Conclusions

This paper examines the use of stream power to characterize channel sensitivity to erosion and deposition dominance. An erosion threshold is identified which defines the necessary stream power to trigger erosion processes within the channel. The threshold compares favourably with previous attempts to define an SSP threshold for channel stability for similar river types. The present paper also uses stream power profiles to assess the potential contribution of sediment supply from upstream. These parameters are important in inferring process dominance. The joint configuration of local and upstream stream power is able to successfully identify four channel classes which can be interpreted in term of their sensitivity to erosion and deposition dominance. The potential of stream power as an indicator of erosion and deposition processes is particularly interesting for the novel availability of high precision DEM which promises to improve the precision of future stream power calculations. The type of findings provided by the paper support geomorphic characterizations of river especially at wide scales for which suitable process based assessment frameworks are still lacking.

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TABLES

Table 1. Criteria used for the identification of deposition and erosion features from RHS variables

Feature	***Criteria***
Confined Channel	
Deposition	*Extended* if the sum of all the types(1) of unvegetated bars is >2(2) and the occurrence of exposed bedrock and boulders is not extended(3) *limited* otherwise
Erosion	*Extended* if Eroding earth cliff>2(2) and Vertical/undercut bank profile is extended(3) and the occurrence of bedrock as bank material is <3(2) *limited* otherwise
Unconfined Channel	
Deposition	*Extended* if the sum of all the types(1) of unvegetated bars is >3(2) *limited* otherwise
Erosion	*Extended* if eroding earth cliff>4(2) or Eroding earth cliff>2(2) and Vertical/undercut bank profile is extended(3) *limited* otherwise

(1) point, side or mid-channel bars as recorder in the RHS ten-spot checks form

(2) refers to presence/absence within the RHS ten-spot checks;

(3) refers to RHS sweep-up section, it is considered extended if present over >33% of the 500m reach surveyed

Table 2. Channel classes, criteria to be fulfilled and dominant process associated for confined and unconfined channel types. These criteria are based on the work of Newson et al. (1998), who analysed a similar dataset, and on the authors' experience in analysing the RHS dataset (Bizzi et al. 2009).

Class	**Criteria**	**Sediment process**
Confined Channel		
Stable equilibrium	Limited deposition and erosion features	Transport/ Potential Source
Deposition dominated	Extended deposition features and limited erosion ones	Sink
Unconfined Channel		
Stable equilibrium	Limited deposition and erosion features	Transport
Deposition dominated	Extended deposition features and limited erosion ones	Sink
Erosion dominated	Extended erosion features and limited deposition ones	Source
Unstable equilibrium	Extended deposition and erosion features	Transport

S. Bizzi and David N. Lerner, 2015. The use of stream power as indicator of channel sensitivity to erosion and deposition processes. *River Research and Applications*, **31**, 16-27. DOI: 10.1002/rra.2717. *FINAL VERSION*

FIGURES

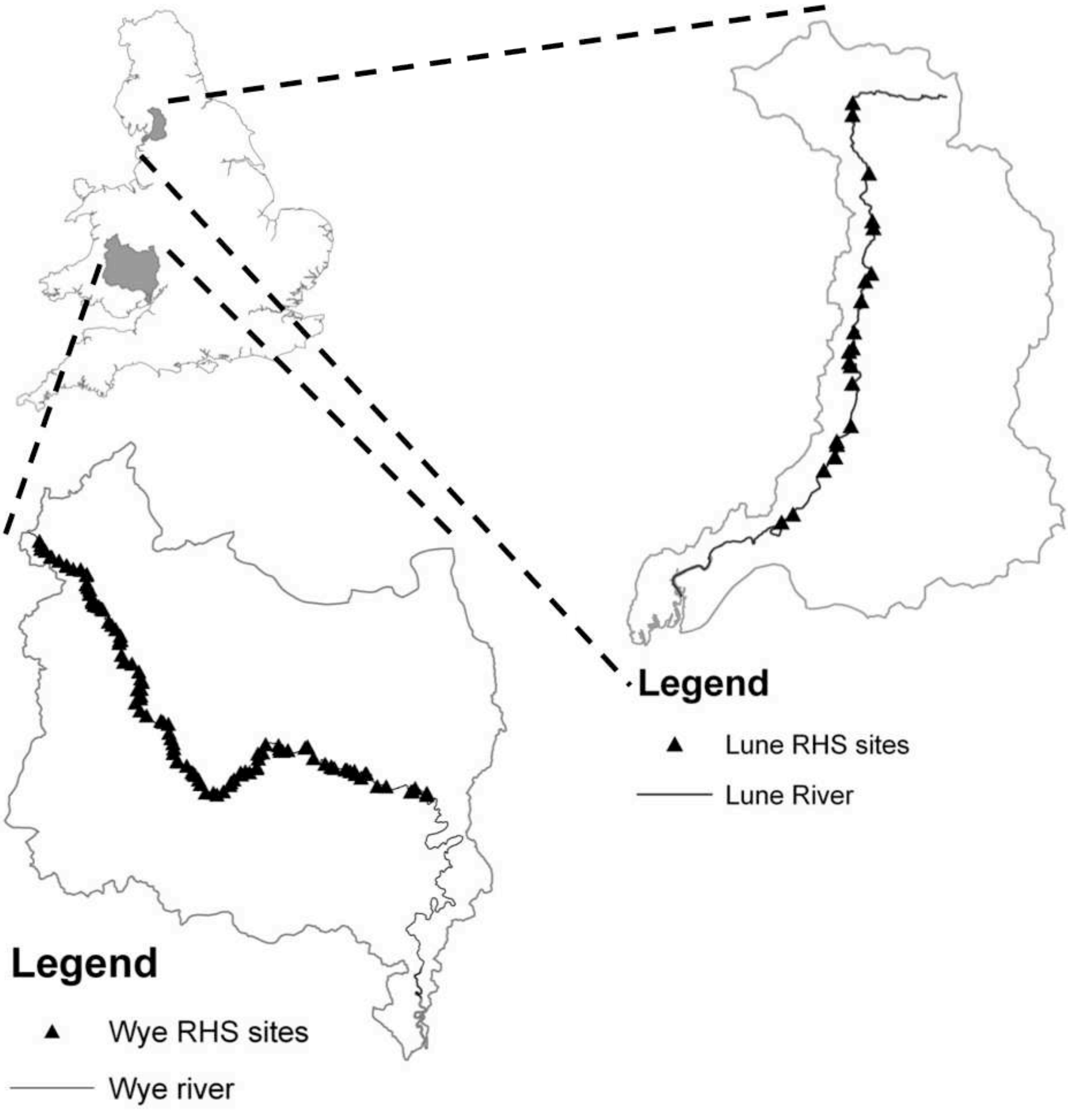


Figure 1. Locations of the Lune and Wye catchments and of the RHS sites along the two river courses

S. Bizzi and David N. Lerner, 2015. The use of stream power as indicator of channel sensitivity to erosion and deposition processes. *River Research and Applications*, **31**, 16-27. DOI: 10.1002/rra.2717. *FINAL VERSION*

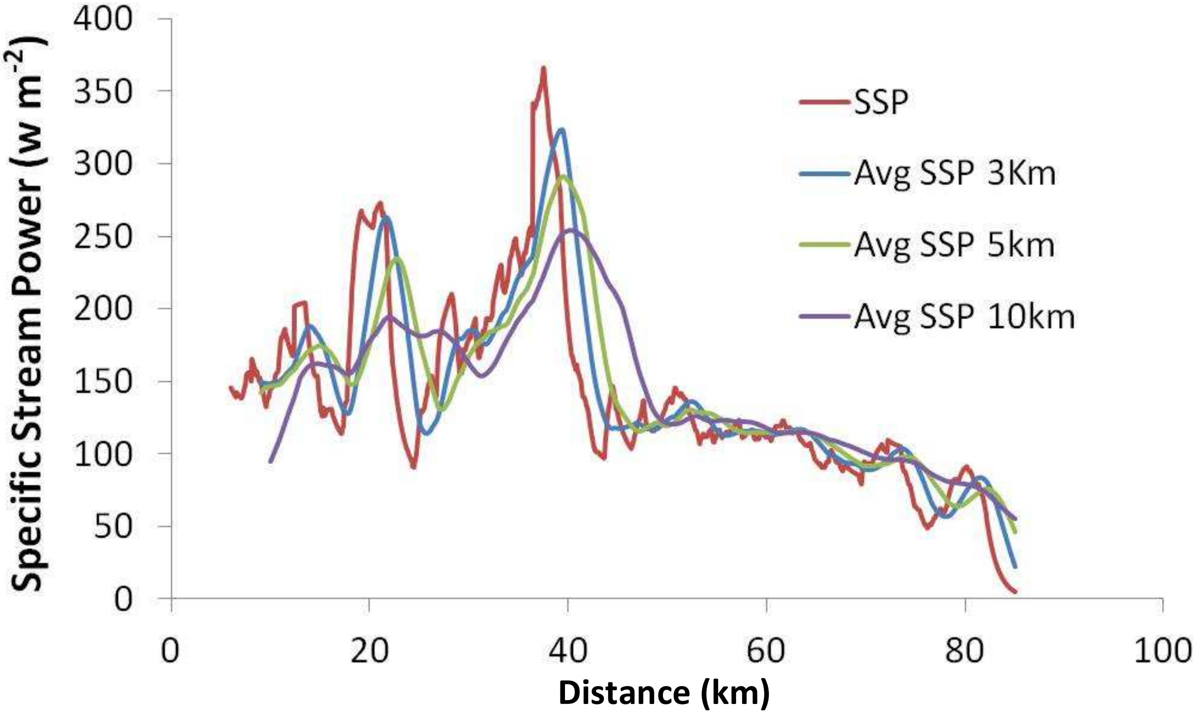


Figure 2. Comparison between local SSP and SSP$_{up}$ averaged over 3, 5 and 10 km.

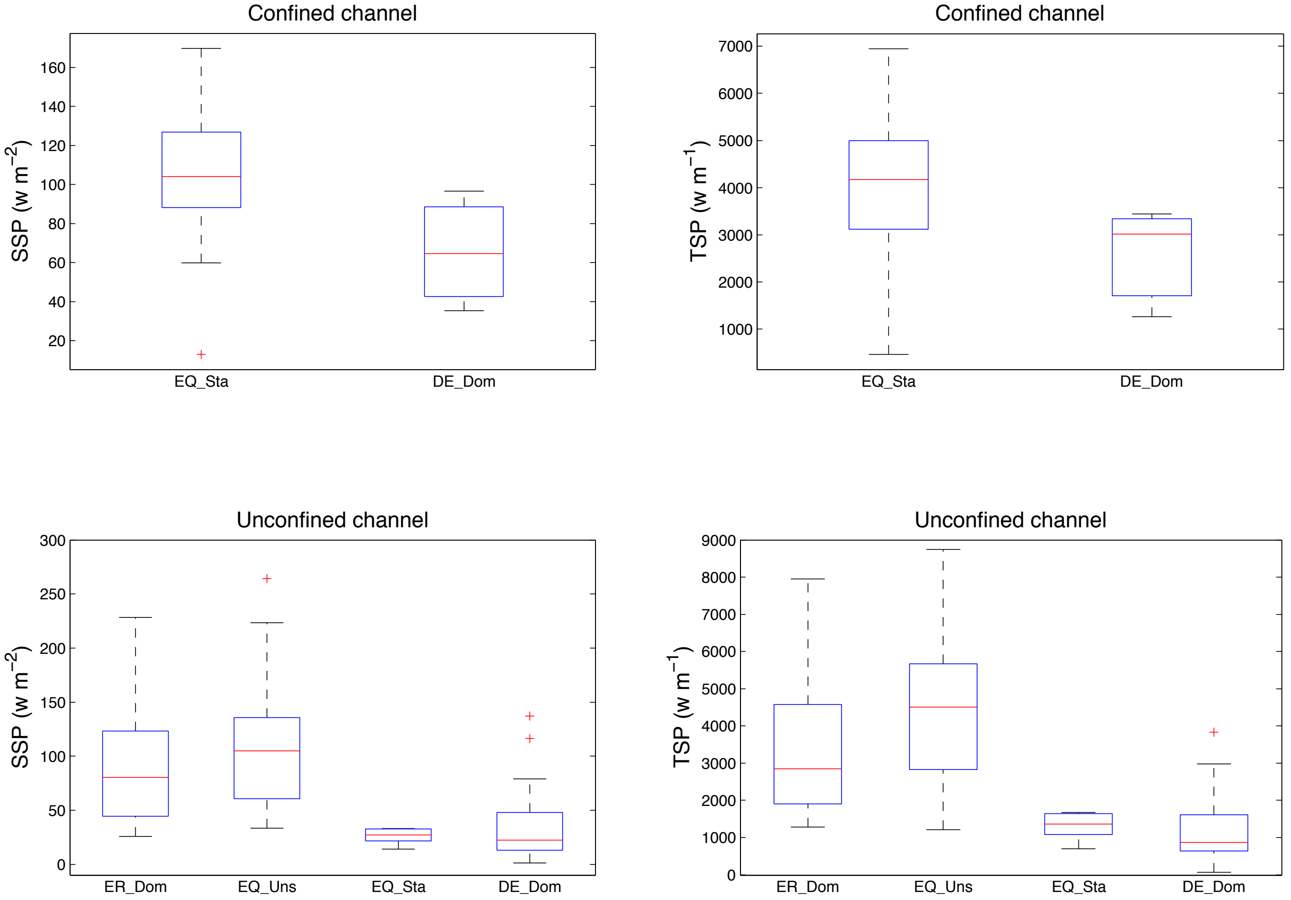


Figure 3. SSP and TSP distributions for each channel class, for confined and unconfined channels: ER_Dom, EQ_Uns, EQ_Stable and De_Dom stands respectively for Erosion Dominated, Equilibrium Unstable, Stable Equilibrium and Deposition Dominated.

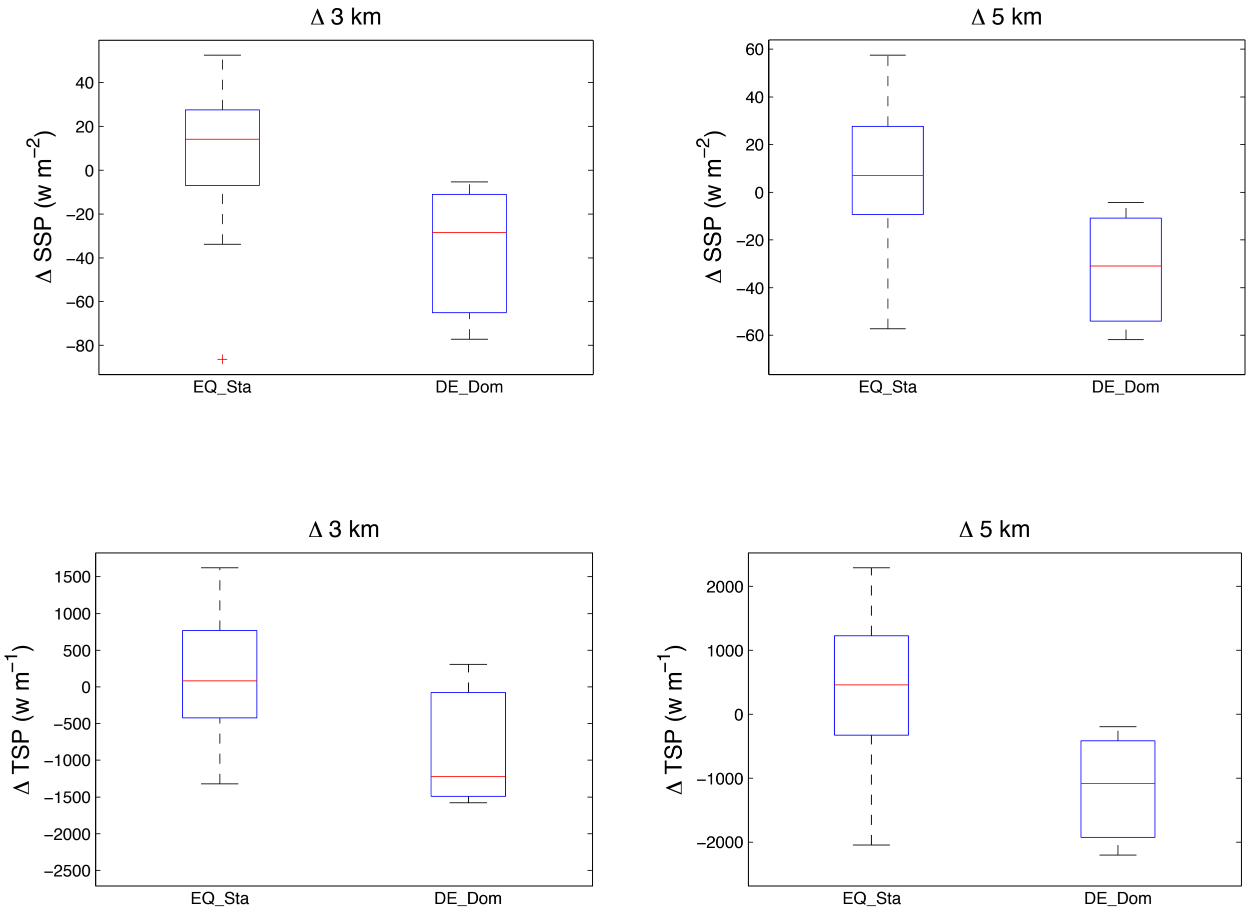
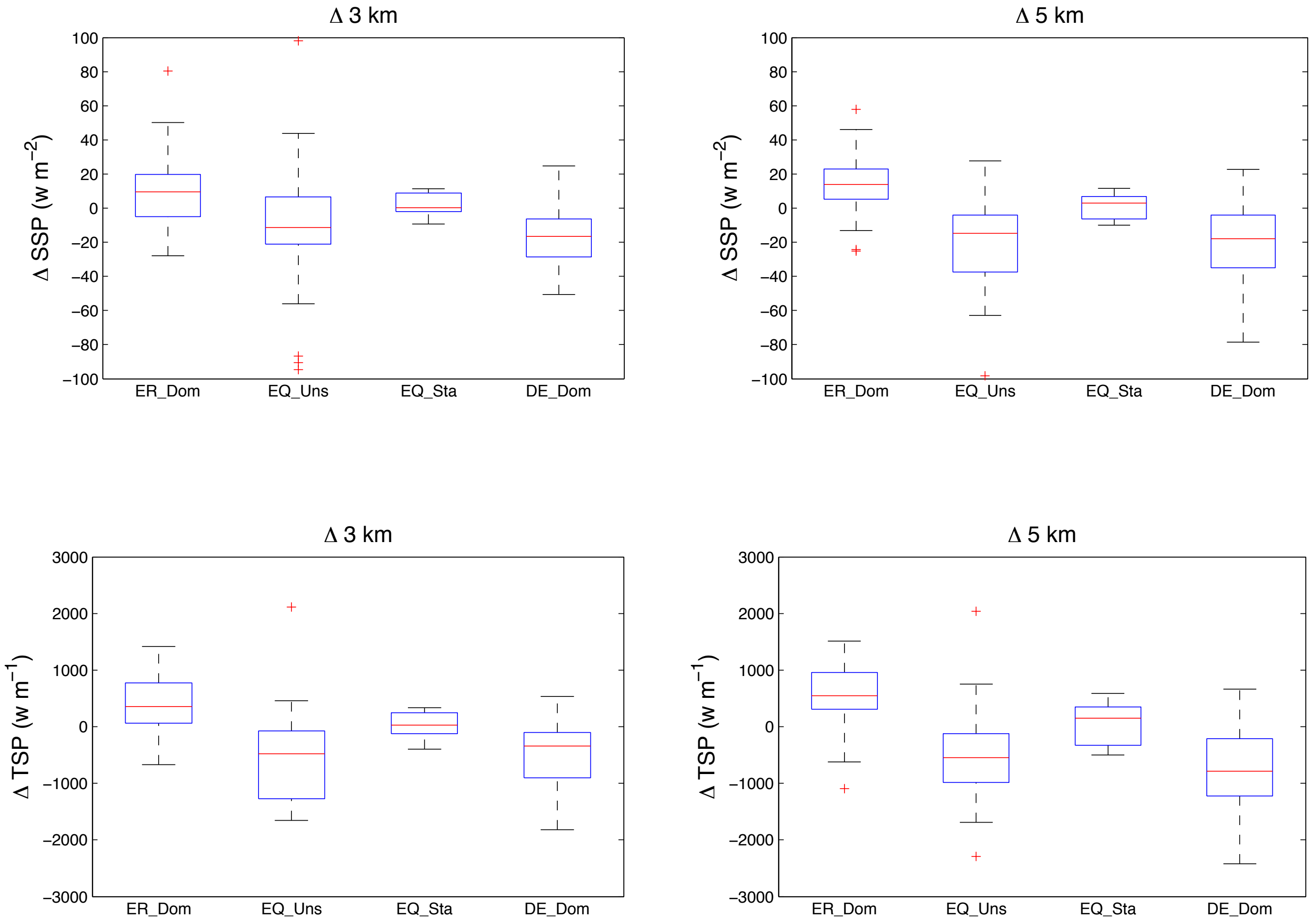


Figure 4. ΔSSP and ΔTSP distributions for each channel class of confined channel: ER_Dom, EQ_Uns, EQ_Stable and De_Dom stands respectively for Erosion Dominated, Equilibrium Unstable, Stable Equilibrium and Deposition Dominated.


Δ 3 km
Δ 5 km
Δ SSP (w m^{-2})
100
80
60
40
20
0
−20
−40
−60
−80
−100
ER_Dom
EQ_Uns
EQ_Sta
DE_Dom
Δ 3 km
Δ 5 km
Δ TSP (w m^{-1})
3000
2000
1000
0
−1000
−2000
−3000
ER_Dom
EQ_Uns
EQ_Sta
DE_Dom

7

Figure 5. ΔSSP and ΔTSP distributions for each channel class of unconfined channel: ER_Dom, EQ_Uns, EQ_Stable and De_Dom stands respectively for Erosion Dominated, Equilibrium Unstable, Stable Equilibrium and Deposition Dominated.

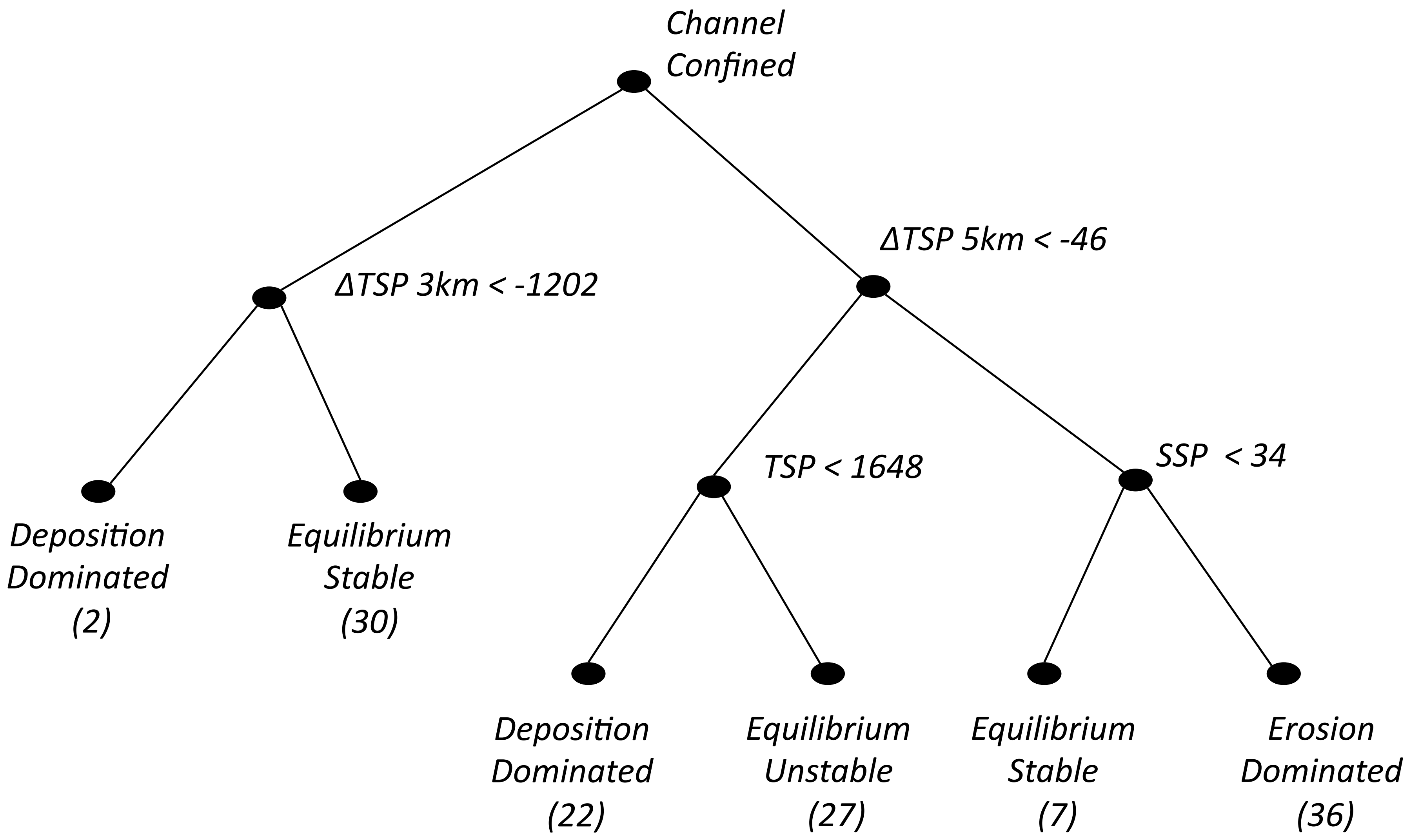

Channel Confined
ΔTSP 3km < -1202
ΔTSP 5km < -46
TSP < 1648
SSP < 34
Deposition Dominated (2)
Equilibrium Stable (30)
Deposition Dominated (22)
Equilibrium Unstable (27)
Equilibrium Stable (7)
Erosion Dominated (36)

Figure 6. The regression tree identifies channel classes as a function of conditions set on TSP, ΔTSP and channel type. The condition on each node is satisfied on the left branch. Numbers within brackets indicate the number of sites belonging to each channel class on the branch.

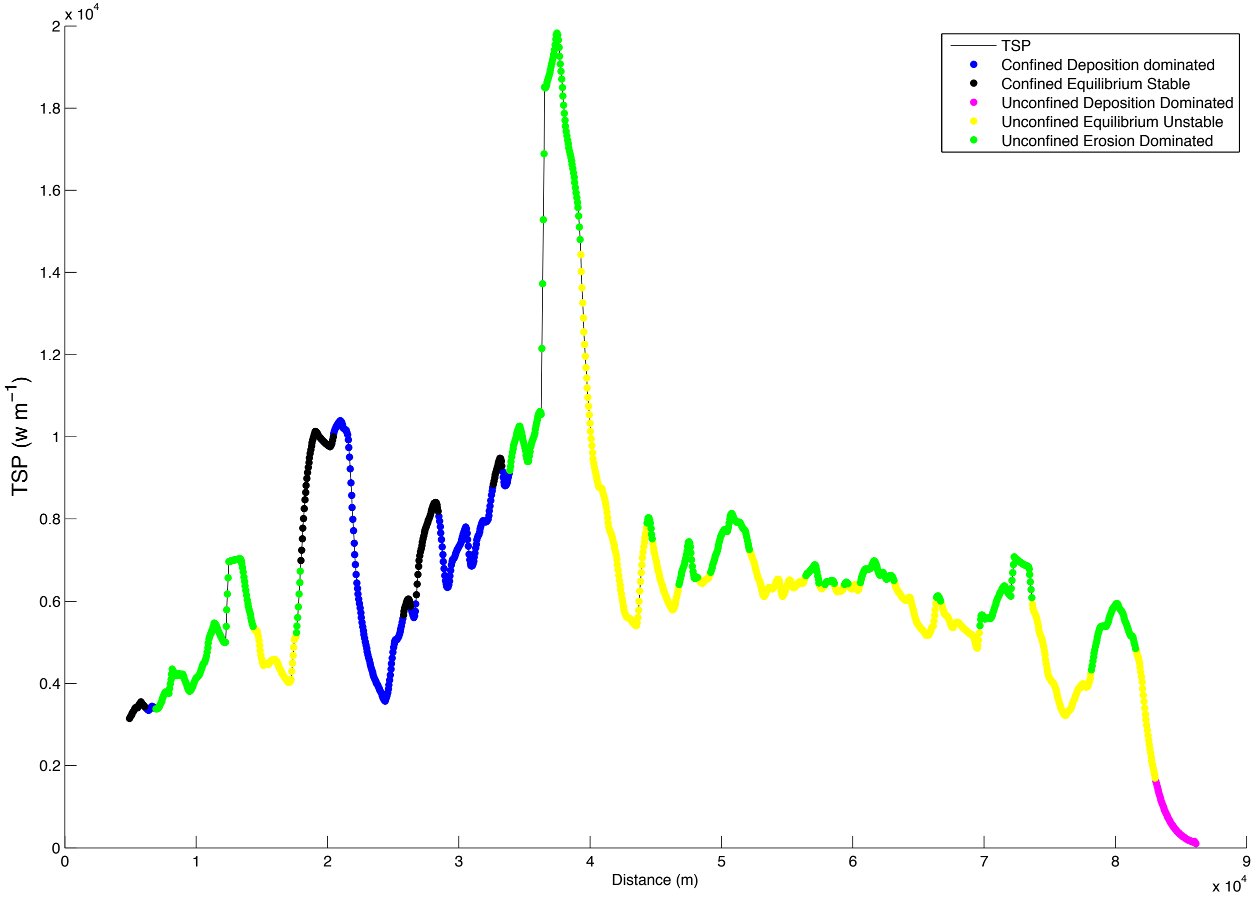
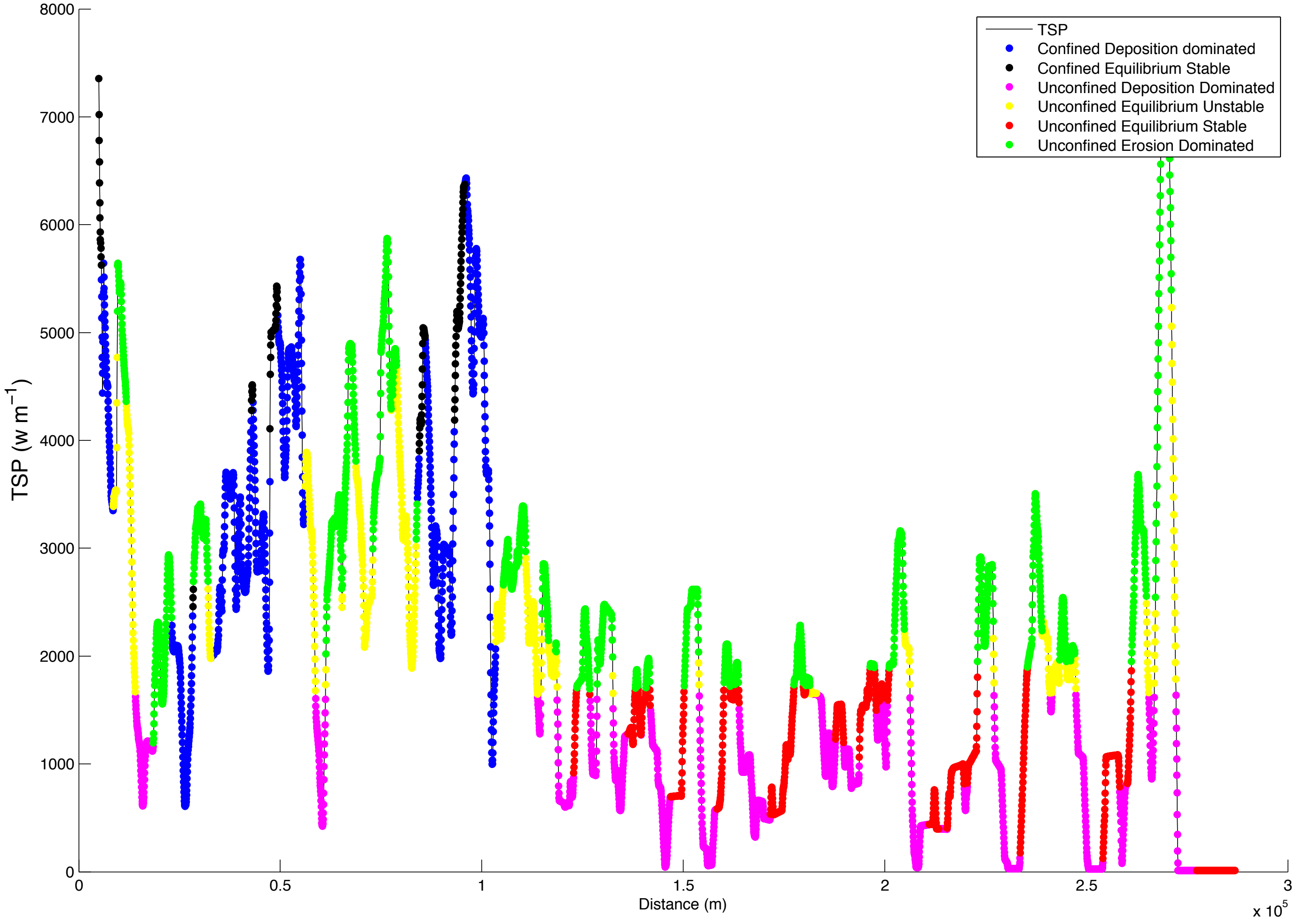


Figure 7. TSP profile for the river Lune. Points of different colours represent different channel type and classes.


TSP
Confined Deposition dominated
Confined Equilibrium Stable
Unconfined Deposition Dominated
Unconfined Equilibrium Unstable
Unconfined Equilibrium Stable
Unconfined Erosion Dominated
TSP (w m^{-1})
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.5
1
1.5
2
2.5
3
Distance (m)
x 10^5

17 Figure 8. TSP profile for the river Wye. Points of different colours represent different channel type and classes.