Development of ST:REAM: a reach-based stream power balance approach for predicting alluvial river channel adjustment

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Abstract

River channel sediment dynamics are important in integrated catchment management because changes in channel morphology resulting from sediment transfer have important implications for many river functions. However, application of existing approaches that account for catchment-scale sediment dynamics has been limited, largely due to the difficulty in obtaining data necessary to support them. It is within this context that this study develops a new, reach-based, stream power balance approach for predicting river channel adjustment.

The new approach, named ST:REAM (Sediment Transport: Reach Equilibrium Assessment Method), is based upon calculations of unit bed area stream power (ω) derived from remotely sensed slope, width and discharge datasets. ST:REAM applies a zonation algorithm to values of ω that are spaced every 50m along the catchment network in order to divide the branches of the network up into relatively homogenous reaches. ST:REAM then compares each reach's ω value with the ω of its upstream neighbour in order to predict whether or not the reach is likely to be either erosion dominated or deposition dominated.

The paper describes the application of ST:REAM to the River Taff in South Wales, UK. This test study demonstrated that ST:REAM can be rapidly applied using

remotely sensed data that are available across many river catchments and that ST:REAM correctly predicted the status of 87.5% of sites within the Taff catchment that field observations had defined as being either erosion or deposition dominated. However, there are currently a number of factors that limit the usefulness of ST:REAM, including inconsistent performance and the need for additional, resource intensive, data to be collected to both calibrate the model and aid interpretation of its results.

Introduction

The importance of alluvial channel adjustment within river management

Lane (1955) described alluvial river channels as tending towards a state of balance using

$$Q.S \propto Q_s.D_{50}$$

Equation 1

where Q is water discharge (m^3/s), S is channel slope, Q_s is sediment supply rate (kg/m/s), D_{50} is the median diameter of sediment supplied (m), the terms on the left represent the sediment transport capacity of the flow, and the terms on the right represent the sediment supply. Alluvial channel adjustments are driven by imbalances in the transfer of channel-forming sediment through the fluvial system, with marked and concerted changes in the morphology of a reach being associated with a significant disparity between the quantity of sediment input to the reach (supply) and the quantity that can be transferred downstream (capacity). These imbalances can have important implications for the management of both flood risk and ecological status.

Deposition dominated channels can experience increased probability of flooding due to a reduction in channel conveyance capacity (Stover and Montgomery, 2001). This reduces the standard of protection provided by defences, creates maintenance issues (Sear, et al., 1995), and generates challenges for strategic planning (Lane, et al., 2007). Conversely, erosion dominated reaches can have increased risk of flood defence infrastructure failure or instability (Wallerstein, et al., 2006). As a result, assessments of channel geomorphic processes have been applied within the design of recent flood management schemes (Wallerstein, et al., 2006, Rinaldi, et al., 2009).

Whilst a complete understanding of how channel form influences in-stream biology has not yet been achieved (Palmer, et al., 2010) the influence of channel geomorphic processes and forms on freshwater biotic communities is well recognized (Lorenz, et al., 2004). Excessive sediment delivery within deposition dominated reaches can negatively impact salmonid spawning, with infiltration of fine sediment into gravel matrices increasing spawned egg mortality rates (Soulsby, et al., 2001). In addition, channel widening and incision within erosion dominated reaches can greatly reduce the quality of the physical habitat necessary to sustain healthy ecosystems (Shields, et al., 1998, Hendry, et al., 2003). As a result, the importance of morphological adjustment to river channel ecological status is recognised within a European Union directive that requires the evaluation of hydro-morphological quality for all river networks in order to assess river ecological status and to deliver catchment management plans (EU, 2000).

The need for resource-light approaches to predicting alluvial adjustment

Whilst there have been substantial improvements to our understanding of river channel morphological adjustment (Lane, 1955, Schumm, 1969, Ashworth and Ferguson, 1986, Harvey, 1991, Coulthard and Van de Wiel, 2007) it is still rarely taken into account within the management of river flood risk and ecological status (Wallerstein, et al., 2006, Thorne, et al., 2010). This is partly due to the paucity of practical tools available to the end user community that can be applied routinely at the catchment scale (Bizzi and Lerner, 2013). Where channel adjustment is considered within river management it is usually investigated by field-based fluvial audits (Harvey, 2001, Rinaldi, et al., 2009, Sear, et al., 2010) and by hydrodynamic models (ISIS, 1999, Olsen, 2003, Brunner, 2006). These latter approaches require very detailed inputs on channel discharges, cross sections and grain-size distributions which are not widely available. Methods which can be applied using resources that are easily accessible would be of great value for catchment-scale assessment at the regional and national level (Newson and Large, 2006, Wallerstein, et al., 2006).

As an alternative to comparatively sophisticated hydrodynamic models, reach-based sediment balance models such as RAT (Graf, 1996), SIAM (Gibson and Little, 2006) and REAS (Wallerstein, et al., 2006) have been developed as a means of predicting river channel status. This type of approach employs Exner’s (1925) principle of the conservation of mass and Lane’s (1955) fluvial balance concept to define how the amount of sediment stored in a reach changes in response to a net difference between the incoming and outgoing rates of sediment transport. In disequilibrium situations, the direction and degree of sediment imbalance indicates the potential for erosion or deposition-led morphological adjustments. However, despite the assumptions and simplifications made within these models, their widespread applicability is limited by their data requirements because they require data describing the flow regime, cross-sectional geometry, slope, roughness, and particle size distributions (Wallerstein, et al., 2006). Much of this information is unavailable without primary fieldwork that is seldom feasible at the catchment scale outside of well-funded project-related or research studies. Methods that require fewer resources than those described above would be of great value for regional or national assessments (Wallerstein, et al., 2006, Newson and Large, 2006, Bizzi and Lerner, 2013).

Predicting alluvial adjustment using catchment-scale representations of stream power

Stream power, a measure of the energy used to drive geomorphological change (Bagnold, 1966), is a parameter that can be approximated using widely available measurements of channel width, discharge and slope. For example, stream power has been used extensively to explain sediment transport (Bagnold, 1966), bedrock channel incision (Whipple and Tucker, 1999), and bank erosion (Lawler, et al., 1999). To help explain such processes at basin scales, the downstream distribution of stream power has been modelled conceptually (Lawler, 1992) and investigated empirically (Bull, 1979, Graf, 1983, Magilligan, 1992, Lecce, 1997, Knighton, 1999, Reinfelds, et al., 2004, Jain, et al., 2006, Barker, et al., 2009, Biron, et al., 2013).

More recently, the development of geo-spatial analysis software and the increased availability and accuracy of spatial data (particularly digital elevation models) allow the high resolution quantification of stream power throughout entire river catchment networks (Barker, et al., 2009). Building upon this, recent studies have begun to explore the opportunities for using this type of representation of stream power as a stream assessment tool: Vocal Ferencevic and Ashmore (2012) calculated stream power values across Highland Creek near Toronto in Canada and compared the outputs against morphological changes observed during an extreme flood event; Bizzi and Lerner (2013) calculated a range of stream power-based parameters for the River Lune and the River Wye in England and compared the results against field-based observations of erosional and depositional channel forms; and Biron et al. (2013) calculated stream power values within two watersheds in Quebec and compared the values against field evidence of bank erosion.

Study aims

Recognising the need for a method of predicting river channel morphological status that can be applied at the catchment-scale using readily available datasets, this paper describes the development of a new reach-based, stream power balance approach for predicting river channel adjustment: 'ST:REAM' (Sediment Transport: Reach Equilibrium Assessment Method). This new approach aims to combine the work of studies that have developed high resolution representations of stream power across river catchment networks (Barker, et al., 2009, Vocal Ferencevic and Ashmore, 2012, Bizzi and Lerner, 2013) with the work of studies that have developed reach-based sediment balance models (Graf, 1996, Gibson and Little, 2006, Wallerstein, et al., 2006).

To achieve this aim this paper first describes the characteristics of the River Taff in South Wales, which acts as a case study for the new method, along with the datasets used within the study. Next, the paper describes the stages incorporated within the new modelling approach, which include: calculation of stream power across the catchment network; delineation of reach boundaries within the catchment network; and calculation of reach stream power balances. The results are then presented, which include the stream power values calculated across the catchment network of the River Taff, the calibration of the reach boundary hunting algorithm and the stream power balance thresholds, along with the final predictions of reach status across the Taff catchment. Finally, the performance and potential applications of the new approach are discussed.

Method

Case study and data sets: River Taff, South Wales, UK

The River Taff in South Wales, UK, was selected as a case study for the development of the new approach. The Taff was selected due to the availability of a wide range of data that might have been useful to the study, although not all of the data sources available were subsequently used in the production of this paper. In addition, the River Taff is typical of many British rivers in that it is a steep, coarse-bedded watercourse with a predominantly alluvial channel that is partially controlled by bedrock outcrops and artificial structures.

The Taff catchment drains approximately 500km^2 of South Wales, including a southern area of the Brecon Beacons National Park and the settlements of Merthyr Tydfil, Aberdare, Mountain Ash, Treorchy, Abercynon, Porth, Pontypridd and Cardiff. Its main stem rises in the Brecon Beacons south-west of Pen Y Fan and flows more than 60km south to enter the Severn Estuary at Cardiff. Its major tributaries include the Nant Ffrwd, Taff Fechan, Nant Morlais, Taff Bargoed, Cynon and Rhondda (Figure 1). The geology of the catchment consists of mainly coal measures in the south with carboniferous limestone and old red sandstone in the north, some peat on the hills and boulder clay and alluvium in the valleys (CEH, 2014). Land use is dominated by pasture, forestry and moorland in the headwaters with some urban development in the lower valleys (CEH, 2014). Annual rainfall across the catchment ranges from 950mm/year at Cardiff to 2400mm/year in the Brecon Beacons (CEH, 2014). At the flow gauge at Tongwynlais, near Cardiff, (drainage area of 486.9 km^2) the mean flow is 21.373 m^3/s, with a median annual flood (Q_{med}) of 320.0m^3/s (EA, 2014).

The method applied within this paper required the following datasets for the River Taff catchment: a digital elevation model of the entire catchment; Q_{med} values from flow gauges across the catchment; river channel width data for the catchment network; and observations of river channel status at points across the catchment.

A representation of catchment elevation was obtained using a vector dataset containing Ordnance Survey Land-form Profile contours and spot heights (Edina, 2014). The contours are generally at 5 metre vertical intervals but are at 10 metre vertical intervals in some mountain and moorland areas. Contour accuracy values are typically better than half the contour interval – ±2.5 metres for areas with 5 metre vertical intervals and ±5 metres for areas with 10 metre vertical intervals (Edina, 2014).

Flow gauge Q_{med} values were obtained from the eight flow gauges within the CEH National River Flow Archive database (CEH, 2014). River channel widths were obtained from the water theme within the Ordnance Survey MasterMap Topography Layer (Edina, 2014). Observations of channel status were recorded during field reconnaissance of 152 points along the Taff catchment network in 2010.

Figure 1. The River Taff, South Wales

Classifying observed channel status

The dominant process acting within a river channel can be qualitatively evaluated by interpretation of field observations (Sear, et al., 2003). 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. 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 (Osman and Thorne, 1988).

Based on the assumption that dominant channel processes can be identified based on observed channel form, Table 1, adapted from Sear et al.'s (2003) Table 4.3, presents form-based indicators that can be used to identify erosion or deposition dominated channels. These indicators were used to define which of the 152 points within the Taff catchment network visited during the 2010 field reconnaissance are either erosion or deposition dominated: if a point has one or more indicators of a particular channel status (erosion dominated or deposition dominated), without any indicators of the other status, then its status was defined by those indicators. Points without any indicators, or with a mixture of indicators from different status types were not classified due a lack of confidence in whether they were either inactive (no erosion or deposition), in steady-state equilibrium (a balance between erosion and deposition), erosion dominated with some depositional features, or deposition dominated with some erosional features.

The 152 locations at which channel observations were made during the 2010 field reconnaissance were selected based on their accessibility and so, in general, are where footpaths or roads run alongside or across the river channel. The length of channel upon which observations of channel form were based was 100m, although at several sites the length of channel visible was less than this. In order to encourage consistency, the same geomorphologists were responsible for all of the 152 channel observations but it is recognised that there is an element of subjectivity within this method of defining channel status. This may result in inconsistencies between different geomorphologists and also inconsistencies from an individual as their perspective changes.

Table 1. Criteria used for the definition of erosion dominated and deposition dominated channels. Modified from Sear et al’s (2003) Table 4.3.

Calculating unit bed area stream power across a river catchment network

Unit bed area stream power (ω, Wm^{-2}) is defined as

$$\omega = \frac{\gamma . Q . S}{w}$$

Equation 2

where γ is the unit weight of water (9810N/m^3), Q is an indicative discharge (m^3/s), slope is energy slope (m/m), which is often approximated by bed slope, and w is the width of the flow (m), often approximated by channel bankfull width when using flood flow discharges (Bagnold, 1966, Barker, et al., 2009).

The approach applied within this study involved calculating unit bed area stream power across the river channel network at a series of separate points spaced 50m apart along each of the branches of the river catchment network. To establish the topology of the river catchment network and the location of the points along the network it was necessary to apply a series of spatial analysis techniques (within ESRI's ArcGIS software) on the Ordnance Survey Land-form Profile contour and spot height data (Figure 2):

1. A digital elevation model (DEM) raster dataset (cells of 10m x 10m) was interpolated from the Ordnance Survey Land-form Profile contour and spot height data using the 'Topo to Raster' tool.
2. Any pits (local elevation minima) within the DEM raster dataset were filled in order to prevent them obstructing the modelled progress of water flowing downslope across the catchment surface. This was achieved using the 'Fill' tool.
3. The outgoing flow direction for each raster cell was established using the D8 algorithm available through the 'Flow Direction' tool.
4. For each raster cell, the total number of other cells that contribute flow into in was calculated using the 'Flow Accumulation' tool.
5. The drainage area of each raster cell was calculated by multiplying the cell's flow accumulation value by the area of each cell (0.0001km^2) using the 'Raster Calculator' tool.
6. A raster representation of the predicted river catchment network was then established by applying a drainage area threshold of 0.5km^2 using the 'Great Than Equal' tool.
7. The raster representation of the predicted river catchment network was then converted to a vector polyline representation using the 'Stream to Feature' tool.
8. A new DEM was interpolated from the original contour and spot height data and the newly created polyline representation of the river catchment network. This was to reduce the influence of any 'stair-step' artefacts that might have been

created as an artefact of the interpolation from the contour lines (Wobus, et al., 2006).

9. Steps 2-7 were then repeated using the newly created DEM.
10. The vector polylines of the river network branches large enough to be included in the model were then identified (based on them contributing at least 1% of the total catchment drainage area).
11. Points spaced 50m apart along each of the river network branches included in the model were then created.

Figure 2. Flowchart of processes involved in creating a ST:REAM model

In most recent studies involving high-resolution stream power calculations across river catchment networks the median annual flood (Q_{med}) is used in the calculation of ω (Jain, et al., 2006, Barker, 2008, Bizzi and Lerner, 2013). The Q_{med}, also known as the 2-year flood (Q_2) was also selected as the representative flow discharge in this study as it approximates the morphologically significant, bankfull condition in single-thread, meandering rivers like the Taff (Wolman and Miller, 1960), confines fluvial action to the channel (Wharton, 1995), and has sufficient energy to mobilise the bed material (Ryan, et al., 2005). To estimate the Q_{med} values for each of the points throughout the river catchment network Q_{med} was first identified for each of the eight gauging stations in the catchment through analysis of their annual maxima series. A power regression was then established between Q_{med} and drainage area (A, km^2) across the eight gauging stations in a manner similar to that suggested by Knighton (1999). The derived relationship for the flow gauges in the Taff catchment is $Q_{med} = 1.8632.A^{0.8422}$, with an r^2 value of 0.94. It was then possible to use this relationship, along with the drainage area raster dataset, to predict the Q_{med} for each of the points across the river catchment network.

The channel bed slope was approximated for each point by dividing the DEM-based elevation drop between that point and its downstream neighbour by the downstream distance between the two points (50m). In other stream power based approaches for predicting channel adjustment slope measurements have been taken over longer horizontal distances of 200m (Vocal Ferencevic and Ashmore, 2012), 1km (Bizzi and Lerner, 2013), and 4km (Barker, et al., 2009). In these approaches lower resolution slope measurements are justified on the basis of capturing reach-scale changes relevant to sediment budgets rather than the breaks of slope associated with morphological unit changes. However, the reach-averaging procedure applied within this approach means that the final stream power balance calculations are based upon reach-averaged slope measurements, not those taken over 50m. Therefore, the purpose of these initial measurements of slope over 50m is to capture the local breaks of slope within the reach boundary identification process rather than to directly inform the reach-based stream power balances.

Unlike some other attempts to represent stream power across a river catchment network, which estimate channel bankfull widths using empirical downstream hydraulic geometry relationships (Knighton, 1999, Bizzi and Lerner, 2013), this study measured bankfull width for each point within the river catchment network using the Ordnance Survey MasterMap representation of the river channel in a manner similar to that described by Barker et al. (2009). It is considered preferable to measure river channel width as those predicted by empirically derived relationships will not accurately represent local variation in channel form that could be responsible for significant sediment erosion or deposition (Bizzi and Lerner, 2013).

Using the Q_{med}, slope and width measurements described above it was possible to calculate the unit bed area stream power of the median annual flood (ω_{med}) for each of the 4627 points within the Taff catchment network using Equation 2.

Defining reach boundaries within a river catchment network

In a reach-based approach, the input variables are reach-averaged and so the method used to identify reach boundaries is crucial as it affects the modelled parameters and, consequently, its outcomes. In applying the reach-based, Riverine Accounting and Transport (RAT) model, Graf (1996) sought to divide the system into 'functional' reaches where processes and forms were internally consistent and noticeably different to those in neighbouring reaches. Graf was able to do this based on his detailed a prior knowledge of the morphology of the fluvial system in question, however this detailed knowledge is often unavailable and so an alternative method has been applied in this study.

The approach applied here searches for ‘functional’ reach boundaries statistically using Gill’s (1970) global zonation algorithm, which was originally designed for geological borehole zonation. Following a review of a number of alternatives, Parker et al. (2011) identified Gill’s global zonation algorithm as the most suitable statistical means of identifying of reaches of channel with internally homogenous and comparatively heterogenous characteristics. When applying the algorithm, which uses an iterative analysis of variance approach, a data sequence begins as a single, long zone (Figure 3A) and is temporarily divided into two zones, with the provisional partition falling between the first and second points in the sequence. At this stage, the sum of squares within the two temporary zones (SS_w) is calculated using:

$$SS_w = \sum_{j=1}^{m} \sum_{i=1}^{n_j} (x_{ij} - \bar{X}_{*j})^2 \Big/ \sum_{j=1}^{m} n_j - m$$

Equation 3

where, x_{ij} = the ith point within zone j, $\bar{X}_{*j}$ = mean of the jth zone, n_j = number of points in the jth zone, and m = number of zones. The partition between the two zones is then moved along the sequence to successive positions and SS_w is calculated for every possible position of the partition. The partition which results in the lowest SS_w is selected as the first zonal boundary, forming two zones (Figure 3B). The procedure is then repeated, with the SS_w calculated for every possible position of the second partition, the minimum of which is used to divide the sequence into three zones (Figure 3C). In this manner, Gill’s (1970) method finds the zonation that minimises variance within each zone (reach) and maximises the difference between the zones (reaches). The zonation procedure continues to insert new reach boundaries until the proportion of total variance explained by the zonation ($R = \frac{SS_W}{SS_T}$) reaches a specified level. As a result, with higher R values a greater number of reaches (of shorter length) are identified by the algorithm.

In the method applied here, Gill’s (1970) global zonation algorithm has been applied to the sequence of ω_{med} values for the points spread 50m apart along each of the branches of the River Taff catchment network. The method used to select an appropriate R value when applying the zonation algorithm to the Taff catchment is described at the end of the next section.

Figure 3. Example of the reach boundary hunting process using Gill's (1970) global zonation algorithm. The sequence of figures shows how the entire river branch starts as one reach (A), then is divided into two reaches at the point that explains the most amount of variation (B), and then again into three reaches (C), and so on until the user-specified value of R is met – for example 0.01 (D).

Calculating reach stream power balances

Following the calculation of ω_{med} values for the points spread 50m apart across the river catchment network, and the aggregation of those points into reaches that are relatively internally homogenous and comparatively heterogenous, the unit bed area stream power balance ($\omega_{balance}$) for each reach was calculated (Figure 4). This was achieved by dividing the ω_{med} value of the reach in question by the ω_{med} value of its immediate upstream neighbour (or upstream neighbours if the reach was immediately downstream of a confluence).

This method assumes that the ω_{med} value of the reach in question is an indicator of the sediment transport capacity of the reach and that the ω_{med} value of its immediate upstream neighbour is an indicator of the sediment transport supply that is delivered from upstream. As a result, $\omega_{balance}$ values close to 1 should be indicative of reaches that are in equilibrium, with $\omega_{balance}$ values significantly greater than 1 indicating reaches that are likely to be erosion dominated and $\omega_{balance}$ values significantly less than 1 indicating reaches that are likely to be deposition dominated.

In order to identify the most appropriate value of R to use within the zonation algorithm, the impact that the assigned R value has on the accuracy of the stream balance method was explored. To do this, 19 different models of the Taff catchment were created with reach boundary configurations based on values of R ranging from 0.001 to 0.1. The $\omega_{balance}$ values for each version of the model were compared with the status of the sites which had been observed as being either erosion or deposition dominated and the proportion of sites that were correctly predicted ($\omega_{balance}$ > 1 where channel is erosion dominated or $\omega_{balance}$ < 1 where channel is deposition dominated) was recorded. The R value that resulted in the highest proportion of observed sites being predicted correctly was then used to produce the final version of the model of the Taff.

After calculating the stream power balance values for each of the reaches across the Taff catchment using the selected R value, the most appropriate $\omega_{balance}$ threshold values for identifying deposition and erosion dominated reaches were explored. Ideally, these thresholds would have been defined by the boundaries between the $\omega_{balance}$ values of steady-state equilibrium sites and the $\omega_{balance}$ values of erosion dominated and deposition dominated sites. However, this was not possible as steady-state equilibrium sites could not be confidently identified using the channel observations available. Instead, the threshold $\omega_{balance}$ values were defined using only the $\omega_{balance}$ values of erosion dominated and deposition dominated sites. The threshold for erosion dominated status was defined using the lower quartile boundary of the $\omega_{balance}$ values of erosion dominated observed sites and the threshold for deposition dominated status was defined using the upper quartile boundary of $\omega_{balance}$ values of deposition dominated observed sites. These threshold values were then used to identify the reaches with the Taff catchment that are predicted as being either erosion or deposition dominated.

Figure 4. Principles of reach-based stream power balance modelling applied in ST:REAM

<u>Results</u>

Classification of observed channel status

Figure 5 displays the observed channel locations classified as either erosion or deposition dominated using the criteria set out in Table 1. Of the 152 sites where observations were made, 45 were classified as erosion dominated and 62 as deposition dominated, with the remainder (45) not showing clear evidence of being either erosion or deposition dominated.

Figure 5. Observed channel locations classified as either erosion or deposition dominated across the River Taff catchment, South Wales

Calculated unit bed area stream power values

Figure 6 displays the calculated unit bed area stream power values (ω_{med}) for points spaced every 50m along the catchment network of the River Taff. Measured ω_{med} values range from $2x10^{-8}$ W/m^2 to 10315 W/m^2. In general, the highest ω_{med} values are found in the first order, headwater channels where slopes are steepest and channel widths are constrained by narrow valleys. The lowest ω_{med} values are generally found in the sections of channel furthest downstream where the topography is flatter. There are a large number of exceptions to this general trend, with local variations driven by factors such as impoundment and geological discontinuities.

Figure 6. Calculated unit bed area stream power (ω_{med}) values for points spaced every 50m across the channel network of the River Taff, South Wales

Calibration of reach boundary hunting algorithm

Figure 7 illustrates the influence of the R value used within Gill's (1970) global zonation algorithm on ST:REAM's ability to correctly identify the points along the channel network that were observed as being either erosion or deposition dominated. The percentage of points predicted correctly increases from 71% when R=0.001 to 87% when R=0.02 before falling down to 55% when R=0.08. As a result, a value of R of 0.02 was selected as being the most appropriate when applying ST:REAM to the River Taff catchment.

Figure 7. Proportion of observed erosion or deposition dominated sites predicted correctly by ST:REAM for different boundary hunting algorithm 'R' values.

Calibration of stream power balance thresholds

The spread of $\omega_{balance}$ values (when R=0.02) for points along the catchment network of the Taff identified as being either erosion or deposition dominates is displayed in Figure 8. As would be expected, the majority of sites identified as being erosion dominated have $\omega_{balance}$ values greater than 1, with an interquartile range of 2.3-11.6. The majority of sites identified as being deposition dominated have $\omega_{balance}$ values less than 1, with an interquartile range of 0.27-0.59. However, there are also a number of erosion and deposition dominated points that have values of $\omega_{balance}$ that fall outside the ranges that would be expected – the minimum $\omega_{balance}$ value for points identified as being erosion dominated is 0.4 and the maximum $\omega_{balance}$ value for points identified as being deposition dominated is 339.7. The upper quartile boundary of $\omega_{balance}$ values for deposition dominated points (0.59) has been selected as the threshold for predicting reaches as being deposition dominated and the lower quartile boundary of $\omega_{balance}$ values for erosion dominated points (2.3) has been selected as the threshold for predicting reaches as being erosion dominated.

Figure 8. Distribution of stream power balances for erosion dominated and deposition dominated sites, using a boundary hunting algorithm 'R' value of 0.02.

Predicted channel status

The output from applying ST:REAM when R=0.02, the threshold $\omega_{balance}$ value for deposition dominated reaches is 0.59, and the threshold $\omega_{balance}$ value for erosion dominated reaches is 2.3 is displayed in Figure 9. The majority of the reaches within the Taff catchment have been predicted as being either erosion or deposition dominated. The majority of reaches predicted as being deposition dominated are those where there has been a drop in the river slope, such as in the piedmont zone downstream of the confluence between the Taff and the Rhondda. The majority of reaches predicted as being erosion dominated are those with locally high slopes, such as the final reach of the Cynon before it joins the Taff. Within the reaches predicted as being either erosion or deposition dominated the status of 87.5% of the observed sites were predicted correctly.

Figure 9. Predicted location of erosion dominated and deposition dominated reaches within the River Taff catchment, South Wales, using ST:REAM with a boundary hunting algorithm 'R' value of 0.02 and deposition and erosion threshold values for $\omega_{balance}$ of 0.59 and 2.3 respectively.

Discussion

Model performance

The results demonstrate that, when ST:REAM is applied to the Taff catchment, there is a close correspondence between the calculated stream power balance of a reach ($\omega_{balance}$) and the occurrence of features that are associated with erosion or deposition dominated channels. This is as expected: reaches with a $\omega_{balance}$ value < 0.59 have ω_{med} values nearly half that of their upstream neighbour(s) and it is therefore expected that their sediment supply exceeds their transport capacity – leading to aggradation (Lane, 1955); reaches with a $\omega_{balance}$ value > 2.3 have ω_{med} values more than double that of their upstream neighbour(s) and it is therefore expected that their transport capacity exceeds their sediment supply – leading to degradation (Lane, 1955).

However, it is evident that the method applied is not consistently accurate in its prediction of channel status. Whilst Figure 8 demonstrated that the majority of $\omega_{balance}$ values for sites observed as being erosion or deposition dominated fall within the ranges that would be expected (>1 and <1 respectively), there are also some values of $\omega_{balance}$ that fall well outside these expected ranges. Some of this error may be due to uncertainties in the measurement of parameters used to calculate ω_{med} for points across a catchment network (Bizzi and Lerner, 2013). There is significant uncertainty regarding the most appropriate means of measuring channel slope from digital elevation models (Vocal Ferencevic and Ashmore, 2012) and measurements are very sensitive to errors in elevation data, particularly across shallow slopes (Lane and Chandler, 2003). In addition, the method used to estimate the Q_{med} values for points across the catchment is based upon an empirical relationship and will not represent any local variability. An alternative would have been to use a physically-based hydrological model (Barker et al., 2009).

As well as the uncertainty in the calculation of ω_{med} for points across a catchment network (Bizzi and Lerner, 2013), error within the predictions made by ST:REAM may derive from the simplifications made within the model. These simplifications include: an assumption that the rate of sediment transport out of a reach is directly related to its ω_{med}; an assumption the supply of sediment into a reach is directly related to the ω_{med} of its upstream neighbour(s); a static representation of a system that evolves over time and is influenced by feedback; and a reach-based representation of a system that varies continuously across space. Some of these simplifications are explored in more detail in the paragraphs below.

In making its predictions of channel sediment dynamics, the reach-based stream power balance approach assumes that each reach will be able to transport sediment out of the reach at a rate that is directly proportional to the unit bed area stream power of its median annual flood. Whilst it has been demonstrated both theoretically and empirically that unit bed area stream power is closely associated with sediment transport rates (Bagnold, 1966, Parker, et al., 2011), the entrainment threshold of the channel boundary material (generally controlled by particle size/weight) is also important (Bull, 1979). As a result, variations in the entrainment threshold of channel boundaries between reaches can cause discrepancies in the application of ω_{med} as an approximation of outgoing sediment transport rate. In addition, the relationship between sediment transport rate and ω_{med} is assumed to be linear within ST:REAM when it has been found to be non-linear (Bagnold, 1986). Therefore, ω_{med} is likely to under represent the outgoing transport rate of high powered reaches and over represent the outgoing transport rate of low powered reaches. A final simplification in the representation of outgoing sediment transport within ST:REAM is that ω_{med} is an indicator of transport capacity and does not take into consideration the availability of sediment for transport. In reality, two reaches with similar values for ω_{med} will have different influences on downstream reaches if they have different levels of sediment availability but this is not reflected within ST:REAM.

These assumptions in the representation of outgoing sediment transport rate clearly also have an impact on the representation of the incoming sediment supply to each reach, as ST:REAM assumes that the supply of sediment into a reach is directly related to the ω_{med} of its upstream neighbour(s). This assumption has a particularly large impact on the predictions for a reach whose upstream neighbour has a high stream power but has highly resistant channel boundaries (e.g. bedrock or artificial) – in this scenario the upstream ω_{med} applied within ST:REAM will be high but the actual incoming sediment supply will be limited to sediment that has been transferred through the upstream neighbour from the next reach upstream. In addition, ST:REAM assumes that the only sediment input into a reach is from its upstream neighbour(s). Whilst this assumption may be reasonable within lowland channels, in headwater streams hillslope-channel coupling can provide a significant proportion of a channel's sediment input (Harvey, 2001, Michaelides and Wainwright, 2002) and so ST:REAM may under-represent the incoming sediment supply.

The reach-based balance approach employed within ST:REAM allows for the comparison of the stream power of a reach (and therefore its assumed outgoing sediment transport rate) against the stream power of its upstream neighbours (and therefore its assumed incoming sediment supply). However, the reach-based nature of the approach may reduce its accuracy by exaggerating between reach differences and not representing within reach differences. Re-examination of Figure 3D illustrates that significant local variation in ω_{med} can exist within a reach – this might be associated with local variation in channel sediment dynamics that are not represented within ST:REAM. Figure 3D also demonstrates how the changes in ω_{med} across reach boundaries are more sudden than the changes across the point-based representation of ω_{med}. In addition, ST:REAM's reach-based nature also means that its outputs are sensitive to the reach boundaries that are identified. Figure 7 demonstrates this sensitivity by illustrating how the accuracy with which $\omega_{balance}$ values can be associated with erosion or deposition dominated sites varies with the number of reach boundaries identified. As a result of this sensitivity, ST:REAM is limited in terms of consistency and therefore more research is necessary to improve understanding of the influence of the location of reach boundaries on the model outputs.

Model application

Possible applications for an approach like ST:REAM within the contexts of integrated catchment, river basin and flood risk management include planning actions for sediment management performed as part of flood risk management. Currently, locations where sediment must be managed are identified on the basis of stakeholder pressure, experience and past practice, with little regard to whether the cause of the problem is local or is a symptom of an imbalance in the sediment transfer system and no consideration of the possible impacts of sediment management for continuity and connectivity in the sediment transfer system (Thorne, et al., 2010). An approach such as ST:REAM provides a science-base for examining local sediment problems and the risks associated with different options for sediment management, within the wider contexts of the catchment, fluvial and ecosystems. For example, alongside local knowledge of the catchment system, Figure 9 could be used to justify sediment extraction in the lower reaches of the main stem of the Taff as it approaches and flows through Cardiff. Similarly, it could be used to help justify spending on erosion protection on the lower reaches of the Cynon and Rhondda just before their confluences with the main stem of the Taff.

In addition, an approach like ST:REAM could be used to link habitat degradation to excessive sediment scour or accumulation when restoring rivers. It could provide a means of rapidly relating system-scale sediment dynamics and local sediment imbalances to reaches experiencing loss of habitat quality and/or diversity. This is important as it allows river scientists and engineers charged with implementing restorative or mitigating actions to account for sediment processes as well as morphological forms in their designs. For example, where supported by local observations, Figure 9 could be used to explain poor ecological status as a result of excessive sediment deposition within the second order reaches of the Rhondda.

Specific applications like those above represent potentially valuable uses of the type of approach developed herein, but perhaps the most useful contribution that an approach like ST:REAM could make to river management is by providing a broad understanding of catchment-scale sediment transfer systems nationally. The importance of understanding the fluvial system when managing flood risk, morphological adjustment and ecological status is emerging as the movement towards integrated catchment management gains momentum. In this context, it will no longer be sufficient to rely on qualitative description of sediment dynamics and classification of sediment sources, transfers or sinks. Identification of causal links in the sediment transfer system will be required to infer whether sediment imbalance in a reach results from the natural operation of the sediment transfer system or is the unintended consequence of a poorly designed management intervention, and to predict the probable morphological responses to proposed mitigating or adaptive actions – including that of 'doing nothing'. The fact that climate and anthropogenic pressures are likely to grow means that accounting for sediment status is central to managing a catchment holistically and sustainably. This is evident in the identification of geomorphology as a component of the English and Welsh Environment Agency's Catchment Flood Management Plans (CFMPs) and River Basin Management Plans (RBMPs). However, there is currently no means of considering sediment dynamics at the catchment scale due to data and operational constraints. ST:REAM goes some way towards addressing this problem thanks to its relatively low data requirements and ease of application. For example, Figure 9 indicates that whilst the entire length of the main steam of the Taff downstream of its confluence with the Taff Bargoed is likely to be deposition dominated many of its tributaries (notably the Rhondda, Cynon and Nant Morlais) are likely to be erosion dominated just before their confluence with the main stem.

However, there are limitations on the suitability of ST:REAM to widespread application within river management – the two most significant of which result from uncertainty regarding its accuracy and its calibration requirements. Given that the simplifications explored above limit the reliability of ST:REAM's outputs, it is important that the outputs from an approach like ST:REAM are not used in isolation when making river management decisions. Instead, it is recommended that they are considered in conjunction with field reconnaissance, desk-based and archival investigations and careful examination of aerial photographs and satellite imagery, to check whether the outputs of ST:REAM are supported by both historical records and contemporary observations of sediment issues, channel forms and sedimentary features. As a result, whilst the outputs from ST:REAM can be produced with minimal resources, for them to be interpreted confidently at a local scale, it is necessary for significant additional investment to be made.

As demonstrated in its application to the River Taff, when applying ST:REAM it is necessary to select a value of R to control the number of reaches that a catchment network is divided into. It is also necessary to select threshold values of $\omega_{balance}$ to discriminate the reaches that are predicted to be either erosion or deposition dominated. The most suitable values for these parameters have been established for the Taff catchment but it is unknown whether these will be suitable for other river catchments. Therefore, unless an alternative means of calibrating ST:REAM can be identified it will be necessary to use the method applied here, which requires significant investment of resources into recording observations of channel status.

Conclusion

This paper has described the application of a reach-based stream power balance approach for predicting river channel adjustment within the River Taff catchment in South Wales. The approach, named ST:REAM, can be rapidly applied using datasets that are commonly available across river catchments. When applied to the River Taff, ST:REAM correctly predicted the status of 87.5% of sites that field observations had defined as being either erosion or deposition dominated. However, whilst this demonstrates the potential that this type of approach has as a tool within river catchment management there are currently a number of factors that limit its usefulness. These limitations include the inconsistent performance that may result from inaccuracies in the calculation of ω_{med}, or from simplifications made within the reach-based stream power balance approach, or a combination of both of these. Additionally, the approach is limited by the need to consider the outputs from ST:REAM against the context of observations of channel status. A final limitation is the current need to calibrate ST:REAM for each catchment against observations of channel status.

These conclusions need to be considered in the context of the limitations of this particular study, the most significant of which is that the reach-based stream power balance approach has only been applied to one catchment. As a result, it is not possible to confidently conclude whether or not the R value and $\omega_{balance}$ thresholds selected or the level of accuracy observed within the Taff catchment will apply in other catchments. Further testing of ST:REAM is planned across a wider range of rivers to explore this.

Additional planned future work will involve investigation into alternative approaches for predicting catchment-scale sediment dynamics using remotely sensed-based calculations of stream power. Whilst there has already been a significant amount of recent research into this area (Barker, et al., 2009, Vocal Ferencevic and Ashmore, 2012, Biron, et al., 2013, Bizzi and Lerner, 2013) there is an opportunity to not only derive new approaches but also to compare the accuracy and utility of the approaches that already exist.

Acknowledgements

The majority of the research for this paper was carried out as part of a Ph.D. thesis funded by EPSRC doctoral training account EP/P502632 as part of the Flood Risk Management Research Consortium, supervised at the University of Nottingham by Professors Colin Thorne and Nicholas Clifford. The ST:REAM approach was based on earlier work carried out by Philip Soar (University of Portsmouth) and Nick Wallerstein (Heriot Watt University) in their development of REAS (River Energy Audit Scheme). Ordnance Survey Land-form Profile and MasterMap data was provided by Edina Digimap, catchment hydrology data was obtained from the Centre for Ecology and Hydrology.

References

Ashworth PJ, Ferguson RI. 1986. Interrelationships of Channel Processes, Changes and Sediments in a Proglacial Braided River*. Geografiska Annaler. Series A, Physical Geography* **68** : 361-371.

Bagnold RA. 1986. Transport of solids by natural-water flow - evidence for a worldwide correlation. In: Thorne CR, MacArthur RC, Bardley JB (eds). *The Physics of Sediment Transport by Wind and Water*. American Society of Civil Engineers, New York; 346-351.

Bagnold RA. 1966. An approach to the sediment transport problem from general physics. In: Thorne CR, MacArthur RC, Bradley JB (eds). *The Physics of Sediment Transport by Wind and Water*. American Society of Civil Engineers, New York; 231-291.

Barker DM, Lawler DM, Knight DW, Morris DG, Davies HN, Stewart EJ. 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.

Barker DM. 2008. A new approach for determining downstream change in river flood power at a catchment scale based on the Flood Estimation Handbook and NextMap Britain DEM. Ph.D. Dissertation. Department of Civil Engineering and School of Geography, Earth and Environmental Sciences - University of Birmingham, Birmingham.

Biron PM, Choné G, Buffin Bélanger T, Demers S, Olsen T. 2013. Improvement of streams hydrogeomorphological assessment using LiDAR DEMs*. Earth Surface Processes and Landforms* **38** : 1808-1821.

Bizzi S, Lerner DN. 2013. The use of stream power as an indicator of channel sensitivity to erosion and deposition processes*. River Research and Applications*DOI: 10.1002/rra.2717.

Brunner GW. 2006. HEC-RAS, River Analysis System Version 4.0 User's Manual.

Bull WB. 1979. Threshold of critical power in streams*. Geological Society of America Bulletin* **90** : 453-464.

CEH. 2014. National River Flow Archive - 57003 Taff at Tongwynlais
. http://www.ceh.ac.uk/data/nrfa/data/station.html?57003.

Coulthard TJ, Van de Wiel MJ. 2007. Quantifying fluvial non linearity and finding self organized criticality? Insights from simulations of river basin evolution*. Geomorphology* **91** : 216–235.

EA. 2014. Environment Agency HiFlows-UK - Taff at Tongwynlais (57003). http://www.environment-agency.gov.uk/hiflows/station.aspx?57003.

Edina. 2014. Digimap Ordnance Survery Help. http://digimap.edina.ac.uk/webhelp/os/osdigimaphelp.htm#data_information/os_products/.

EU. 2000. Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy.

Exner FM. 1925. Uber die wechselwirkung zwischen wasser und geschiebe in flussen*. Sitzungber der Akademie der Wissenscaften* : 165-180.

Gibson SA, Little CDJ. 2006. Implementation of the Sediment Impact Assessment Model (SIAM) in HEC-RAS. Eighth Federal Interagency Sedimentation Conference. Federal Interagency Subcommittee on Sedimentation. 65-72.

Gill D. 1970. Application of a Statistical Zonation Method to Reservoir Evaluation and Digitized-Log Analysis*. Bulletin of the American Association of Petroleum Geologists* **54** : 719-729.

Graf WL. 1996. Transport and deposition of plutonium-contaminated sediments by fluvial processes, Los Alamos Canyon, New Mexico*. Geological Society of America Bulletin* **108** : 1342-1355.

Graf WL. 1983. Downstream changes in stream power in the Henry Mountains, Utah*. Annals of the Association of American Geographers* **73** : 373-387.

Harvey AM. 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.

Harvey AM. 1991. The influence of sediment supply on the channel morphology of upland streams: Howgill Fells, Northwest England*. Earth Surface Processes and Landforms* **16** : 675-684.

Hendry K, Cragg-Hine D, O'Grady M, Sambrook-Smith H, Stephen A. 2003. Management of habitat for rehabilitation and enhancement of salmonid stocks. *Fisheries Research* **62** : 171-192.

ISIS. 1999. ISIS Sediment User Manual. Halcrow / HR Wallingford, Swindon.

Jain V, Preston N, Fryirs K, Brierley G. 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 AD. 1999. Downstream variation in stream power. *Geomorphology* **29** : 293-306.

Lane EW. 1955. Design of stable channels. *Transactions of the American Society of Civil Engineers* **120** : 1234-1279.

Lane EW. 1955. The importance of fluvial morphology in hydraulic engineering. *Proceedings of the American Society of Civil Engineers* **81**.

Lane SN, Tayefi V, Reid SC, Yu D, Hardy RJ. 2007. Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment. *Earth Surface Processes and Landforms* **32** : 429-446.

Lane SN, Chandler JH. 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.

Lawler DM, Grove JR, Couperthwaite JS, Leeks GJL. 1999. Downstream change in river bank erosion rates in the Swale-Ouse system, northern England. *Hydrological Processes* **13** : 977-992.

Lawler DM. 1992. Process dominance in bank erosion systems. In: Carling PA (ed). *Lowland Floodplain Rivers: Geomorphological Perspectives*. John Wiley & Sons Ltd; 117-143.

Lecce SA. 1997. Nonlinear downstream changes in stream power on Wisconsin's Blue River. *Annals of the Association of American Geographers* **87** : 471-486.

Lorenz A, Hering D, Feld C, Rolauffs 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.

Magilligan FJ. 1992. Thresholds and the spatial variability of flood power during extreme floods. *Geomorphology* **5** : 373-390.

Michaelides K, Wainwright J. 2002. Modelling the effects of hillslope–channel coupling on catchment hydrological response. *Earth Surface Processes and Landforms* **27** : 1441-1457.

Newson MD, Large ARG. 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 NRB. 2003. 3D CFD Modeling of a Self-Forming Meandering Channel. *Journal of Hydraulic Engineering - ASCE* **129** : 366-372.

Osman AM, Thorne CR. 1988. Riverbank stability analysis. I. Theory. *Journal of Hydraulic Engineering - ASCE* **114** : 134-150.

Palmer MA, Menninger HL, Bernhardt E. 2010. River restoration, habitat heterogeneity and biodiversity: a failure of theory or practice?. *Freshwater Biology* **55** : 205-222.

Parker C, Clifford NJ, Thorne CR. 2011. Automatic delineation of functional river reach boundaries for river research and applications. *River Research and Applications*DOI: 10.1002/rra.1568.

Parker C, Clifford NJ, Thorne CR. 2011. Understanding the influence of slope on the threshold of coarse grain motion: Revisiting critical stream power. *Geomorphology* **126** : 51-65.

Reinfelds I, Cohen T, Batten P, Brierley G. 2004. Assessment of downstream trends in channel gradient, total and specific stream power: a GIS approach. *Geomorphology* **60** : 403-416.

Rinaldi M, Simoncini C, Piégay 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.

Ryan SE, Porth LS, Troendle CA. 2005. Coarse sediment transport in mountain streams in Colorado and Wyoming, USA. *Earth Surface Processes and Landforms* **30** : 269-288.

Schumm SA. 1969. River metamorphosis. *Journal of the Hydraulics Division - ASCE* **95** : 255-273.

Sear D, Newson MD, Thorne CR. 2010. Guidebook of Applied Fluvial Geomorphology. Thomas Telford, London.

Sear DA, Newson MD, Thorne CR. 2003. Guidebook of Applied Fluvial Geomorphology. Environment Agency R&D Dissemination Centre, Swindon.

Sear DA, Newson MD, Brookes A. 1995. Sediment-related river maintenance - the role of fluvial geomorphology. *Earth Surface Processes and Landforms* **20** : 629-647.

Shields FD, Knight SS, Cooper CM. 1998. Rehabilitation of aquatic habitats in warmwater streams damaged by channel incision in Mississippi. *Hydrobiologia* **382** : 63-86.

Soulsby C, Youngson AF, Moir HJ, Malcom IA. 2001. Fine sediment influence on salmonid spawning habitat in a lowland agricultural stream: a preliminary assessment. *The Science of The Total Environment* **265** : 295-307.

Stover SC, Montgomery DR. 2001. Channel change and flooding, Skokomish River, Washington. *Journal of Hydrology* **243** : 272-286.

Thorne CR, Henshaw A, Bates P, Brown D, Coulthard TJ, Gurnell A, Lewin J, Longfield S, Maas G, Macklin MG, Newson M, Nicholas AP, Parker C, Rees J, Sear D, Surendran S, Walker J, Warburton J. 2010. Applied fluvial geomorphology for sustainable flood risk management. DEFRA Annual Flood and Coastal Risk Management Conference.

Thorne CR, Wallerstein NP, Soar P, Brookes A, Wishart D, Biedenharn DS, Gibson SA, C.D. L,Jr, Watson CC, Coulthard TJ, Van de Wiel MJ. 2010. Accounting for Sediment in Flood Risk Management. In: Pender G, Faulkner H (eds). *Flood Risk Science and Management*. John Wiley & Sons, Chichester; 87-113.

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 NP, Soar P, Thorne CR. 2006. River Energy Auditing Scheme (REAS) for catchment flood management planning. In: Ferreira RML, Alves ECTL, Leal JGAB, Cardosa AH (eds). *River Flow 2006*. Taylor & Francis, Lisbon, Portugal.

Wharton G. 1995. Information for channel geometry-discharge relations. In: Gurnell A, Petts G (eds). *Changing River Channels*. John Wiley & Sons, Chichester; 442.

Whipple KX, Tucker GE. 1999. Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs*. Journal of Geophysical Research-Solid Earth* **104** : 17661-17674.

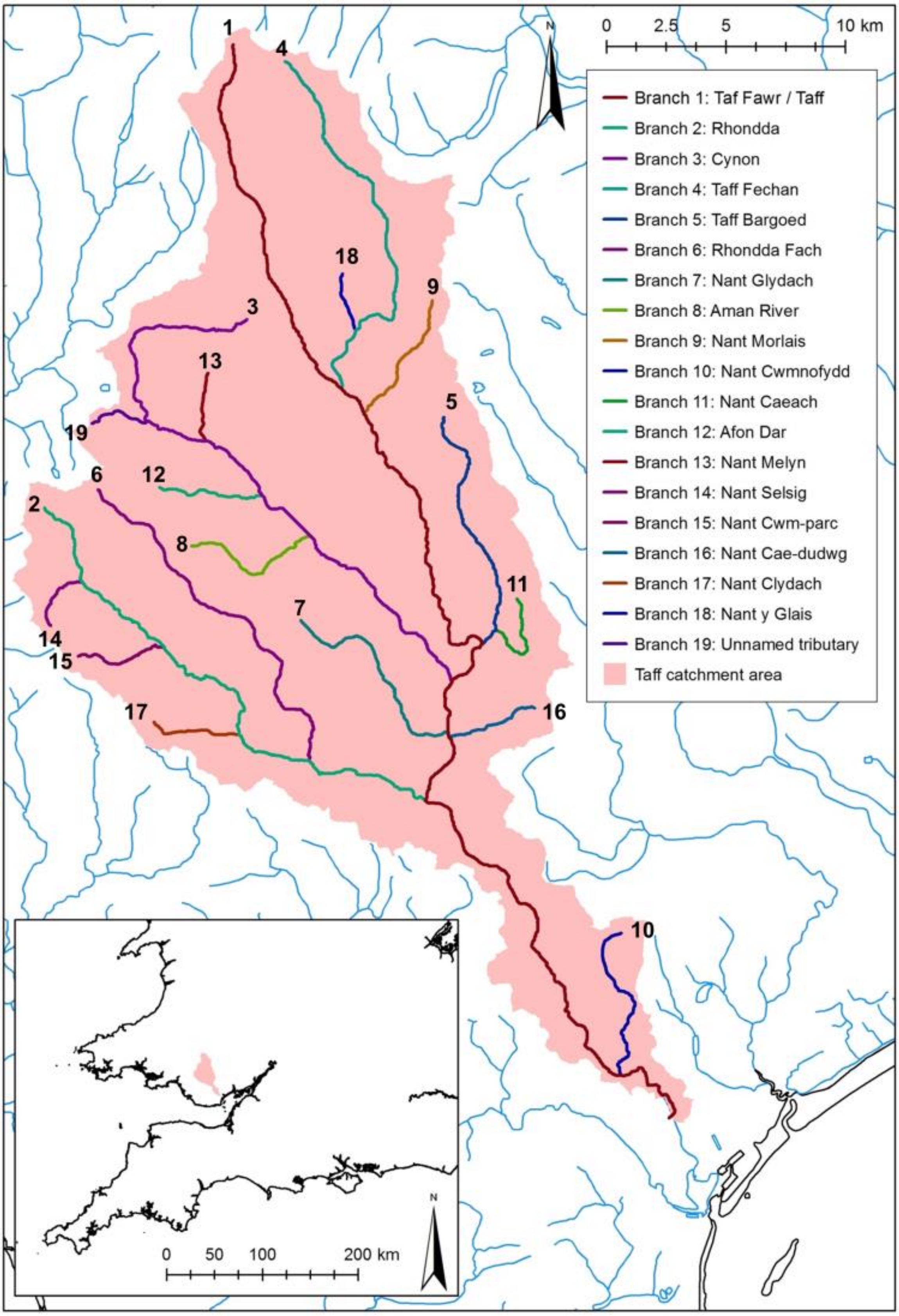
Wobus C, Whipple KX, Kirby E, Snyder N, Johnson J, Spyropolou K, Crosby B, Sheehan D. 2006. Tectonics from topography: Procedures, promise, and pitfalls*. Special papers of the Geological Society of America* **398** : 55.

Wolman MG, Miller JP. 1960. Magnitude and frequency of forces in geomorphic processes*. Journal of Geology* **68** : 54-74.

Table 1. Criteria used for the definition of erosion dominated and deposition dominated channels. Modified from Sear et al's (2003) Table 4.3.

Chanel status	Indicators
Erosion dominated channels	Terraces Old channels in floodplain Undermined structures Exposed tree roots Tree collapse (both banks) Trees leaning towards channel (both banks) Downed trees in channel Narrow/deep channel Bank failures (both banks) Thick gravel exposure in the banks overlain by fines Armoured/compacted bed
Deposition dominated channels	Buried structures Buried soils Many uncompacted 'overloose' bars Eroding banks at shallows Contracting bridge openings Deep, fine sediment overlying coarse particles in bed/banks Many unvegetated bars

Figure 10. The River Taff, South Wales



931 *Figure 11. Flowchart of processes involved in creating a ST:REAM model*

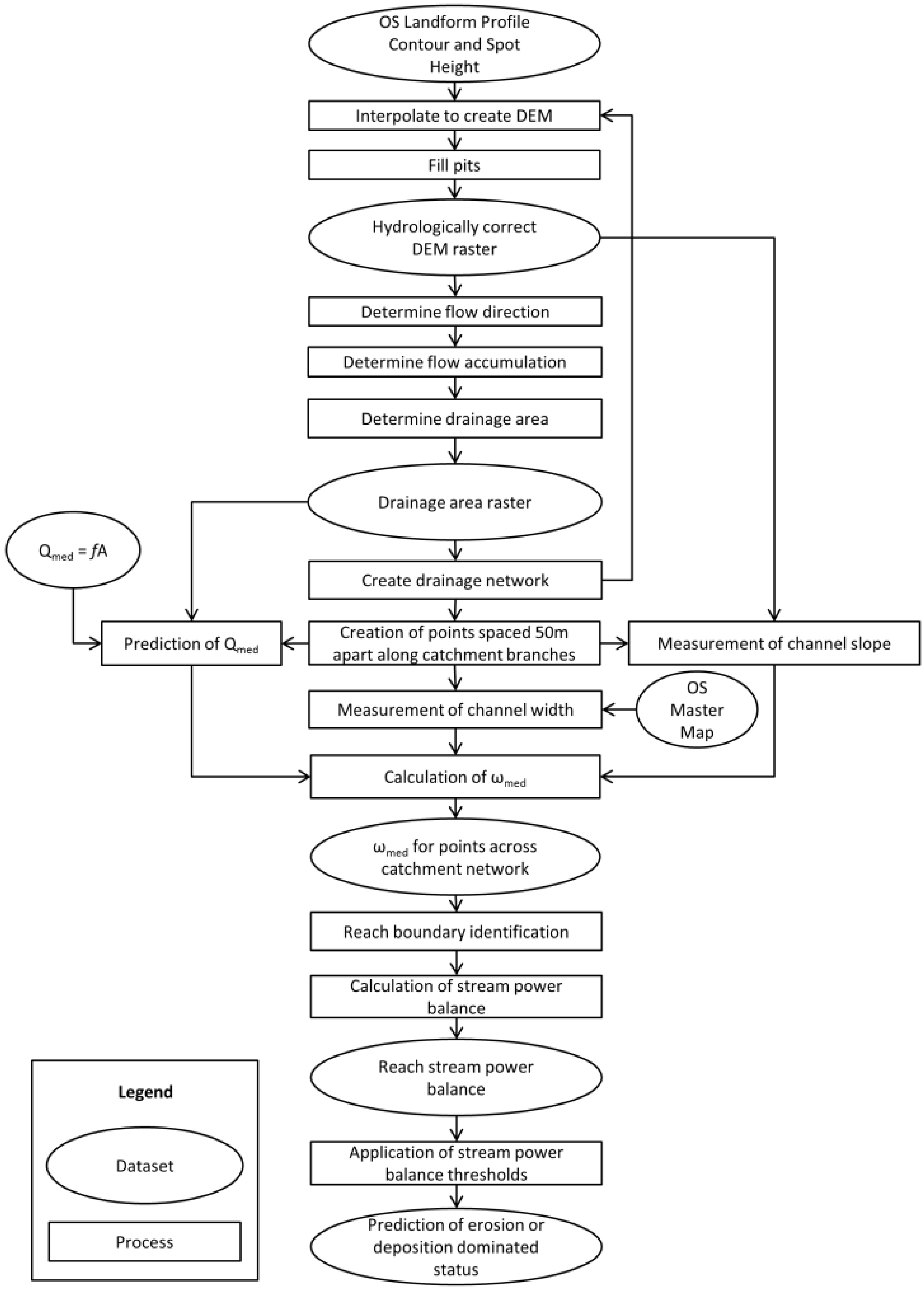


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Figure 12. Example of the reach boundary hunting process using Gill's (1970) global zonation algorithm. The sequence of figures shows how the entire river branch starts as one reach (A), then is divided into two reaches at the point that explains the most amount of variation (B), and then again into three reaches (C), and so on until the user-specified value of R is met – for example 0.01 (D).

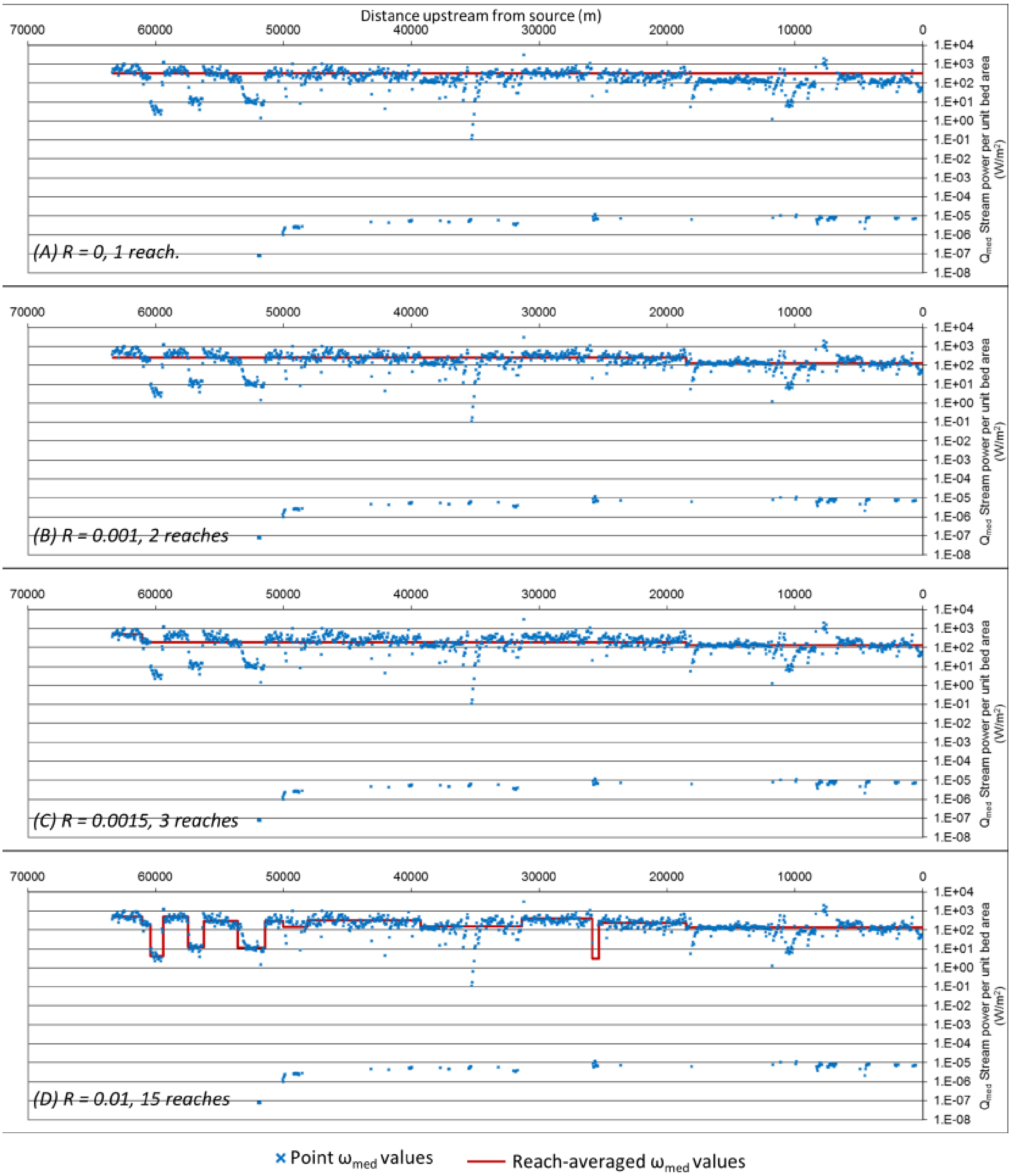

Figure 13. Principles of reach-based stream power balance modelling applied in ST:REAM

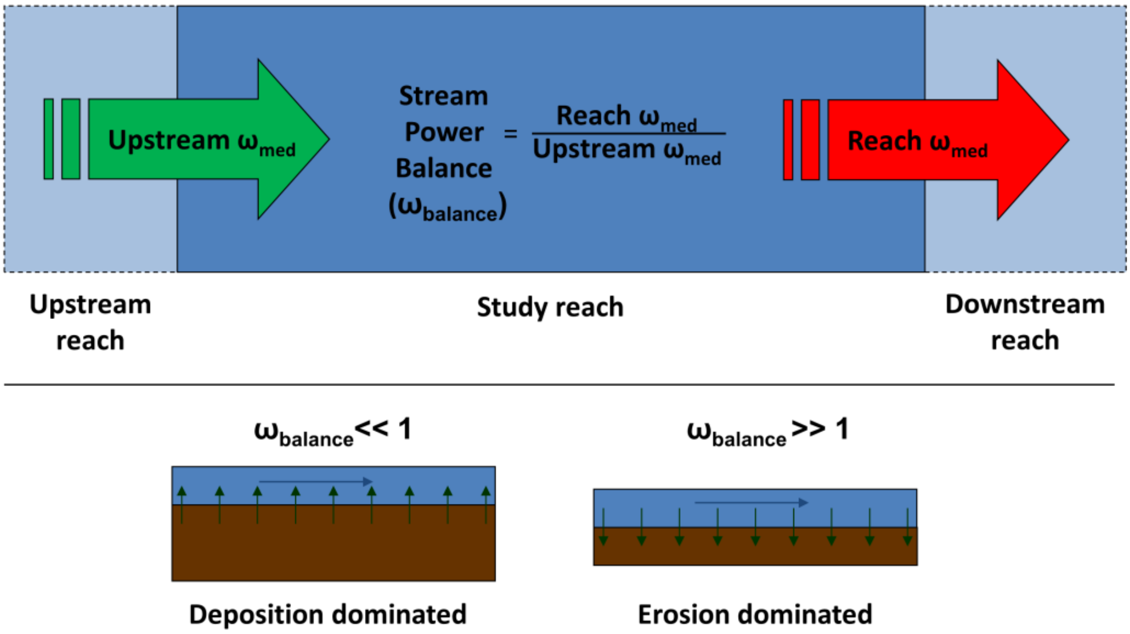

Figure 14. Observed channel locations classified as either erosion or deposition dominated across the River Taff catchment, South Wales

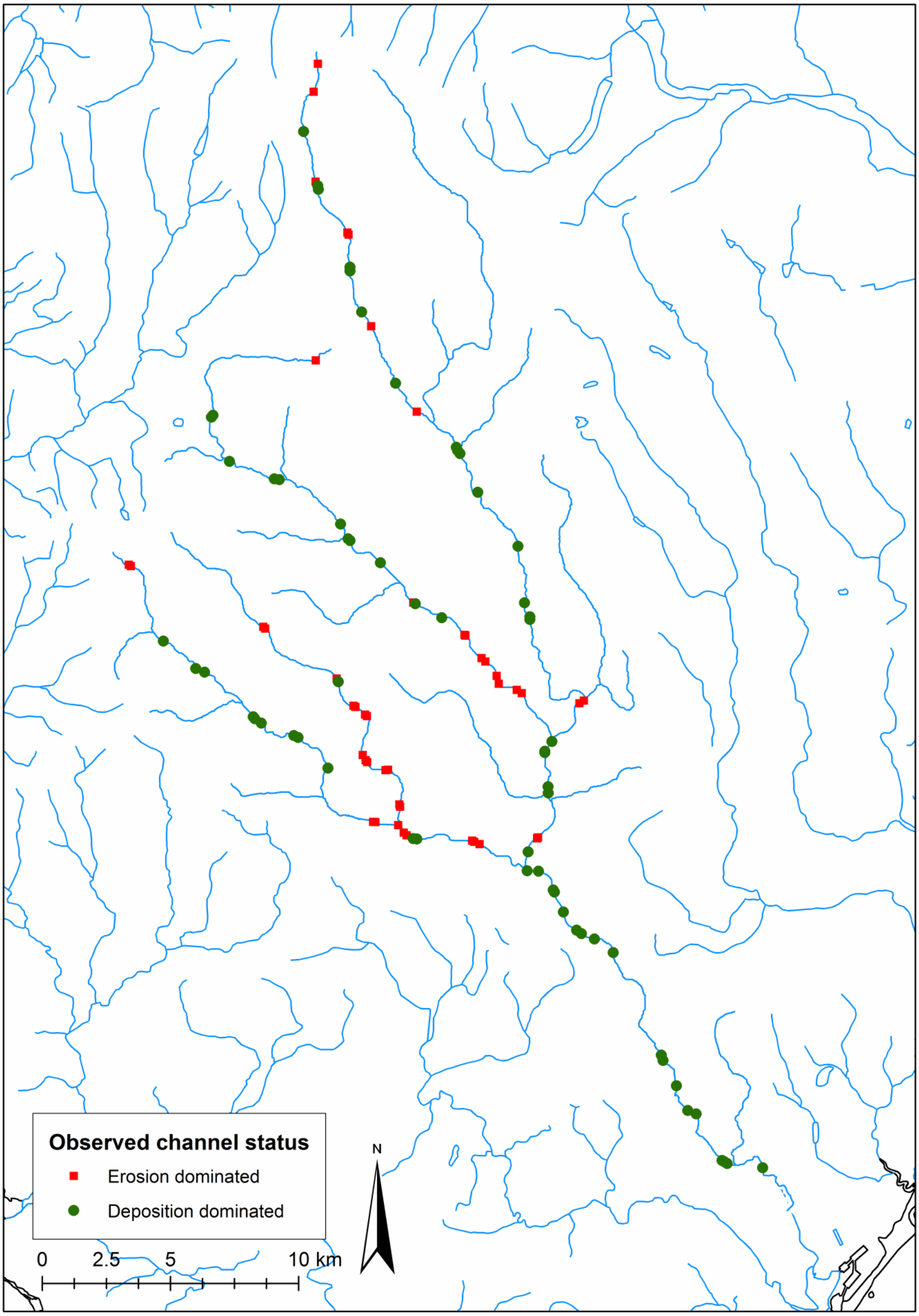

Figure 15. Calculated unit bed area stream power (ω_{med}) values for points spaced every 50m across the channel network of the River Taff, South Wales

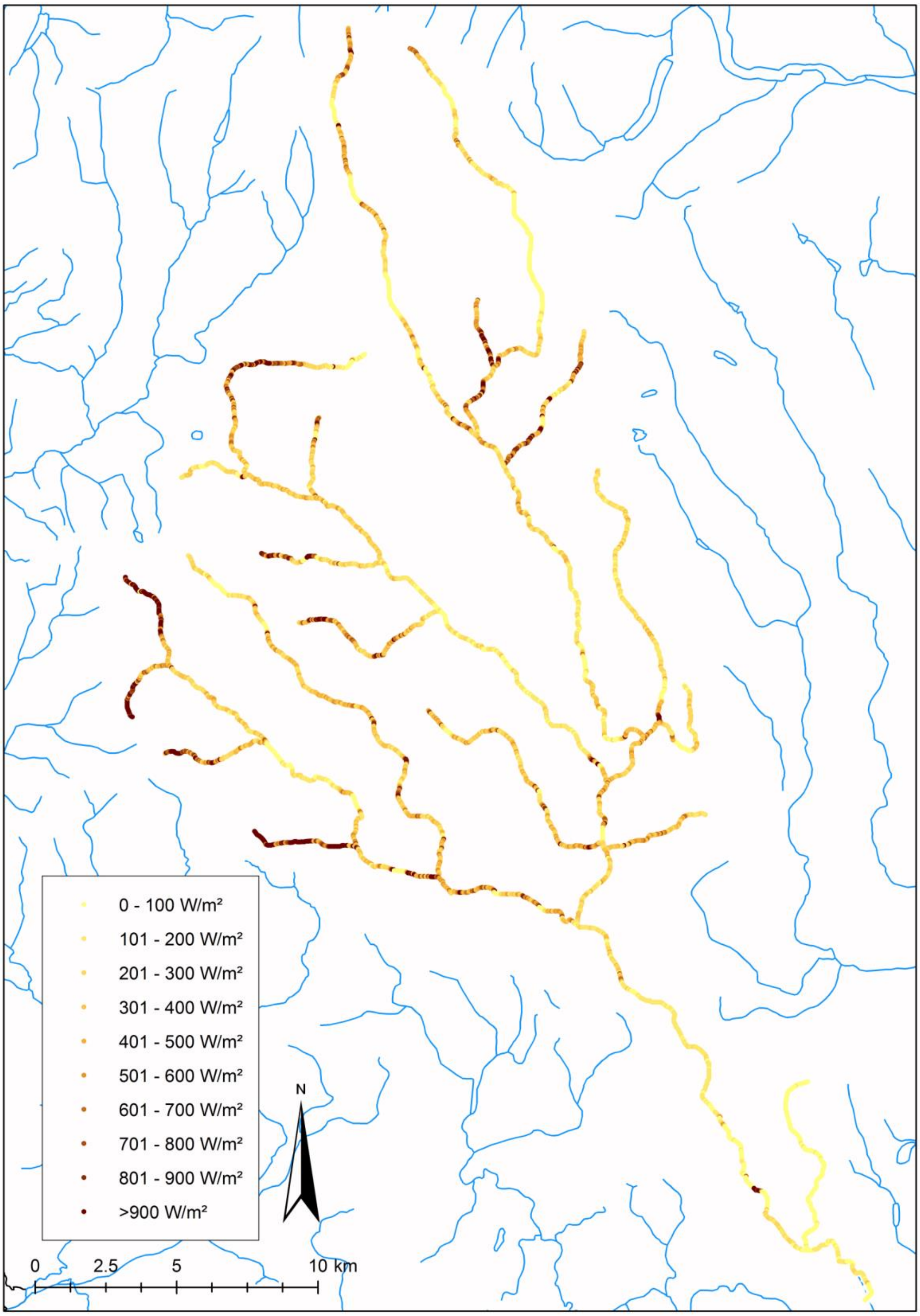

Figure 16. Proportion of observed erosion or deposition dominated sites predicted correctly by ST:REAM for different boundary hunting algorithm 'R' values.

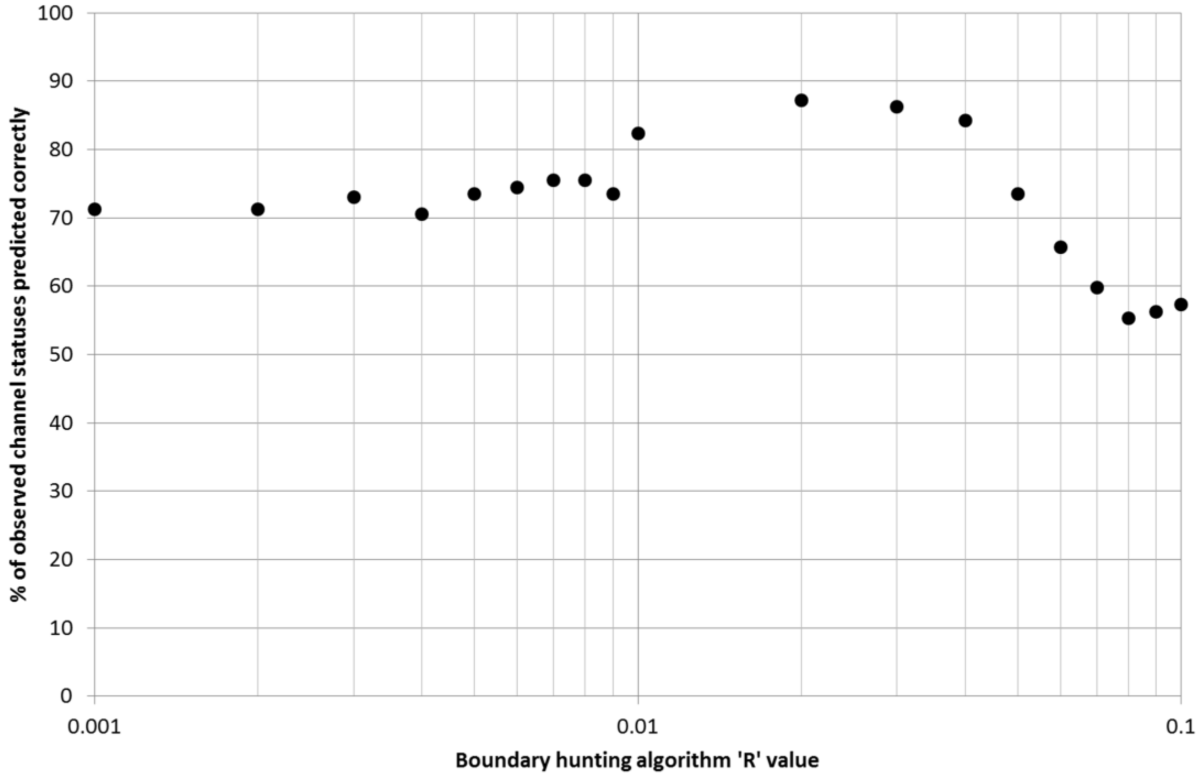

Figure 17. Distribution of stream power balances for erosion dominated and deposition dominated sites, using a boundary hunting algorithm 'R' value of 0.02.

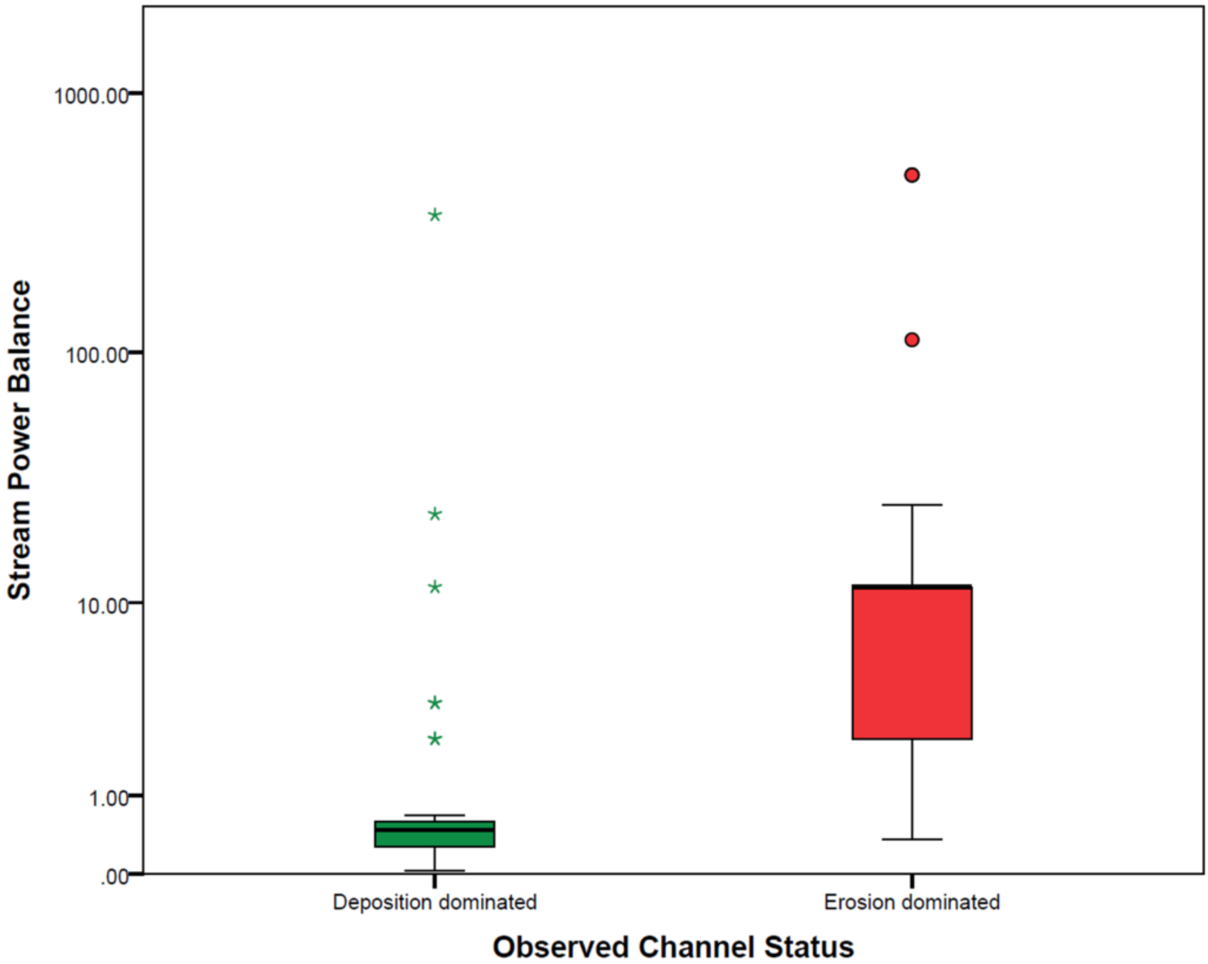

Figure 18. Predicted location of erosion dominated and deposition dominated reaches within the River Taff catchment, South Wales, using ST:REAM with a boundary hunting algorithm 'R' value of 0.02 and deposition and erosion threshold values for $\omega_{balance}$ of 0.59 and 2.3 respectively.