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 ($\omega$) derived from remotely sensed slope, width and discharge datasets. ST:REAM applies a zonation algorithm to values of $\omega$ that are spaced every 50 m 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 $\omega$ value with the $\omega$ of its upstream neighbour in order to predict whether or not the reach is likely to be 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. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS: river; sediment; stream power; erosion; deposition

Introduction

The importance of alluvial channel adjustment within river management

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

$$Q \cdot S = Q_0 \cdot D_{50}$$  

(1)

where $Q$ is water discharge ($m^3/s$), $S$ is channel slope, $Q_0$ 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).

While 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 recognized 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

While 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., 2010a). 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 that 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 (Newson and Large, 2006; Wallerstein et al., 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 Ferencievic 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

Recognizing 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 Ferencievic 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 datasets: 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 500 km² 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 60 km 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 950 mm/year at Cardiff to 2400 mm/year in the Brecon Beacons (CEH, 2014). At the flow gauge at Tongwynlais, near Cardiff (drainage area 486.9 km²) the mean flow is 21.373 m³/s, with a median annual flood (Q_{med}) of 320.0 m³/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 Landform Profile contours and spot heights (Edina, 2014). The contours are generally at 5 m vertical intervals but are at 10 m vertical intervals in some mountain and moorland areas. Contour accuracy values are typically better than half the contour interval – ±2.5 m for areas with 5 m vertical intervals and ±5 m for areas with 10 m 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.

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 IV.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

| Channel status          | Indicators                                                                                                                                 |
|-------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|
| Erosion dominated       | Terraces                                                                                                                                  |
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 100 m, 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 recognized 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.

Calculating unit bed area stream power across a river catchment network

Unit bed area stream power \( \omega \) (W/m²) is defined as

\[
\omega = \gamma \frac{Q \cdot S}{W}
\]

where \( \gamma \) is the unit weight of water (9810 N/m³), \( Q \) is an indicative discharge (m³/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 50 m 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 Landform Profile contour and spot height data (Figure 2):

1. A digital elevation model (DEM) raster dataset (cells of 10 m × 10 m) was interpolated from the Ordnance Survey Landform Profile contour and spot height data (Figure 2):
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 it 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 (0.0001 km²) 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 0.5 km² 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 50 m apart along each of the river network branches included in the model were then created.

In most recent studies involving high-resolution stream power calculations across river catchment networks the median annual flood \( Q_{\text{med}} \) is used in the calculation of \( \omega \) (Jain et al., 2006; Barker, 2008; Bizzi and Lerner, 2013). The \( Q_{\text{med}} \) 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 mobilize the bed material (Ryan et al., 2005). To estimate the \( Q_{\text{med}} \) values for each of the points throughout the river catchment network \( Q_{\text{med}} \) 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 \( Q_{\text{med}} \) and drainage area \( A \), and the resulting relationship for the flow gauges in the Taff catchment is \( Q_{\text{med}} = 1.8632 \times A^{0.8422} \), with an \( r^2 \) value of 0.94. It was then possible to use this relationship, along with the drainage area raster dataset, to

Figure 2. Flowchart of processes involved in creating a ST-REAM model.
predict the $Q_{\text{med}}$ 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 (50 m). In other stream power based approaches for predicting channel adjustment slope measurements have been taken over longer horizontal distances of 200 m (Vocal Ferencevic and Ashmore, 2012), 1 km (Bizzi and Lerner, 2013), and 4 km (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 50 m. Therefore, the purpose of these initial measurements of slope over 50 m 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 $Q_{\text{med}}$, slope and width measurements described above it was possible to calculate the unit bed area stream power of the median annual flood ($\omega_{\text{med}}$) 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 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. (2011a) 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 3(A)) 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 ($SS_a$) is calculated using:

$$SS_a = \sum_{i=1}^{m} \sum_{j=1}^{n_i} (x_{ij} - \overline{x}_j)^2 / \sum_{i=1}^{m} n_j - m$$

where $x_{ij}$ is the $i$th point within zone $j$, $\overline{x}_j$ = mean of the $j$th zone, $n_j$ = number of points in the $j$th zone, and $m$ = number of zones. The partition between the two zones is then moved along the sequence to successive positions and $SS_a$ is calculated for every possible position of the partition. The partition which results in the lowest $SS_a$ is selected as the first zonal boundary, forming two zones (Figure 3(B)). The procedure is then repeated, with the $SS_a$ calculated for every possible position of the second partition, the minimum of which is used to divide the sequence into three zones (Figure 3(C)). In this manner, Gill’s (1970) method finds the zonation that minimizes variance within each zone (reach) and maximizes 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 ($R = \frac{SS_a}{SS_T}$) reaches a specified level. As a result, with higher $R$ values a greater number of reaches (of shorter length) are identified by the algorithm.

Calculating reach stream power balances

Following the calculation of $\omega_{\text{med}}$ values for the points spread 50 m 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 ($\omega_{\text{balance}}$) for each reach was calculated (Figure 4). This was achieved by dividing the $\omega_{\text{med}}$ value of the reach in question by the $\omega_{\text{med}}$ value of its immediate upstream neighbour (or upstream neighbours if the reach was immediately downstream of a confluence).

This method assumes that the $\omega_{\text{med}}$ value of the reach in question is an indicator of the sediment transport capacity of the reach and that the $\omega_{\text{med}}$ value of its immediate upstream neighbour is an indicator of the sediment transport supply that is delivered from upstream. As a result, $\omega_{\text{balance}}$ values close to 1 should be indicative of reaches that are in equilibrium, with $\omega_{\text{balance}}$ values significantly greater than 1 indicating reaches that are likely to be erosion dominated and $\omega_{\text{balance}}$ 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 $\omega_{\text{balance}}$ 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 ($\omega_{\text{balance}} > 1$ where channel is erosion dominated or $\omega_{\text{balance}} < 1$ 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 $\omega_{\text{balance}}$ threshold values for identifying deposition and erosion dominated reaches were explored. Ideally, these thresholds would have been defined by the boundaries between the $\omega_{\text{balance}}$ values of steady-state equilibrium sites and the $\omega_{\text{balance}}$ 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 $\omega_{\text{balance}}$ values were defined using only the $\omega_{\text{balance}}$ values of erosion dominated and deposition dominated sites. The threshold for erosion dominated status was defined using the lower quartile boundary of the $\omega_{\text{balance}}$ values of erosion dominated observed sites and the threshold for deposition dominated status was defined using the upper quartile boundary of $\omega_{\text{balance}}$ 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.

Results

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 I. 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.

Calculated unit bed area stream power values

Figure 6 displays the calculated unit bed area stream power values \( \omega_{\text{med}} \) for points spaced every 50 m along the catchment network of the River Taff. Measured \( \omega_{\text{med}} \) values range from \( 2 \times 10^{-8} \) W/m\(^2\) to 10315 W/m\(^2\). In general, the highest \( \omega_{\text{med}} \) values are found in the first order, headwater channels where slopes are steepest and channel widths are constrained by narrow valleys. The lowest \( \omega_{\text{med}} \) 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.

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.

Calibration of stream power balance thresholds

The spread of \( \omega_{\text{balance}} \) 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 \( \omega_{\text{balance}} \) values greater than 1, with an interquartile range of 2.3–11.6. The majority of sites identified as being deposition dominated have \( \omega_{\text{balance}} \) 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 \( \omega_{\text{balance}} \) that fall outside the ranges that would be expected – the minimum \( \omega_{\text{balance}} \) value for points identified as being erosion dominated is 0.4 and the maximum \( \omega_{\text{balance}} \) value for points identified as being deposition dominated is 339.7. The upper quartile boundary of \( \omega_{\text{balance}} \) 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 \( \omega_{\text{balance}} \) values for erosion dominated points (2.3) has been selected as the threshold for predicting reaches as being erosion dominated.

### Predicted channel status

The output from applying ST:REAM when \( R = 0.02 \), the threshold \( \omega_{\text{balance}} \) value for deposition dominated reaches is 0.59, and the threshold \( \omega_{\text{balance}} \) 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.

### 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 (\( \omega_{\text{balance}} \)) and the occurrence of features that are associated with erosion or deposition dominated channels. This is as expected: reaches with a \( \omega_{\text{balance}} \) value < 0.59 have \( \omega_{\text{med}} \) 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 \( \omega_{\text{balance}} \) value > 2.3 have \( \omega_{\text{med}} \) 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. While Figure 8 demonstrated that the majority of \( \omega_{\text{balance}} \) 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 \( \omega_{\text{balance}} \) that fall well outside these expected ranges. Some of this error may be due to uncertainties in the measurement of parameters used to calculate \( \omega_{\text{med}} \) 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 \( Q_{\text{med}} \) 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 \( \omega_{\text{med}} \) 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 \( \omega_{med} \); an assumption the supply of sediment into a reach is directly related to the \( \omega_{med} \) 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. While 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., 2011b), 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 \( \omega_{med} \) as an approximation of outgoing sediment transport rate. In addition, the relationship between sediment transport rate and \( \omega_{med} \) is assumed to be linear within ST:REAM when it has been found to be non-linear (Bagnold, 1986). Therefore, \( \omega_{med} \) is likely to under- or over-estimate the outgoing transport rate of high powered reaches and over- or underestimate the outgoing transport rate of low powered reaches. A final simplification in the representation of outgoing sediment transport within ST:REAM is that \( \omega_{med} \) 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 \( \omega_{med} \) 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 \( \omega_{med} \) 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 \( \omega_{med} \) applied within ST:REAM will be high but the actual incoming sediment supply will be limited to sediment that has been transported 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 3(D) illustrates that significant local variation in \( \omega_{med} \) can exist within a reach – this might be associated with local variation in channel sediment dynamics that are not represented within ST:REAM. Figure 3(D) also demonstrates how the changes in \( \omega_{med} \) across reach boundaries are more sudden than the changes across the point-based representation of \( \omega_{med} \). 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., 2010b). 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 Taif 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 Taif.

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 while the entire length of the main stem 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, while 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 \( \omega \) 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, while 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 \( \omega_{\text{med}} \) 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 \( \omega_{\text{balance}} \) 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. While 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.

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