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

27 *Introduction*

28 An understanding of sediment transport and channel sensitivity to erosion or deposition processes
29 is essential for river management. For instance, deposition dominated reaches may have reduced
30 channel conveyance, making overtopping more likely. Erosion dominated reaches have increased
31 risk of infrastructure failure or instability. Recent flood management schemes have used
32 assessments of channel geomorphic processes in order to design suitable and effective solutions
33 (Wallerstein *et al.* 2006; Rinaldi *et al.* 2009). The influence of channel geomorphic processes and
34 forms on freshwater biotic communities is also well recognised (Poff & Ward 1990; Lorenz *et al.*
35 2004; Jahnig *et al.* 2009) and the focus of research (Vaughan *et al.* 2007; Palmer *et al.* 2010;
36 Vaughan & Ormerod 2010). A recent EU directive requires the evaluation of hydro-morphological
37 quality for all the river networks in order to assess river ecological status and to deliver catchment
38 management plans (EC 2000).

39 Channel geomorphic behaviours are usually investigated by field-based fluvial audits (e.g. Harvey
40 2001; Surian & Rinaldi 2003; Rinaldi *et al.* 2009) and by sophisticated hydrodynamic models (e.g.
41 HEC 1976; Olsen 2003; ISIS 2006; Langendoen 2008). These approaches require very detailed
42 inputs on channel discharges, cross sections and grain size distributions. This information is
43 normally provided through intensive fieldwork and uses experienced staff for interpretation.
44 Methods which require fewer resources would be of great value for regional or national
45 assessments (Newson *et al.* 1998; Newson & Large 2006; Wallerstein *et al.* 2006).

46 River geomorphic processes and the resulting morphological forms are driven by a balance of
47 driving (e.g. channel gradient and discharge) and resisting (e.g. bed and bank resistance to
48 transport) forces. The various equilibria which can be established between these contrasting
49 forces are functions of the geological setting, catchment hydrology and the geomorphic history of
50 the catchment and create the variety of river styles present in nature (Knighton 1998; Nanson &
51 Huang 2008). The ability to perform geomorphic work, commonly expressed as stream power, is a
52 measure of the main driving forces acting in the channel, i.e. the joint effect of channel gradient

53 and discharge. Stream power has been widely used to assess sediment transport and channel
54 geomorphic patterns in general (e.g. Bagnold 1977; Chang 1979; Nanson & Croke 1992; Ferguson
55 2005). Modern digital elevation models (DEMs) allow the quantification of channel slope at high
56 resolution, exploration of stream power variability along the full length of a river (Barker *et al.*
57 2009), and offer the potential to use stream power as a stream assessment tool (Vocal Ferencevic
58 & Ashmore 2012).

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

68 *Method*

69 Stream power

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

$$71 \quad TSP = \gamma QS \quad (1)$$

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

$$73 \quad SSP = \frac{TSP}{w} \quad (2)$$

74 where γ is the unit weight of water ($=9800 \text{ N/m}^3$), Q is discharge (m^3/s), and S is energy slope
75 (m/m) which is often approximated by bed slope, and w is the channel bankful width (m) (Bagnold
76 1966, 1977).

77 Field observations

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

94 Case studies and datasets

95 The rivers Wye and Lune have been chosen as case studies because both are characterized by
96 sinuous single-thread channels with predominantly boulder, cobble and gravel beds and because a
97 good number of field observations are available. The Lune catchment has an area of 1223 km² and
98 the river is more than 90 km long (see Figure 1). The geomorphology of the area has been strongly
99 influenced by glaciation. The upper reaches of the Lune and its tributaries flow through a
100 limestone landscape, which provides a significant, albeit flashy, contribution to surface waters,
101 whereas the lower part is dominated by Millstone Grit. The river Wye is the fifth longest river in
102 the UK and flows between England and Wales (see Figure 1). This catchment is 4136 km² and the
103 river is 215 km long. The geology includes limestone, mudstone and sandstone rocks. The
104 information that was available for both the catchments include flow discharges at monitored

105 stations, river network maps and DEMs at 50 m grid resolution. Higher resolution DEMs became
106 available after the project, and their potential impact is discussed later.

107 Field observations are provided by the River Habitat Survey (RHS) which is a well established
108 protocol to survey physical and habitat features of a river reach (Raven *et al.* 1998; Environment
109 Agency 2003). Data is collected by a field survey along a standard 500 m river reach.

110 Morphological and physical habitat features within the channel and the adjacent river corridor are
111 recorded at 10 spot checks at 50 m intervals, while other features are qualitative described for the
112 entire 500 m reach.

113 124 sites surveyed between 1996 and 2000 were judged suitable for the present analysis (22 along
114 the river Lune and 102 along the river Wye, see Figure 1). Sites which are strongly affected by
115 artificial infrastructures or altered conditions were omitted because the interpretation of
116 morphological forms is affected: for instance, bank protection prevents erosion, conversely
117 livestock damage increases it. The survey dates are close to the DEM which was updated in 2004.
118 Configurations of geomorphological controls along the river course and associable morphological
119 forms do not normally change significantly over a few years.

120 Calculating TSP and SSP

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

134 relations between flow and distance downstream due to the tributaries. Relating Q_{MED} directly to
135 catchment area gave similar results with a slightly lower R^2 .

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

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

157 Channel classification

158 Geomorphological processes and forms vary, for instance from an unconfined alluvial reach to a
159 confined stable bed reach and, consequently, the interpretation of process dominance needs to
160 take river type into account (Schumm 1985; Nanson & Croke 1992). For this reason the entire
161 dataset is subdivided by expert judgment into confined and unconfined channels. The information
162 to classify qualitatively the two channel classes includes the bed and the bank material at the site

163 (as recorded by the RHS), valley setting, and the extent of the floodplain. This latter is taken as the
164 width of the zone with an altitude ≤ 2 m above the channel (Bizzi & Lerner 2012).

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

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

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

195 *Results*

196 *Stream power and channel classes relationships*

197 Plot boxes in Figures 3, 4 and 5 report lower quartile, median and upper quartile values of TSP,
198 SSP, Δ SSP and Δ TSP for each channel class. Whiskers from each end of the box show the data
199 range or, if smaller, the most extreme values within 1.5 times the inter quartile range from the
200 ends of the box. Outliers beyond the ends of the whiskers are marked with a '+'.
201

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

216 The results confirm some hypotheses stated above: i) a decrease in both SSP and TSP from
217 upstream to downstream leads to deposition dominance, and ii) local stream power (SSP and TSP)
218 drives local erosion processes. Indeed unstable equilibrium and deposition dominated classes have
219 extensive deposition features (see Table 2) and both these classes are characterized by negative
220 Δ SSP (see Figure 4 and 5), whereas erosion features are extensive for erosion dominated and

221 unstable equilibrium classes, both characterized by SSP higher than 40 W m^{-2} or TSP above 2000 W
222 (see Figure 3).

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

229 For unconfined channels, deposition dominated and unstable equilibrium have ΔTSP at 5 km lower
230 than -46 W m^{-1} . Both the classes are characterized by the extensive presence of sediment bars
231 (see Table 2) indicating that a decrease in TSP from upstream to downstream (i.e. a negative ΔTSP)
232 creates some of the conditions necessary to deposit part of the entering sediment from upstream
233 within the reach. Unstable equilibrium reaches are divided by deposition dominated ones by a
234 $\text{TSP} > 1648 \text{ W m}^{-1}$, which could be seen as the threshold necessary to trigger the formation of
235 some erosion features within the this type of reach. The concurrent presence of extensive erosion
236 and deposition features which characterizes this channel class (see Table 2) is the result of the
237 concurrent ability of the reach to develop erosion process ($\text{TSP} > 1648 \text{ W m}^{-1}$) and to deposit part
238 of the entering sediment from upstream (negative ΔTSP).

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

243 Extending the results to the whole river course

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

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

258 *Discussion*

259 *Relationships between channel classes and stream power*

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

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

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

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

293 Current limitations and future agenda

294 The framework provides a characterization of the river driving forces, i.e. the potential ability to
295 transport, erode and store sediment within its course. However the present analysis does not
296 properly assess sediment availability and connectivity as these would require large datasets.
297 Instead, it uses averaged stream power over 3, 5 and 10 km upstream to assess the river potential
298 to supply sediment from upstream reaches. This approach could be a notable limitation when
299 analysing rivers where a recent severe imbalance has occurred and the river is still recovering by
300 changing its slope, width and depth (Simon & Rinaldi 2006). In this situation, a negative ΔSP would
301 not guarantee the necessary input of sediment from upstream to balance the river transport
302 capacity in the reach. However, since continuous stream power profiles are available for the river,
303 statistics can be extracted and compared with available field data. This paper found strong
304 correlations between specific patterns of upstream stream power and channel features for

305 confined and unconfined channel types. Similar results were recently found by Vocal Ferencevic
306 and Ashmore (2012) who successfully used stream power as an assessment tool to understand
307 river processes on Highland Creek in Canada. Further research in this direction promises to enrich
308 our understanding of the role of stream power in driving river processes.

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

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

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

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

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

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

350 The risk of erosion for the river Lune is particularly elevated where the uplands join the lowland
351 area (around the 40th km, Figure 6) and upstream within the first 15 km (Figure 6). Orr and Carling
352 (2006) reported evidence of extensive bank erosion particularly in the piedmont area (over 40% of
353 the bank length). They also found evidence of adjustment to channelization in the upper Lune
354 where erosion and incision have increased in rate during the last 30 years. The proposed
355 framework correctly identifies erosion domination for unconfined channels in upstream reaches
356 (within the first 15 km), whereas further downstream the channel becomes confined and is
357 classified as stable equilibrium. Our current ability to detect possible incision for this class is
358 limited due to the deficiencies of RHS features surveyed.

359 Along the river Wye there are some reaches within the first 90 km where stream power drops
360 rapidly creating conditions for severe deposition. Rowan and Walling (1992) analysed the
361 transport and fluvial redistribution of Chernobyl-derived radiocaesium within the river Wye basin.
362 Interestingly, they identified that the ^{134}Cs maxima in the upper 15 cm of floodplain sediment

363 occurred between 50 and 90 km downstream; specifically, maxima occurred at the 60th and 80th
364 km and match the deposition zones identified by Figure 7.

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

377 Our method contributes towards the goal of developing automated GIS and statistical procedures
378 able to provide regional or even national assessment of river geomorphic characteristics. These
379 tools are urgently required in the context of modern catchment management (Alber & Piégay
380 2011; Bizzi & Lerner 2012; Vocal Ferencevic & Ashmore 2012). They will have inherent limitations
381 for assessments of large areas but are needed for strategic planning (Schmitt *et al.* 2007; Alber &
382 Piégay 2011). In the future, large area assessments will help to plan more detailed smaller scale
383 fluvial geomorphic assessments, with the latter enriching the former in a virtuous circle.

384 *Conclusions*

385 This paper examines the use of stream power to characterize channel sensitivity to erosion and
386 deposition dominance. An erosion threshold is identified which defines the necessary stream
387 power to trigger erosion processes within the channel. The threshold compares favourably with
388 previous attempts to define an SSP threshold for channel stability for similar river types. The
389 present paper also uses stream power profiles to assess the potential contribution of sediment
390 supply from upstream. These parameters are important in inferring process dominance. The joint

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391 configuration of local and upstream stream power is able to successfully identify four channel
392 classes which can be interpreted in term of their sensitivity to erosion and deposition dominance.
393 The potential of stream power as an indicator of erosion and deposition processes is particularly
394 interesting for the novel availability of high precision DEM which promises to improve the
395 precision of future stream power calculations. The type of findings provided by the paper support
396 geomorphic characterizations of river especially at wide scales for which suitable process based
397 assessment frameworks are still lacking.

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REFERENCES

- Alber A. & Piégay H. (2011) Spatial disaggregation and aggregation procedures for characterizing fluvial features at the network-scale: Application to the Rhône basin (France). *Geomorphology* **125**, 343–360.
- Bagnold R.A. (1966) An approach to the sediment transport problem from general physics. *United States Geological Survey Professional Paper 4221*.
- Bagnold R.A. (1977) Bed load transport by natural rivers. *Water Resources Research* **13**, 303–312.
- Barker D.M., Lawler D.M., Knight D.W., Morris D.G., Davies H.N. & Stewart E.J. (2009) Longitudinal distributions of river flood power: the combined automated flood, elevation and stream power (CAFES) methodology. *Earth Surface Processes and Landforms* **34**, 280–290.
- Bizzi S., Harrison R.F. & Lerner D.N. (2009) The Growing Hierarchical Self-Organizing Map (GHSOM) for analysing multi-dimensional stream habitat datasets. In: *Proceeding of 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation*. pp. 734–740. Cairns, Australia.
- Bizzi S. & Lerner D.N. (2012) Characterizing physical habitats in rivers using map-derived drivers of fluvial geomorphic processes. *Geomorphology* **169-170**, 64–73.
- Brookes A. (1988) *Channelized rivers: perspectives for environmental management*. Wiley, Chichester.
- Brookes A. (1987) The distribution and management of channelized streams in Denmark. *Regulated Rivers* **1**, 3–16.
- Brookes A. & Shields F.D. (1996) *River channel restoration: Guiding principles for sustainable projects*. John Wiley and Sons, Chichester.
- Chang H.H. (1979) Minimum stream power and river channel patterns. *Journal of Hydrology* **41**, 303–327.
- Church M. (1992) Channel morphology and typology. In: *The Rivers Handbook: Hydrological and Ecological Principles, vol. 1*. (Eds P. Calow & G.E. Petts), pp. 126–143. Blackwell Scientific Publications, Oxford.

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

EC (2000) Directive 2000/60/EC of the European Parliament and of the council: establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities* **L327**, 1–71.

Environment-Agency (2003) River Habitat Survey in Britain and Ireland. Field Survey Guidance Manual.

Erskine W.D. & White L.J. (1996) Historical river metamorphosis of the Cann River, East Gippsland, Victoria. In: *First National Conference on Stream Management in Australia*. (Eds I. Rutherford & M. Walker), pp. 277–282. Merri jig.

Ferguson R.I. (2005) Estimating critical stream power for bedload transport calculations in gravel-bed rivers. *Geomorphology* **70**, 33–41.

Harvey A.M. (2001) Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity, illustrated from the Howgill Fells, northwest England. *Catena* **42**, 225–250.

HEC (1976) *HEC-6: Scour and deposition in rivers and reservoirs: Users Manual*. Hydrologic Engineering Centre. US Army Corps of Engineers. Computer Program 723-G2-L2470, California.

Hey R.D. & Thorne C.R. (1986) Stable Channels with Mobile Gravel Beds. *Journal of Hydraulic Engineering* **112**, 671–689.

ISIS (2006) *ISIS Flow / Hydrology*. Wallingford Software Ltd. and Halcrow Group Ltd, Wallingford.

Jahnig S.C., Brunzel S., Gacek S., Lorenz A.W. & Hering D. (2009) Effects of re-braiding measures on hydromorphology, floodplain vegetation, ground beetles and benthic invertebrates in mountain rivers. *Journal of Applied Ecology* **406**, 406–416.

Jain V., Preston N., Fryirs K.A. & Brierley G.J. (2006) Comparative assessment of three approaches for deriving stream power plots along long profiles in the upper Hunter River catchment, New South Wales, Australia. *Geomorphology* **74**, 297–317.

Knighton A.D. (1999) Downstream variation in stream power. *Geomorphology* **29**, 293–306.

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

Knighton A.D. (1998) *Fluvial Forms and Processes. A New Perspective*. Arnold, London.

Lane S.N. & Chandler J.H. (2003) Editorial: The generation of high quality topographic data for hydrology and geomorphology: new data sources, new applications and new problems. *Earth Surface Processes and Landforms* **28**, 229–230.

Langendoen E.J. (2008) Modeling the Evolution of incised streams: model formulation and validation of flow and streambed evolution components. *Journal of Hydraulics Engineering* **134**, 749–762.

Little W.C., Thorne C.R. & Murphey J.B. (1982) Mass bank failure analysis of selected Yazoo Basin streams. *Trans. ASAE* **25**, 1321–1328.

Lorenz A.W., Hering D., Feld C.K. & Rolauuffs P. (2004) A new method for assessing the impact of hydromorphological degradation on the macroinvertebrate fauna of five German stream types. *Hydrobiologia* **516**, 107–127.

Ma Y., Huang H.Q., Xu J., Brierley G.J. & Yao Z. (2010) Variability of effective discharge for suspended sediment transport in a large semi-arid river basin. *Journal of Hydrology* **388**, 357–369.

Nanson G.C. & Croke J.C. (1992) A genetic classification of floodplains. *Geomorphology* **4**, 459–486.

Nanson G.C. & Huang H.Q. (2008) Least action principle, equilibrium states, iterative adjustment and the stability of alluvial channels. *Earth Surface Processes and Landforms* **33**, 923–942.

Newson M.D., Clark M.J. & Sear D.A. (1998) The geomorphological basis for classifying rivers. *Aquatic conservation: marine and freshwater ecosystem* **8**, 415–430.

Newson M.D. & Large A.R.G. (2006) “Natural” rivers, “hydromorphological quality” and river restoration: a challenging new agenda for applied fluvial geomorphology. *Earth Surface Processes and Landforms* **31**, 1606–1624.

Olsen N.R.B. (2003) Three-dimensional CFD modelling of self-forming meandering channel. *Journal of Hydraulics Engineering ASCE* **129**, 366–372.

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

Orr H.G. & Carling P.A. (2006) Hydro-climatic and land use changes in the river Lune catchment, north west England, implications for catchment management. *River research and applications* **22**, 239–255.

Orr H.G., Large A.R.G., Newson M.D. & Walsh C.L. (2008) A predictive typology for characterising hydromorphology. *Geomorphology* **100**, 32–40.

Orr H.G. & Walsh C.L. (2007) *Incorporating Climate Change in River Typologies: Results*. Environment Agency, <http://publications.environment-agency.gov.uk/pdf/SCHO0207BLXS-e-e.pdf>.

Palmer M., Menninger H.L. & Bernhardt E. (2010) River restoration, habitat heterogeneity and biodiversity: a failure of theory or practice? *Freshwater Biology* **55**, 205–222.

Poff N.L. & Ward J. V (1990) Physical habitat template of lotic systems: recovery in the context of historical pattern of spatiotemporal heterogeneity. *Environmental Management* **14**, 629–645.

Raven P.J., Holmes N., Dawson F.H., Fox P.J.A., Everard M., Fozzard I.R., *et al.* (1998) River Habitat Quality: the physical character of rivers and streams in the UK and Isle of Man.

Rinaldi M., Simoncini C. & Piegay H. (2009) Scientific design strategy for promoting sustainable sediment management: the case of the Magra river (central-northern Italy). *River research and applications* **25**, 607–625.

Rinaldi M., Surian N., Comiti F. & Bussetini M. (2010) *Manuale tecnico – operativo per la valutazione ed il monitoraggio dello stato morfologico dei corsi d’acqua*. (Ed. Ispra), Roma.

Robson A. & Reed D. (1999) *Flood Estimation Handbook: Volume 3 – Statistical Procedures for Flood Frequency Estimation*. Institute of Hydrology, Wallingford.

Rowan J.S. & Walling D.E. (1992) The transport and fluvial redistribution of Chernobyl-derived radiocaesium within the River Wye basin, UK. *The Science of the Total Environment* **1211**, 109–131.

Schmitt L., Maire G., Nobelis P. & Humbert J. (2007) Quantitative morphodynamic typology of rivers: a methodological study based on the French Upper Rhine basin. *Earth Surface Processes and Landforms* **32**, 1726–1746.

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

Schumm S.A. (1985) Patterns of alluvial rivers. *Annual review of earth and planetary sciences* **13**, 5–27.

Sear D.A., Newson M.D. & Thorne C.R. (2003) Guidebook of Applied Fluvial Geomorphology.

Shreve R.L. (1966) Statistical law of stream numbers. *Journal of Geology* **74**, 17–37.

Simon A. & Rinaldi M. (2006) Disturbance, stream incision, and channel evolution: The roles of excess transport capacity and boundary materials in controlling channel response. *Geomorphology* **79**, 361–383.

Surian N. & Rinaldi M. (2003) Morphological response to river engineering and management in alluvial channels in Italy. *Geomorphology* **50**, 307–326.

Urban M.A. & Rhoads B. (2003) Catastrophic human-induced change in stream-channel planform and geometry in an agricultural watershed, Illinois, USA. *Annals of the Association of American Geographers* **93**, 783–796.

Vaughan I.P., Noble D.G. & Ormerod S.J. (2007) Combining surveys of river habitats and river birds to appraise riverine hydromorphology. *Freshwater Biology* **52**, 2270–2284.

Vaughan I.P. & Ormerod S.J. (2010) Linking ecological and hydromorphological data: approaches, challenges and future prospects for riverine science. *Aquatic conservation: marine and freshwater ecosystem* **20**, S125–S130.

Vocal Ferencevic M. & Ashmore P. (2012) CREATING AND EVALUATING DIGITAL ELEVATION MODEL-BASED STREAM-POWER MAP AS A STREAM ASSESSMENT TOOL. *River Research and Applications* **28**, 1394–1416.

Wallerstein N.P., Soar P.J. & Thorne C.R. (2006) River Energy Auditing Scheme (REAS) for catchment flood management planning. In: *International Conference on Fluvial Hydraulics*. pp. 1923–1932. Lisbon Portugal.

Wharton G. (1995) The channel-geometry method: guidelines and applications. *Earth Surface Processes and Landforms* **20**, 649–660.

TABLES

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

Feature	Criteria
<i>Confined Channel</i>	
<i>Deposition</i>	<i>Extended</i> 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⁾ <i>limited</i> otherwise
<i>Erosion</i>	<i>Extended</i> 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⁾ <i>limited</i> otherwise
<i>Unconfined Channel</i>	
<i>Deposition</i>	<i>Extended</i> if the sum of all the types ⁽¹⁾ of unvegetated bars is >3 ⁽²⁾ <i>limited</i> otherwise
<i>Erosion</i>	<i>Extended</i> if eroding earth cliff>4 ⁽²⁾ or Eroding earth cliff>2 ⁽²⁾ and Vertical/undercut bank profile is extended ⁽³⁾ <i>limited</i> 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

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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
<i>Confined Channel</i>		
<i>Stable equilibrium</i>	Limited deposition and erosion features	Transport/ Potential Source
<i>Deposition dominated</i>	Extended deposition features and limited erosion ones	Sink
<i>Unconfined Channel</i>		
<i>Stable equilibrium</i>	Limited deposition and erosion features	Transport
<i>Deposition dominated</i>	Extended deposition features and limited erosion ones	Sink
<i>Erosion dominated</i>	Extended erosion features and limited deposition ones	Source
<i>Unstable equilibrium</i>	Extended deposition and erosion features	Transport

FIGURES

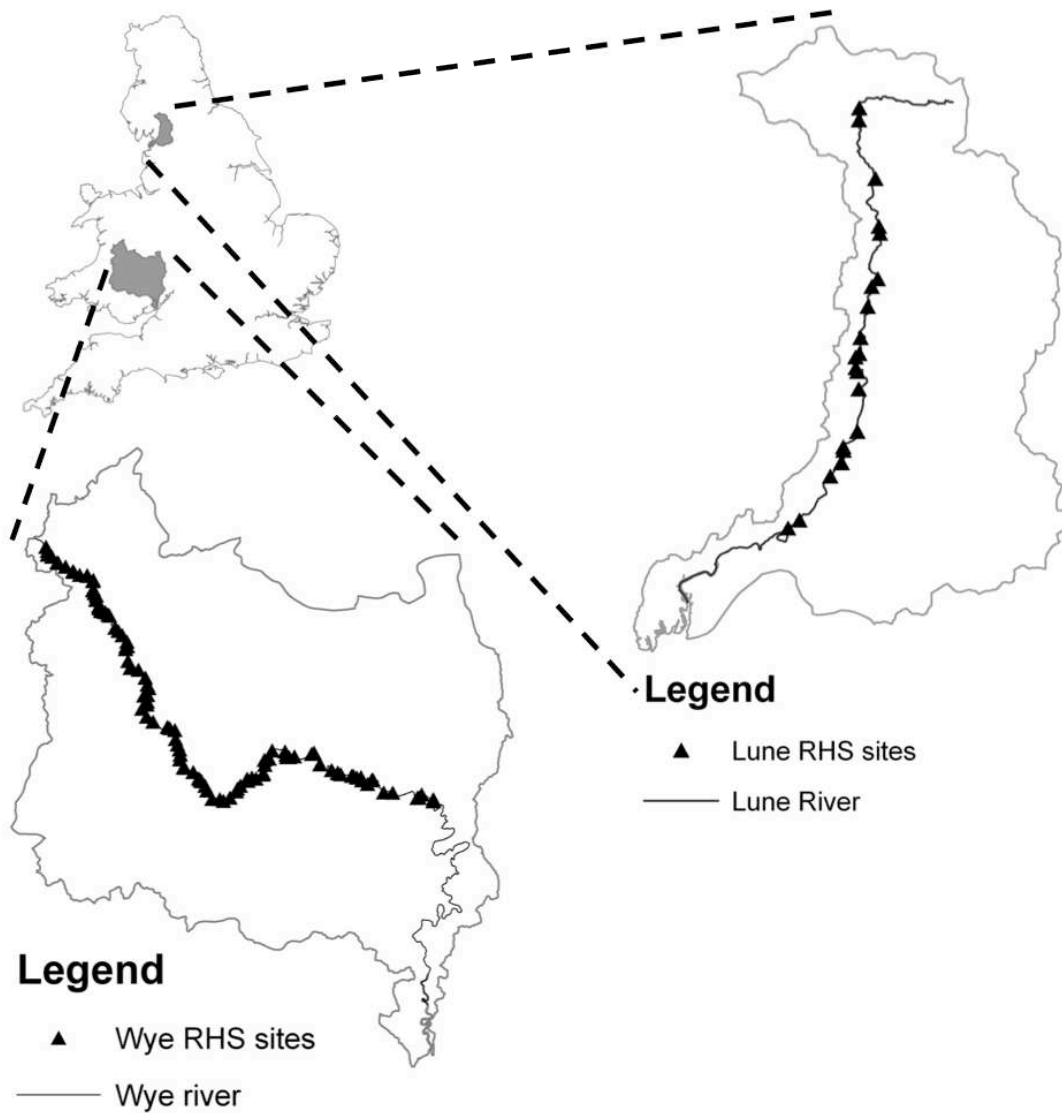


Figure 1. Locations of the Lune and Wye catchments and of the RHS sites along the two river courses

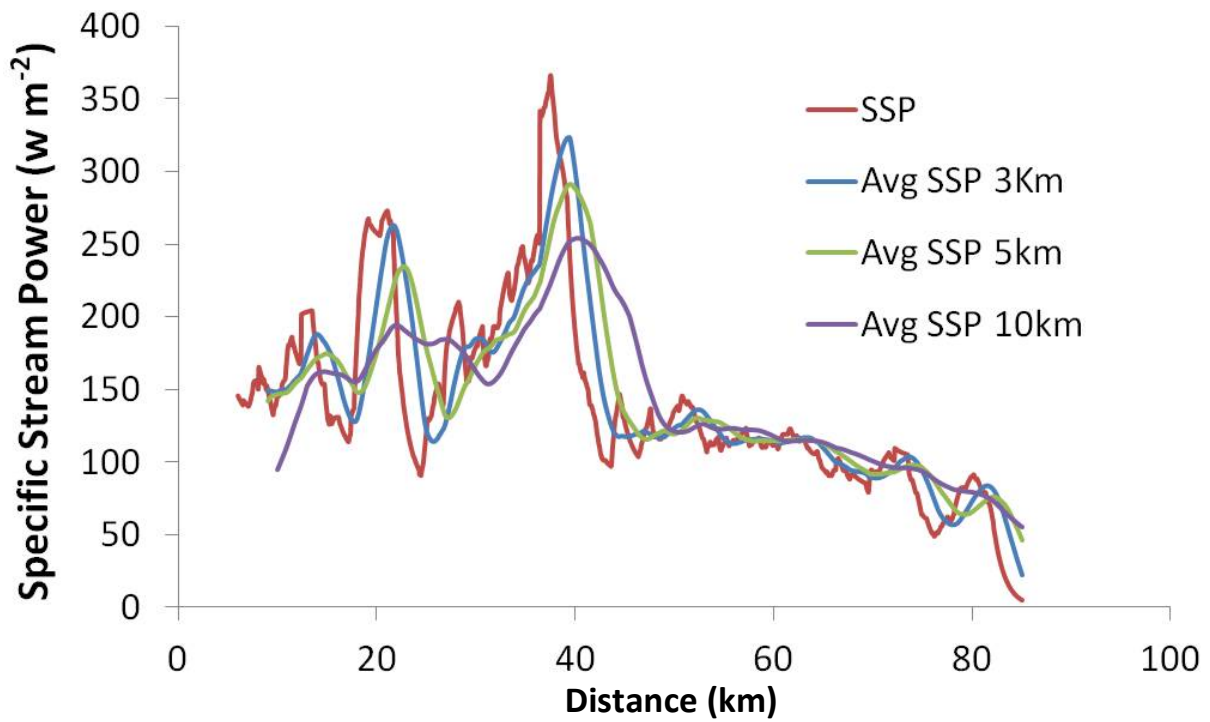
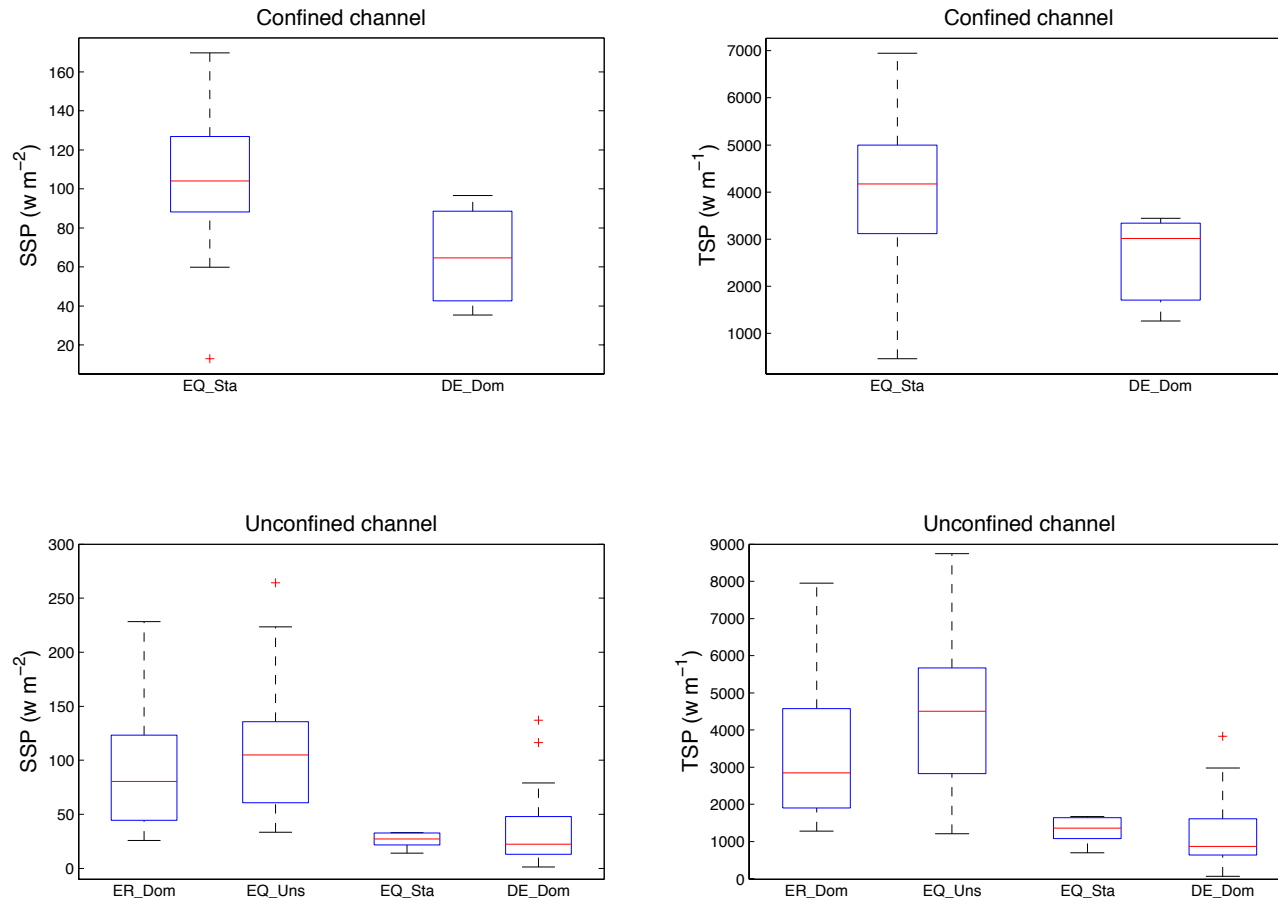
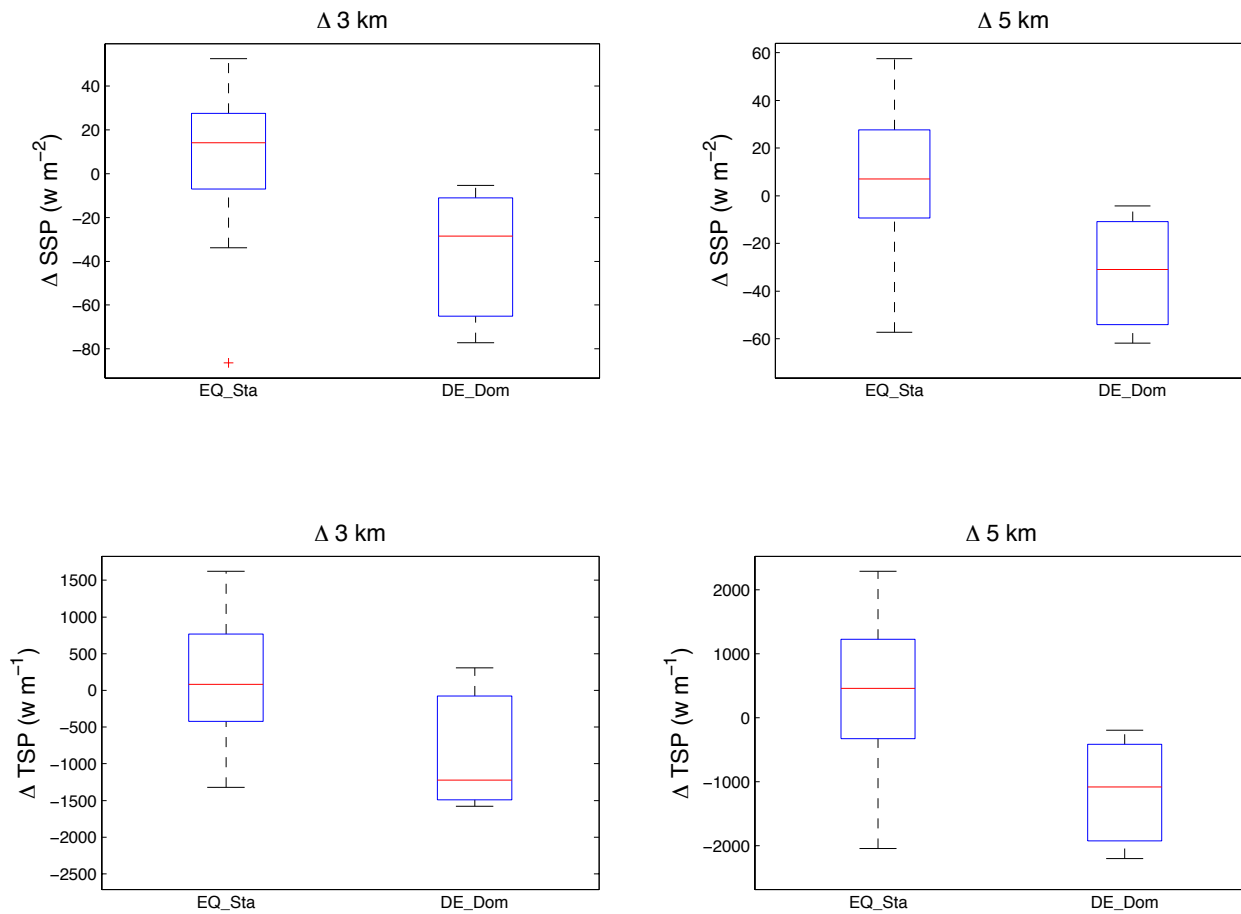


Figure 2. Comparison between local SSP and SSP_{up} averaged over 3, 5 and 10 km.



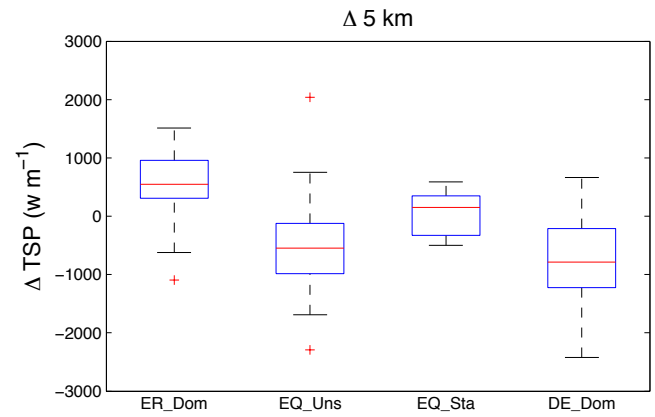
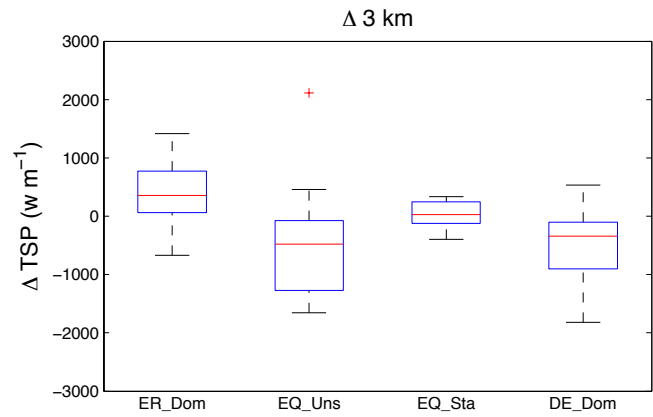
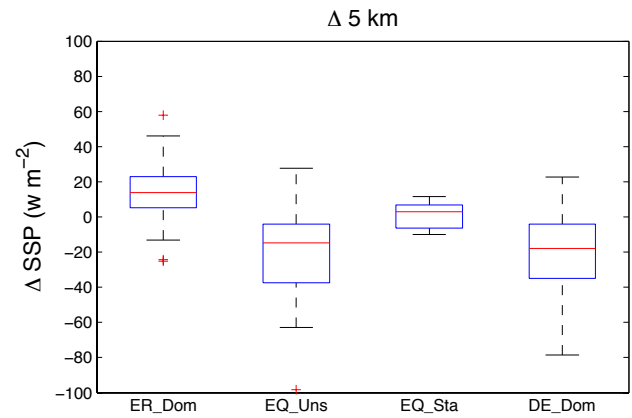
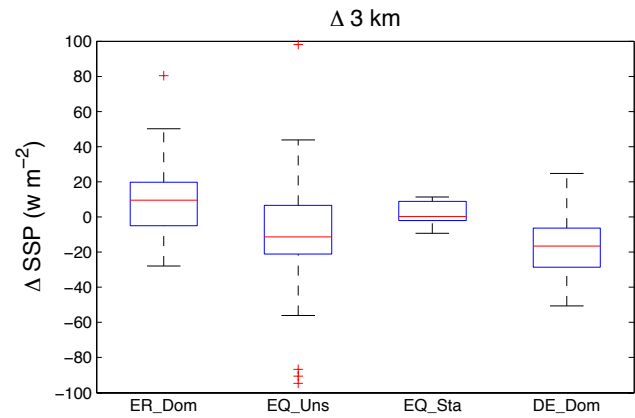
1

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



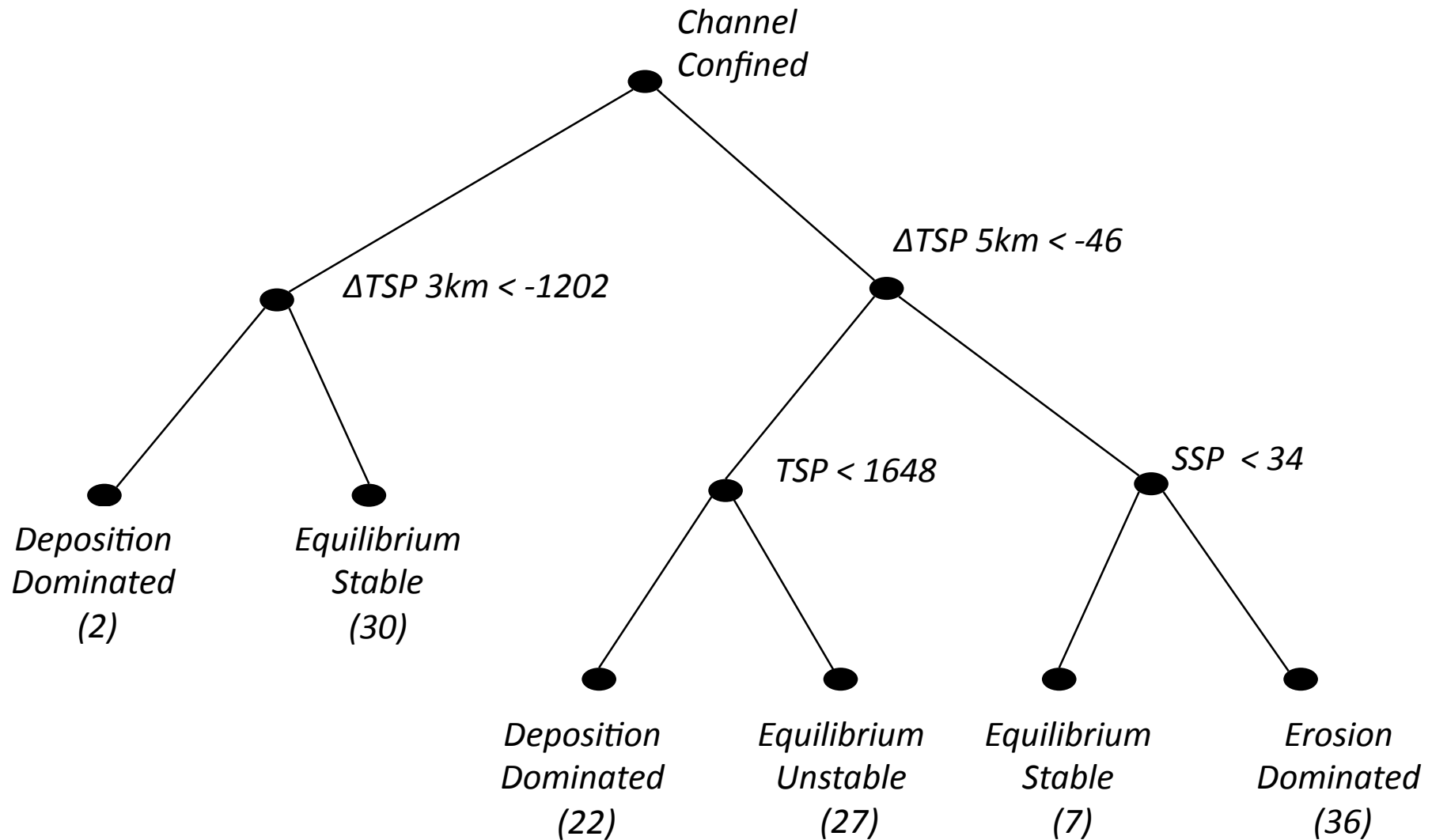
4

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

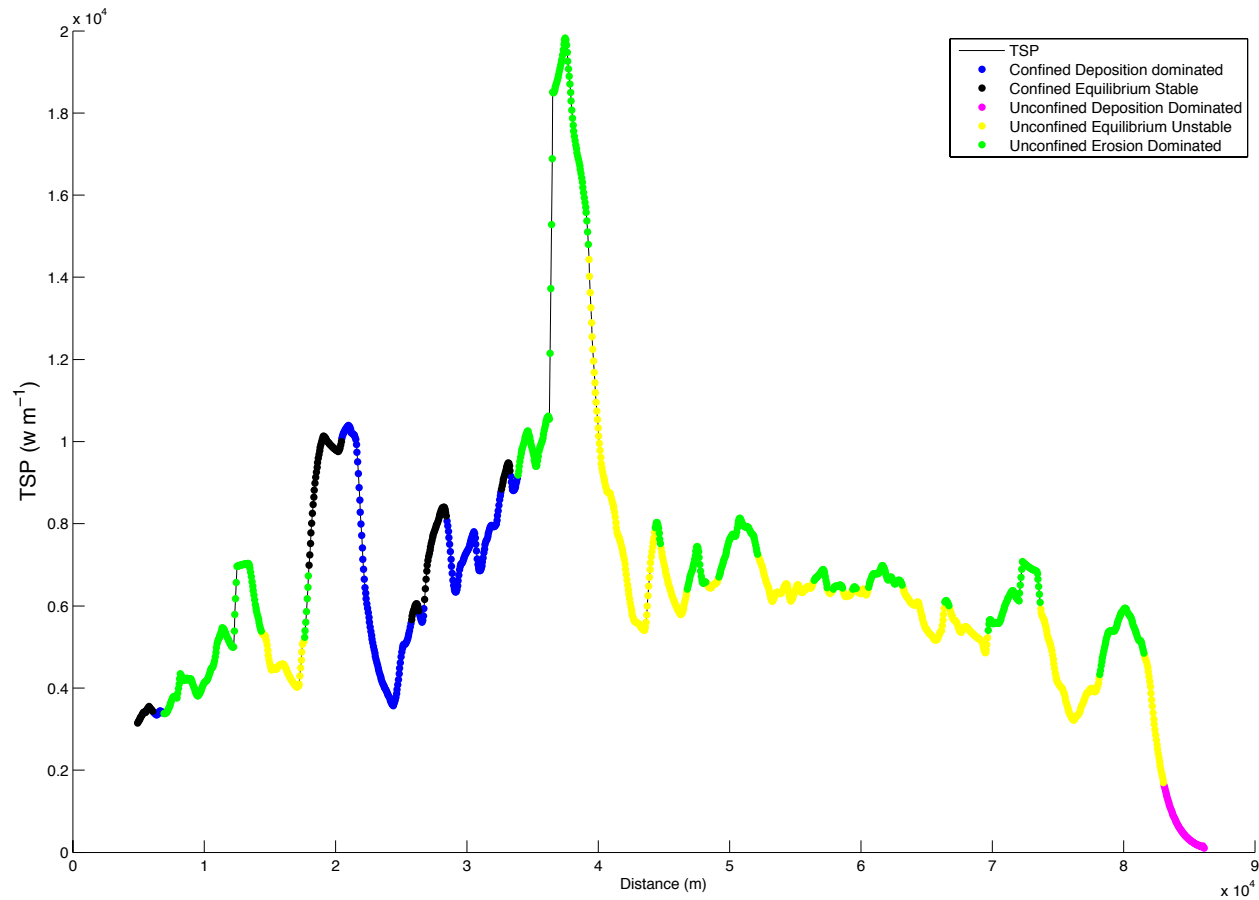


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- 8 Figure 5. Δ SSP and Δ TSP distributions for each channel class of unconfined channel: ER_Dom, EQ_Uns, EQ_Stable and De_Dom stands
9 respectively for Erosion Dominated, Equilibrium Unstable, Stable Equilibrium and Deposition Dominated.



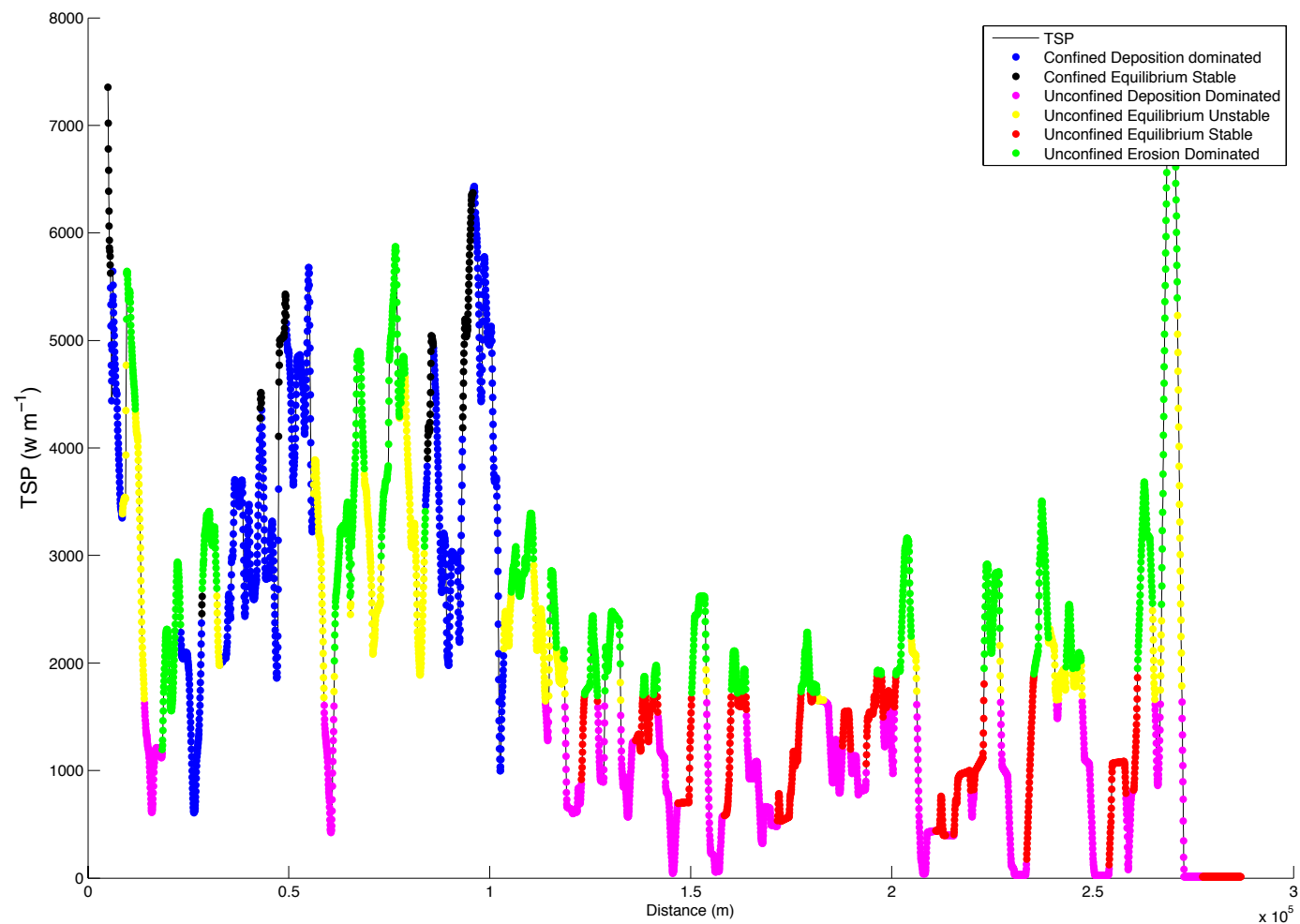
- 11 Figure 6. The regression tree identifies channel classes as a function of conditions set on TSP, Δ TSP and channel type. The condition on each node
12 is satisfied on the left branch. Numbers within brackets indicate the number of sites belonging to each channel class on the branch.



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

15



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