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"Novel Approaches to Assess and Rehabilitate Modified Rivers"
TEMPLATE FOR EXTENDED SUMMARY

PROCESS BASED CLASSIFICATION OF SEDIMENT CONNECTIVITY THE RIVER BASIN SCALE

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Novel approaches allow to trace the fate of sediment contributions from individual river reaches throughout the river network, and to assess the resulting sediment connectivity on the basin scale. The derived information is an unprecedented source of information to assess from where and over which times a downstream river reach recruits its sediment. This information links strongly to the reaches sensitivity to anthropic disturbance or restoration efforts. Here, we present how to make the resulting, complex data-sets accessible for management applications. We introduce "connectivity signatures" that convey the key information on sediment connectivity on the reach scale. We use data driven classification techniques to identify a reduced set of typical connectivity classes. Spatial distribution of connectivity classes reveals that these classes represent specific, functional "connectivity styles" with specific locations and functions for sediment routing in the river network. Results concretize the interpretation of sediment connectivity from a managerial perspective and open the way for its application to large river basins.

1 Introduction

Sediment connectivity is a central driver behind fluvial processes. Here, sediment connectivity refers to transfer processes of sediment between sources and sinks through river networks, from initial mobilization, intermediate storage and remobilization, to the final deposition. Hence it embalms both, a topologic relationship and the potential mass exchange between any two points in a river network. Accordingly, connectivity represents a framework for integrated assessments of sediment transfers in river basins (1). Sediment transfer processes are increasingly altered by human pressures in most river basins (2) in terms of magnitude, timing, and granulometry, resulting in negative downstream externalities. Understanding how sediment transfers operate on the basin scale is imperative for river basin management in order to understand how river channels and fluvial processes will react to past and future disturbances or restoration options (3).
So far, the ability to represent the complexity of fluvial sediment transfer processes is limited. Limitations arise from a lack of data, limited conceptual understanding of processes, and of their spatial distribution through river basins (4, 5). So far, some generic frameworks have been proposed to classify the reaction of rivers to sedimentologic disconnection (6, 7). Suitable numerical models to cover relevant spatio-temporal scales, and to derive management oriented indicators of sediment, and especially bed-load, connectivity were absent until recently. Here, we previously contributed a novel modelling environment for detailed assessments of bed-load movement through large river basins. The model is based on the integration of common

sediment transport formulas into an effective, graph theoretic representation, and traces the fate of each sediment fraction separately. Hence, it allows to consider preferential transport processes due to heterogeneous grain size mixtures, and to assess the impact of such processes on basin scale patterns of sediment transfer. The framework can be applied to very large river basins and allows studying basin scale pattern of sediment connectivity. While the resulting information is of potentially high managerial value on the reach scale, its assessment on the basin scale is hindered by its complexity, and multidimensionality. Here, we aim to reduce the resulting data sets complexity in order to identify common classes of connectivity, for a still process-related, but more generic understanding of connectivity. We apply a data-mining technique to identify if there are groups of reaches that have common connectivity attributes, and evaluate if the derived classification links to spatial distribution and function of the reaches.

2 Method

The calculation of sediment transfers is based on a recently proposed multi-cascade sediment model(8). In this model, each reach is considered the beginning of a distinct sediment cascade (subscript i). Each sediment cascade is assigned a characteristic grain size d_i that reflects the hydrologic forcing and morphologic conditions in its initial reach. Required data are mainly derived from remote sensing products, and some at-station hydrologic data. Sediment cascades are represented in a graph-theoretic framework (9, 10) that allows to efficiently trace transport processes along each cascade. Sediment transport capacity, Q_S, in each reach along a sediment cascade (subscript j) is calculated with well-established sediment transport formulas (11, 12). Parameterization of transport formulas is based on the same data sources used for calculatingd_i. Sediment transport capacity ${Q_{S,i}}^j$ is reduced to ${Q_{S,i}}^{j'}$ to consider for the presence of multiple sediment cascades in a reach, and for the competition between these cascades. The reduction factor ${F_i}^j$ is derived from a dynamic competition function that considers both, sediment supply and local transport limitations (8). A reach-to-reach sediment mass balance is calculated along the cascades based on ${Q_{S,i}}^{j'}$, resulting finally in sediment fluxes along each sediment cascade. Sediment cascades are interrupted, if more than 99% of initial sediment inputs are deposited, or local energy is not sufficient to transport d_i. Such a model was recently shown to represent bulk bed-load fluxes in large river basin well (8). The resulting data-set is a comprehensive sort of information for basin scale bed-load assessments: as any reach receives sediment inputs from multiple cascades, with each cascade conveying information on sediment flux, travel time, and delivered grain size. The information on these three domains of sediment connectivity result in a reach-scale connectivity signature for all reaches in the basin. To conclude, a single sediment cascades carries all information for the travel of sediment from a distinct reach through the fluvial network. The information of all cascades passing through a reach allow, in turn, to identify where the reaches sediment inputs originate, and with which connection time and magnitude they are delivered.

Here we present how this data-set can be aggregated into connectivity indicators. Bracken, et al. (1) proposed that connectivity of a river reach to a downstream reach conceptually maps into a 2 dimensional space that covers the downstream travel distance of sediment, and the sediment load it contributes to the downstream river network. Mapping observations into this phase diagram could help to identify reaches where connectivity is controlled either by detachment or by transport capacity. We start from this notion, but modify and expand it into a management-focused connectivity space. We inversed the direction of analysis from downstream to upstream. This is to analyze how a reach will respond to a change in the upstream fluvial network rather than how it is connected to the downstream fluvial network. We propose to expand the phase diagram by a third dimension, to consider also grain size. Travel distance is replaced by travel time. Hence, the connectivity is described by the indicator in terms of flux, grain size composition, and connection times. Observations are plotted into the 3 dimensional phase diagram spanned by the afore mentioned parameters. The connectivity indicator was derived by an unsupervised *k-means* clustering, that identified reaches with common characteristics within the 3-dimensional phase space. In order to understand the function of connectivity classes we compare their distribution in the phase space with their spatial distribution throughout the river network.

3 Results

We selected the Da River Basin in SE Asia as suitable case study because of its heterogeneity in terms of topography, high sediment production, and the availability of validated hydro-morphologic remote-sensing data sets (your paper). The total length of the fluvial network included into the modelling was 7400 km, or 2123 reaches.Figure 1 depicts the results of the sediment cascade model for the river system under study that contains 2123 reaches, resulting in the same number of sediment cascades. The model identified the flux between any pair of reaches connected by a sediment cascade, considering a total of 56472 connections (Panel A, curved lines), each line convey information on the flux delivered along that cascade. The cutout illustrates that each reach receives sediment contributions from multiple upstream reach, and contributes itself to multiple downstream reaches.

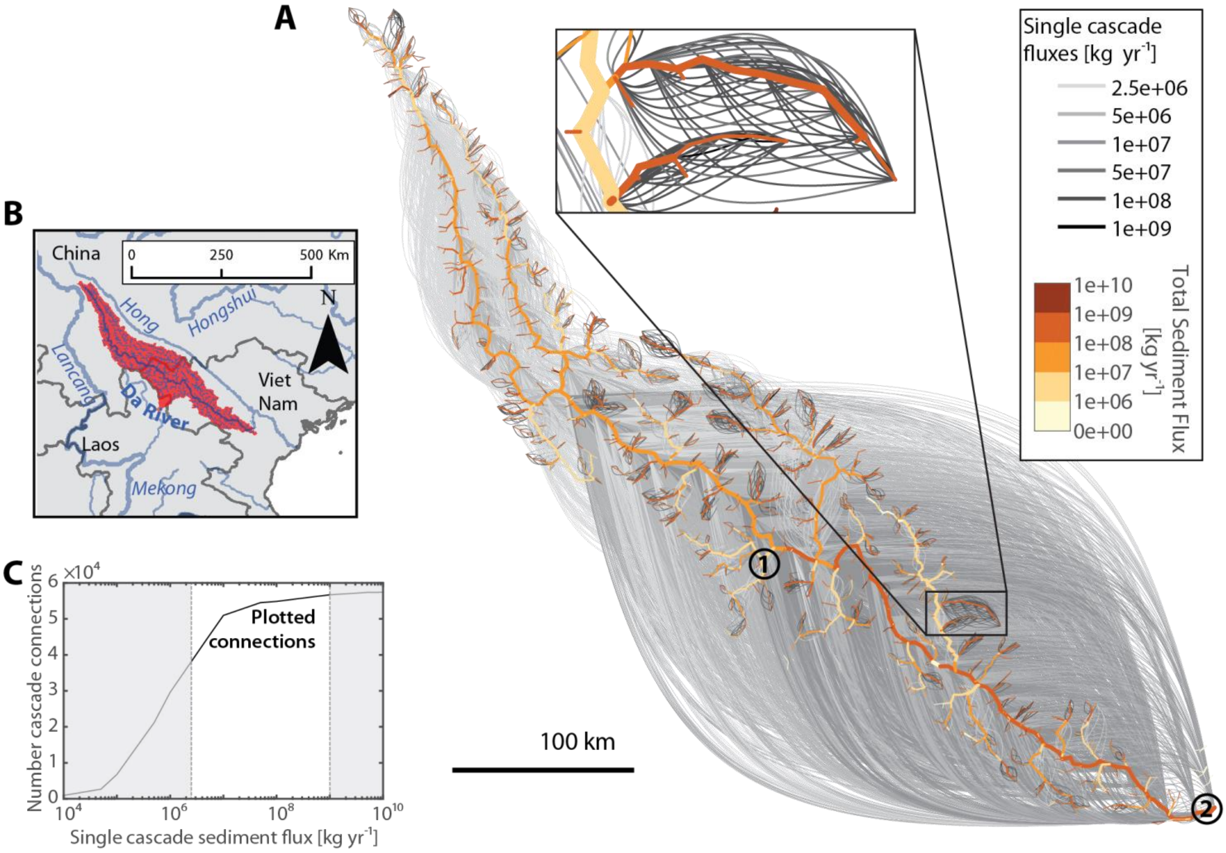

Figure 1: The novel, cascade wise approach to sediment connectivity (Panel A). Grey, curved lines indicate the flux along individual sediment cascades, the red color code indicates the resulting bulk flux in reach. The cutout illustrates the functioning more in detail. Numbers refer to reaches for which connectivity signatures are plotted in Figure 2. Panel B puts the basin into its geographic context. Panel C indicates that only a small number of all connections is plotted here.

Aggregating all sediment fluxes passing through a reach allowed to define the total sediment flux in that reach. Each cascade has a specific grain size assigned to it, which allows, together with the sediment flux information, to calculate a mass-weighted median grain size (d_{50}) of the expected sediment mixture in each reach. The available information on the reach scale is presented is presented in Figure 2 for 2 examples: the terminal reach of a mountainous tributary system, and the basin outlet.

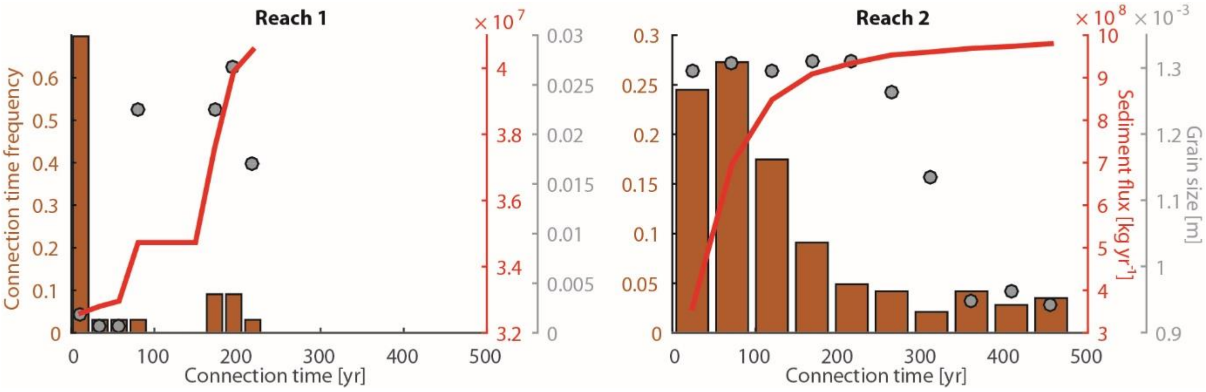

Figure 2: Connectivity signatures (grain size, connection times, sediment flux) for two selected reaches for a mountainous (reach 1), respectively a low land river (reach 2), see Figure 1 for exact location

The characteristics of both reaches show up in the presented signatures. Reach 1, which is a gravel bed reach, receives the highest number of sediment contributions, and around 80 % of its sediment inputs from cascades with relatively small grain sizes (d_i< 5mm). The connection time of these cascades is relatively fast. The remaining local sediment signature is controlled by cascades that contribute medium gravel (d_i > 10 mm). For these contributions, the connection time is relatively long. For reach 2, a sandy river, the majority of sediment is contributed within relatively short connection times (<100yr). Here, smaller grain size (d_i < 1.3 mm) are contributed with longer connection times. That indicates that these fines are derived form more upstream parts of the river network. This examples clarify the type of information that can be derived from the full, basin scale data set for individual reaches (Figure 1). The information contained in the connectivity signatures maps well into a connectivity phase diagram that represents grain size, sediment flux, and connection time (Figure 3, Panel A). End members of the phase diagram are reaches with (i) high fluxes, and low connection times, (ii) high sediment fluxes, but long connection times (iii) low fluxes but high connection times, and (iv) low fluxes, but fast connection times. Overall, the observations are relatively equally distributed throughout the phase diagram. An unsupervised clustering technique identified 7 typical connectivity classes. A spatial analysis indicates that these classes have a characteristic spatial distribution within the river network. Class 1-3, for example, represents headwater reaches, class 4 intermediate reaches, and class 5 and 6 major tributaries and the main stem (Figure 3, Panel B). This clear spatial sequence of classes allows deriving a functional trajectory of sediment connectivity from up- to downstream (Figure 3, Panel C). This trajectory coincides very well with the conceptual understanding of sediment connectivity, and allows understanding the dominant processes in each class. Classes 1-3 are driven by increasing sediment flux production. Class 4, with increasing connection times and decreasing fluxes is dominated by the routing and storage of upstream sediment. Class 5 and 6 see an increase in fluxes and also connection times. Dominant process is here the concentration and routing of the incoming fluxes.

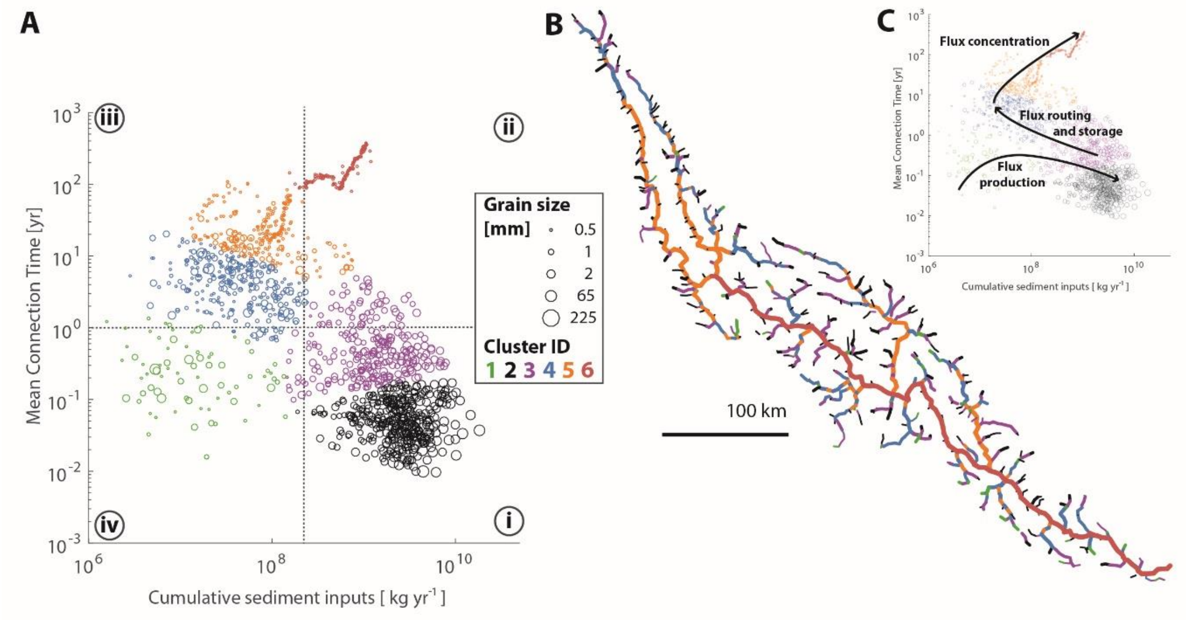

Figure 3: Definition of connectivity classes based on model results. Connectivity properties of all reaches are mapped into the phase space proposed by (1) and divided into typical classes by unsupervised data-mining (Panel A). Panel B indicates the geographic position of members of each class. Panel C presents a functional classification based on results shown in Panel A and B.

4 Discussion and conclusion

Results of the multi-cascade sediment model provide a relevant source of information on sediment transport processes that is for the first time available in this detail over the presented scales. The model adopts a scale spanning perspective and considers reciprocal interactions over scales. It produces detailed sedimentologic information in terms of sediment fluxes, connection times, grain sizes, and sediment source areas. Here we presented how these local information can be successfully classified into broader classes using data-driven approaches. Classes map well into previously proposed categories of connectivity (1). So far, it was not known how these conceptual classes map spatially throughout a river network, or if they fulfill specific functions in basin scale sediment transport. Based on the spatial distribution of class-members we can clarify the function of these categories in general, and for the river basin under study. “Connectivity styles” discern river reaches with a well-defined position in the network, with specific functions, and driving forces. We propose, that “connectivity styles”, and local connectivity signatures are of concrete management interest to assess reach scale reaction to anthropic alterations in sediment connectivity or restoration action.

5 References

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6 IMPORTANT SUBMISSION INFORMATION

All extended summaries must be written in English. The extended summaries should not exceed **5 pages**. Extended summaries must be submitted to reform2015@deltares.nl in both *.pdf and *.doc or *.docx format. The deadline for submission is **2nd of April 2015**.

The organizing committee reserves the right to return accepted extended summaries to the author(s) that do not comply with the format instructions given below.

7 GUIDELINES

7.1 Size, spacing and font type

You should submit your extended summary on standard A4 paper using the font type VERDANA.

Type the title of the extended summary in **12 pt boldface**, all upper case. Authors' names are set in 10 pt , UPPER CASE. All other text including addresses, figure and table captions are in 10 pt lower case. Section headings (e.g. introduction, methods, results, conclusions & recommendations) should be underlined.

7.2 Tables

The tables are designed to have a uniform style throughout the extended summary. The caption heading for a table should be placed at the top of the table.

7.3 Figures

It is best to embed the figures in the text where they are first cited. Please ensure that all labels in the figures are readable. The caption heading for a figure should be placed below the figure.

Figures may be submitted either in black and white or colour. Please prepare the figures in high resolution (300 dpi) for half-tone illustrations or images. Half-tone pictures must be sharp enough for reproduction.

7.4 Equations, and citations

Equations should be aligned to left margin and numbered consecutively, as in Eq. (1). Equation numbers should be aligned to right margin.

A shortlist of references should be given in the end section.

REFERENCES

Shortlist of references.

1st author name, initials, 2nd author, initials (year). Title. Journal title Volume: Page numbers