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Assessing riparian zone impacts on water and sediment movement: a new approach

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Abstract

The state of river channels and their riparian zones in terms of geomorphology and vegetation has a significant effect on water and sediment transport in headwater catchments. High roughness in natural rivers due to vegetation and geomorphological attributes generate drag on flowing water. This drag will slow water discharge, which in turn influences the sediment dynamics of the flow. The impacts of changes in the management of rivers and their riparian zone (either by catchment managers or river restoration plans) impacts both up- as well as downstream reaches, and should be assessed holistically prior to the implementation of these plans.

To assess the river's current state as well as any possible changes in geomorphology and vegetation in and around the river, effective approaches to characterise the river are needed. In this paper, we present a practical approach for making detailed surveys of relevant river attributes. This methodology has the benefit of being both detailed – describing river depth, width, channel morphology, erosive features and vegetation types – but also being practical in terms of time management. This is accomplished by identifying and describing characteristic benchmark reaches (typical sites) in detail against which the remainder of the river course can be rated. Using this method, a large river stretch can be assessed in a relatively short period while still retrieving high quality data for the total river course. In this way, models with high data requirements for assessing the condition of a river course, can be parameterised without major investments on field surveys.

In a small headwater catchment (23 km^2) in southwestern Poland, this field methodology was used to retrieve data to run an existing model (HEC-GeoRAS) which can assess the impact of changes in the riparian and channel vegetation and channel management on sedimentation processes and stream flow velocity. This model determines the impact of channel morphology and in-channel and riparian vegetation on stream flow and sediment transport. Using four return periods of flooding (2, 10, 20 and 100 years), two opposing channel management / morphology scenarios were run; a natural channel and a fully regulated channel. The modelling results show an increase in the effect of riparian vegetation / geomorphology with an increase in return period of the modeled peak discharge. More natural channel form and increased roughness reduces the stream flow velocity due to increasing drag from flow obstructions (vegetation and channel morphological features). The higher the flood water stage, the greater the drag due to vegetation on the floodplains of natural river reaches compared to channelised sections. Slower flow rates have an impact on sediment mobilisation and transport in the river.

Keywords: riparian vegetation, water and sediment transport, channel management, modelling flood retention

Introduction

Riparian vegetation and channel management in headwater catchments play an important role in the resulting water and sediment dynamics of rivers further downstream (Wainwright et al., 2003; Gao, 2008). Detailed knowledge about the quantity and timing of water and sediment delivery from upstream headwater catchments is essential to effectively manage flooding potential (Vanacker et al., 2007), increase the life expectancy of downstream reservoirs (Saavedra, 2005; Liangang et al., 2011), and reduce the impacts of sediment accumulation in navigable fairways downstream.

There are a number of river channel and riparian zone attributes especially in the headwaters that directly impact upon the delivery of water and sediment further downstream. These include flow retardation caused by vegetation within the channel and on the river banks, channel sinuosity, multiple channels and flow paths, and channel and bank roughness due to natural bed and bank variability. Flow retardation results in back water effects which increase the flood frequency and duration of floods within a headwater catchment (cf. Newson & Large, 2006). Furthermore, the resulting flood hydrographs have a longer flow duration with lower peak flow rates (Lane et al., 2007) resulting in decreased sediment transport capacity. This reduction of flow competence can result in changes in the sedimentary regime of the channel with fines in the form of suspended load becoming more dominant over traction and bed-load transport. Jones et al. (2000) identified that the total amount of suspended sediment represented the most important cause of river impairment. Furthermore, suspended sediment often acts as a transporting agent for carrying nutrients, trace metals, semi-volatile organic matter, and pesticides (Jones et al., 2000), with detrimental effects on the physical, chemical, and biological properties of aquatic ecosystem (Newcombe & Macdonald, 1991; Lewis et al., 2006).

Assessing the total suspended sediment loads in rivers using empirically-derived criteria is essential for establishing the sediment threshold that aquatic vegetation can tolerate without significant habitat and biodiversity loss (Fitzgerald et al., 2001; Kuhnle & Wren, 2005). Information on the suspended sediment dynamics of a river and its catchment is also significant for the development of effective erosion management and pollution control strategies (Gao et al., 2007), and for designing and operating efficient irrigation systems and river regulation facilities (Mizumura, 1989).

Detailed information about a specific headwater catchment in terms of channel and riparian zone morphology and vegetation condition, and current vegetation and management practices within the riparian zone requires standardised field surveys (Sear, 1994; Niezgoda & Johnson, 2005) and modelling (Williams et al., 1997; Kondolf et al., 2007). This information can then be used in sediment and water discharge models. However, current methodologies, especially for sediment-related projects, have limited standardisation and are therefore difficult to repeat or compare. Furthermore, most methodologies either focus on channel morphology or vegetation only, or merely focus on single, isolated river reaches (Wohl et al., 2005).

The aim of this study was three fold:

1. To make a simple field survey tool to assess the current state of the headwater riparian zone morphology and vegetation.
2. Using a model to assess the impact of riparian and channel vegetation and channel management on flow and sedimentation processes.
3. To assess the impact of river management for two contrasting scenarios: (a) fully regulated channel devoid of riparian vegetation, and (b) a channel and riparian zone in natural state.

Study area

This study took place in a 23.1 km^2 headwater catchment within the Upper Nysa Szalona catchment (443 km^2; Fig. 1a, b) in southwestern Poland. Mean annual precipitation for this region is 760 mm (1977-2006). Relief ranges from 330 m in the north to 666 m in the west, with slopes varying from 0 to 25.5°. Soil types are predominately cambisols and podsols developed on crystalline or sedimentary rocks. The geologic structure in the catchment (magmatic, sedimentary and metamorphic rocks) determines the appearance of the channel bed, with the upstream riverbed comprised mostly of cobbles and bedrock (slate) with occasional larger boulders.

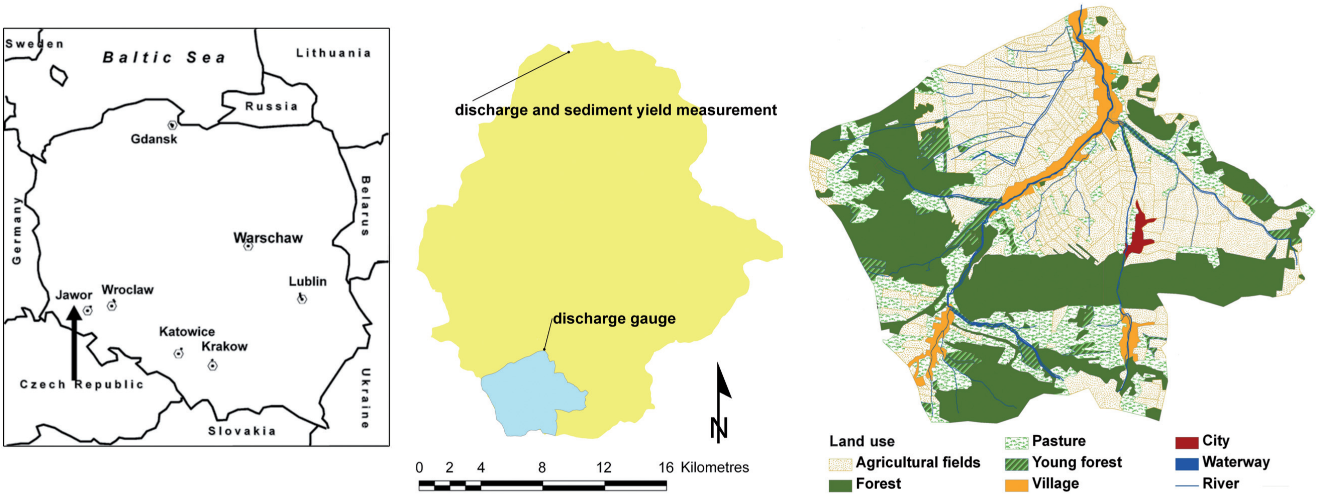
A large part of the Upper Nysa Szalona catchment (as at 2008) remains in a natural state with 39% forested, 16% pastures, 39% agricultural fields, with the remaining 5% urban (Fig. 1c). The upper reaches of the catchment remain largely natural, whilst further downstream, natural to semi-natural reaches occur frequently (Figs 2b and 2c).

Methodology

Field survey: geomorphology and vegetation mapping

To create a database of the current state of the channel and riparian vegetation, we developed a tool to classify the entire river. Several characteristics of the river channel and riparian zone were mapped; the morphology, the vegetation types and vegetation cover. These characteristics were used to classify the river reaches.

The classification system of Rosgen (Ducros & Joyce, 2003; Simon et al., 2007) was adapted to map both channel and floodplain geomorphology and vegetation with individual reaches identified, surveyed and classified. Vegetation cover was mapped using a field based evaluation tool for riparian buffer zones within agricultural catchments known as a 'Buffer Zone Inventory and Evaluation Form (BZIEF)' which incorporates a



a. b. c.

Fig. 1. a. Location of catchment in Poland; b. Location of Upper Nysa Szalona sub-catchment within the Nysa Szalona catchment; c. Land use in the Upper Nysa Szalona (as at 2008).

criteria-based scoring system (Ducros & Joyce, 2003). Vegetation types were mapped using regional vegetation atlases (Atlas of Lower and Opole Silesia, 1997). The attributes of the studied reaches were summarised in tables and maps, which were geo-referenced and processed in a GIS database (Fig. 3).

River discharge

Stage-height measurements at the river outlet (Fig. 1c) were converted to discharge using a rating curve. An average discharge of 0.78 m^3/s (average flow velocity of 0.46 m/s) was measured for the period of field mapping. Flow data were compared with the historical record at the outlet of the larger basin of the Nysa Szalona (see Fig. 1b for location). From the historical data, the flood height with a return period of 2, 10, 20 and 100 years return periods for the Nysa Szalona catchment were derived. By comparing the headwater catchment (the study area) and the larger historical data set, a conversion factor was determined between the large and the smaller catchment from which flood height recurrence intervals (2, 10, 20 and 100 y return periods) were calculated.

Modelling riparian vegetation and channel morphology impact on discharge using HEC-GeoRAS

After the initial field survey involving detailed cross sectional information and discharge measurements of the river channel, riparian zone morphology and vegetation, the HEC-GeoRAS (USACE, 2006) model was used to assess the impact of riparian and channel vegetation and channel management on sedimentation processes and stream flow velocity. The HEC-GeoRAS model calculates the water-surface profile through a river reach for a given flow rate. Furthermore, the impact of riparian vegetation and channel characteristics can also be modeled (e.g. Ghafari et al., 2010). This 1D model can simulate both steady and unsteady flows but in this study, we assumed

a. b. c.

Fig. 2. Examples of the channel and the adjacent riparian zone. a. fully regulated; b. natural reach; c. Semi-natural reach. Photo a and b by E. Kondrlova. Photo c by A. Czajka.

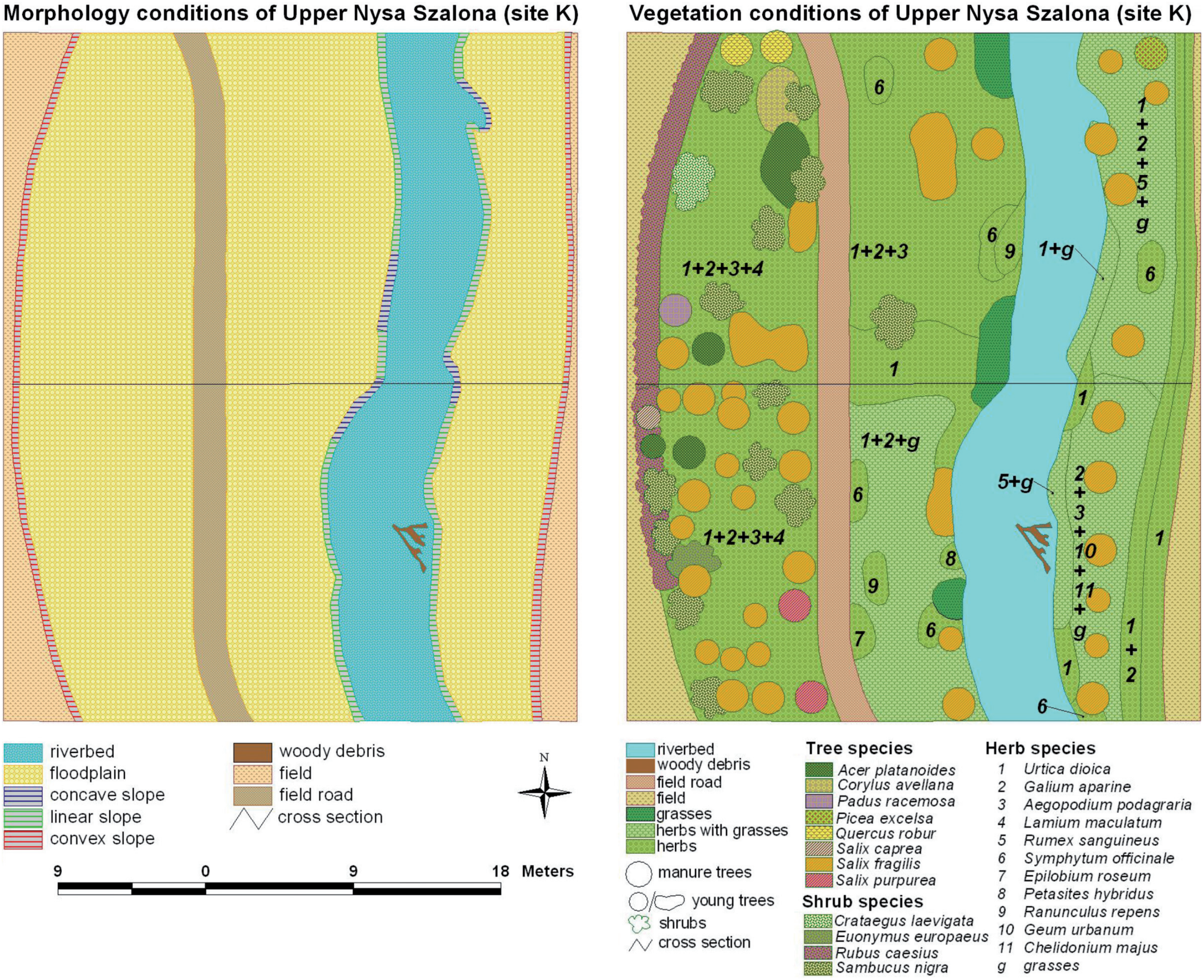


Fig. 3. Example of geomorphological (left) and vegetation condition (right) mapping of reach L.

steady state flows. Under steady state flow conditions, HEC-GeoRAS calculates the water surface elevation (WSE) and velocity profile for a given cross-section taking into account continuity, energy and flow resistance (e.g., Manning's equation).

To assess the impact of river management, two contrasting scenarios were modelled: a fully regulated channel without riparian vegetation (scenario REGULATED); and a channel and riparian zone which was in a natural state (scenario NATURAL). To make the scenarios as real as possible, actual situations in the current channel were used to construct the scenario cross-sections.

Input data for HEC-GeoRAS

Input for the HEC-GeoRAS model includes a DEM of the river valley and cross-sections through the reaches of interest at intervals sufficient to allow hydraulic calculation of the WSE between cross-sections, flow rates for each profile and the estimated hydraulic roughness of the river channel and overbank areas. The model output provides detailed hydrological data for each river reach between the cross-sections and the calculated water-surface elevation (WSE) at all cross-sections for each flow rate. The WSE can then be used to map the extent of inundation in the river valley that would be expected during each modeled river flow rate. Under steady flow, the model requires cross sections, delineation of the channel and discharge estimations for each cross-section. The model was run for a range of flood return intervals (2, 10, 20 and 100 years) to estimate variations in flow velocity.

HEC-GeoRAS requires many more cross-sections along the river channel than the 11 cross-sections that were mapped during the field work (Fig. 4). Therefore, the mapped cross-sections were extrapolated to reaches that were not mapped. In some river sections, it was necessary to reconstruct the floodplain cross-section from the DEM and the topographical map as the surveyed cross-sections were too narrow.

Apart from cross-sectional information, HEC-GeoRAS requires as input the roughness parameter, Mannings' n. This was derived

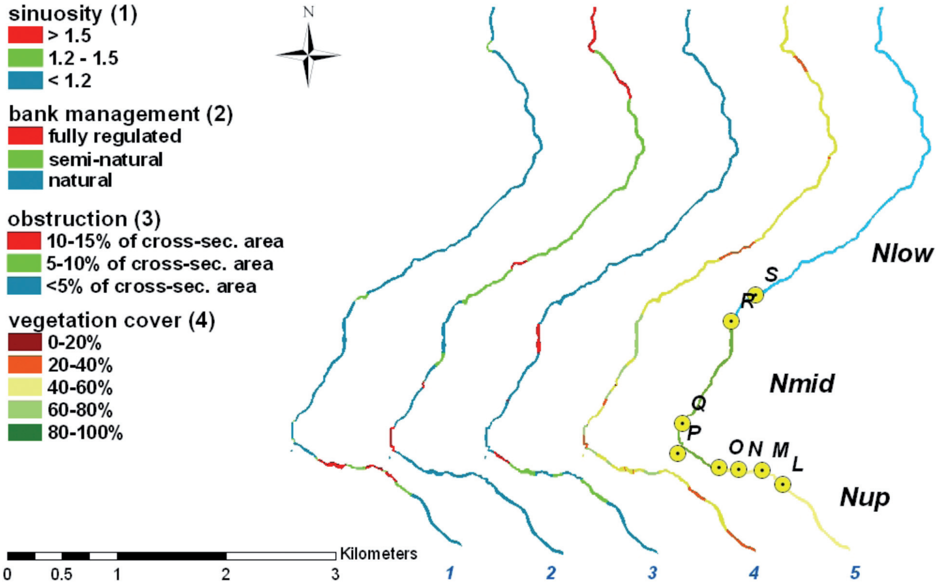


Fig. 4. Riparian zone attributes in the study area. Criteria 1-4 are shown whilst Criteria 5 highlights the position of mapped sites L-S and the division of the Nysa Szalona river channel into 3 reaches: upper (Nup), middle (Nmid) and lower (Nlow).

using details from vegetation maps and mapped river morphology. The Mannings' roughness coefficient of a channel was computed using the formula of Arcement and Schneider (1990). To characterise vegetation cover, Global Canopy Cover (GCC) values were used.

Results

A new approach to channel and riparian zone assessment

The extrapolation of detailed measured riverine sites towards full coverage of a river represents a new approach in establishing a quick but relatively accurate way to map an entire river course in a small catchment. To accomplish this, key representative sites needed to be identified along the entire river from which detailed geomorphological mapping of these sites was developed using cross-sections, in combination with topographic maps at 25 m up and downstream from each cross-section. Key attributes such as flow obstructions, undercutting of river banks, bank slope, sinuosity of the reach, multiple channel, channel narrowing or widening and floodplains were documented and mapped. Along the Upper Nysa river, nine sites (Sites L-S) were mapped highlighting the nine different states evident along the river (Fig. 3a).

From the field survey we observed that natural pool-riffle alternation is the most typical state for the studied stream (Fig. 2b). Riffle areas consist of cobbles accompanied by occasional boulders. Pools are typically lined with finer sediments (gravels and silt). Where bedrock outcrops, the river morphology changes from a pool-riffle to a step-pool morphology. Channelisation in the lower reach (Nlow, Fig. 4) acts as a barrier to the regular spacing of deep pools and shallow riffles in the stream channel and sediments generally consist of gravels; in stark contrast to the frequent boulders in the natural stream sections. Channelised segments display lower sinuosity (P <1.2) resulting in comparatively higher flow velocities. In upper reaches, the flow velocity is influenced by obstructions present in the channel (Abernethy and Rutherford, 1997). These obstructions were mapped according to three categories depending on the width of observed barriers, and the percentage of the rivers width it is blocking (Fig. 5). Barriers to stream flow included fallen trees, leaves, dense plant growth, boulders, and human flood debris. In Upper Nysa Szalona, barriers covering >25% of

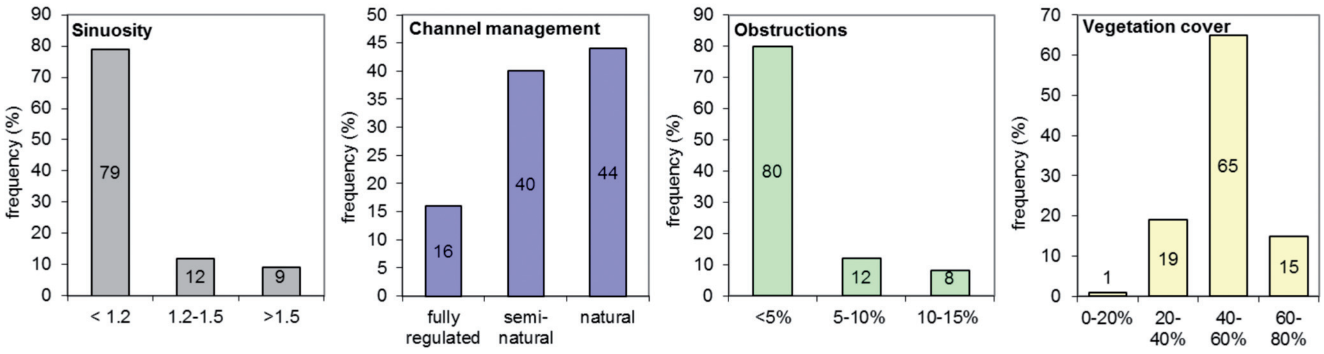


Fig. 5. Frequency histograms summarising the spatial criteria shown in Figure 4.

the wetted channel width occurs on 26% of the channel area predominately in the lower part of the NUp reach and in the NMid reach (Fig. 4). In the middle reaches (NMid, Fig. 4) short channel sections with obstacles (~10 m) alternate regularly with long sections without obstacles (~50 m). Reaches with in-stream barriers displayed higher sinuosity (P >1.5) in most cases (Fig. 3).

Channel characteristics and management

In the upper and middle reach (Fig. 4, Nup and Nmid), bedrock banks create a step-pool morphology (Fig 2b). In the lower reach (Fig. 4, Nlow) the channel is alluvial, consisting of cobbles and gravels (Fig 2c).

Management of the channel and its banks differs along the stream. Some segments have not been altered and thus maintained in their natural condition, whilst other sections are fully regulated with artificial embankment (Fig. 2a). The riverbeds of the artificially embanked channel segments consist of cobbles riprap, and sometimes flagstone paved, while one or both stream banks are built up with granite blocks. Regulated segments are located where the stream flows through residential areas. In upper Nysa Szalona (Nup) 7% of the riparian zone is fully channelised. Full regulation of both banks can be observed in the middle reach (Nmid) (site Q) and predominately in the lower reach (Nlow), where these segments alternate with grassy stream segments (Fig. 5). The upper middle (Nmid) reach shows high variability between embanked and natural segments while in the lower middle (Nmid) reach, regulation is evident on both banks with alternating natural segments, while the lower reach (Nlow) is fully embanked/channelised.

Vegetation cover characteristics and vegetation roughness

Characterisation of vegetation cover of the channel and riparian zone for the purposes of a GIS consisted of detailed species determination of trees, shrubs and most dominant herbs. Grasses, creating an uninterrupted layer, were taken into account but the species were not specified. As we planned to visualise all vegetation types in one layer of the GIS, we had to adjust field mapping to this goal and generalise sketching.

When characterising the tree layer, every mature tree was individually visualised by a circle mark. Every species of tree (or shrub) was classified with different colours. When the young trees were close to each other, these were classified as a group of young trees (Fig. 2). We did not visualise the placement according to treetop width, since the crowns created in most cases a full canopy. Very young trees were added to the shrub layer. Drawing the shrub layer on the map was done similar to the young tree groups. When mapping the lowest layer (grasses, mixed vegetation and herbaceous) the most dominant species were detected in the late spring aspect. In general mapping of all vegetative layers was focused on the dominant species and spatial location, quantity was estimated to give the total percentage of abundancy for each layer.

Manning's n values for riparian vegetation ranged from 0.033-0.1053, and for every value in this range, a C-factor value was assigned from 0.05-0.9. Other land use forms (e.g. arable land, forest, pasture etc.) were given unique values (0.271; 0.05; 0.015 respectively). The land use / land cover of the remainder of the catchment was mapped using geo-rectified Google Earth images (Fig. 6).

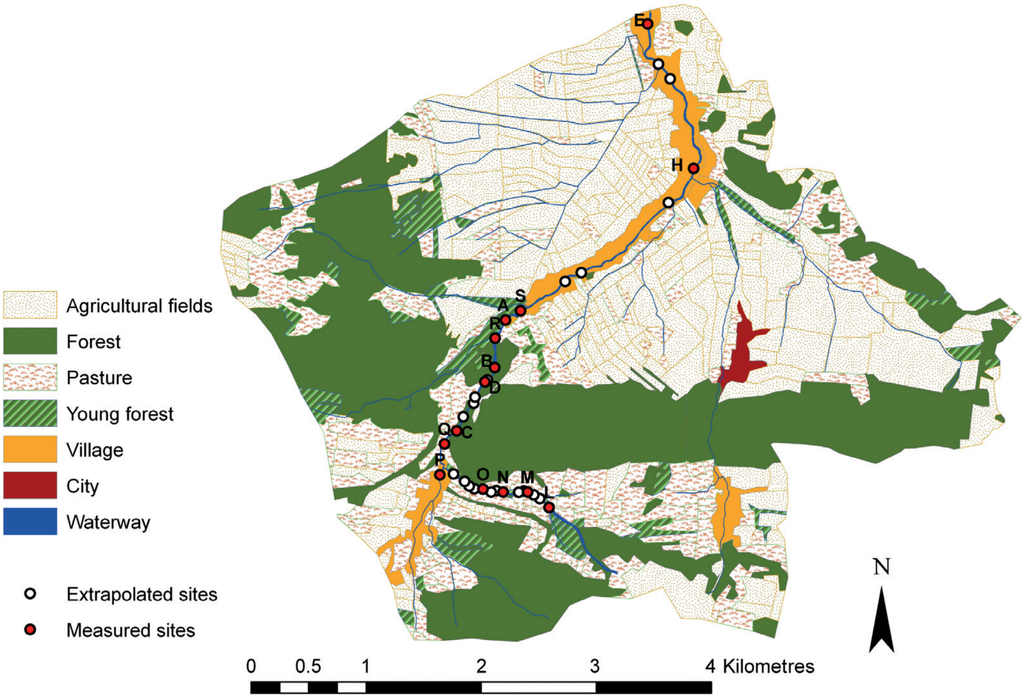


Fig. 6. Land-use map of Upper Nysa with mapped cross-section and extrapolated reaches.

Benchmark sites: combining geomorphological and vegetational characteristics

By combining the detailed vegetation and geomorphological mapping, 14 typical sites were identified (sites A, B, C, D, E, H, L, M, N, O, P, Q, R and S; Fig. 6 for locations). A quick survey of the entire river was undertaken to compare each reach against the benchmark sites (Table 1). The new approach for mapping proved to be effective generating a very detailed and extensive data set by stretching the studied characteristics of the benchmarked sites to the whole river. This approach enables a researcher to acquire a detailed data set as input into a model such as HEC-GeoRAS, with a high level of detail about the river reach characteristics within a small time frame with the level of detail adapted to the requirements of the model.

HEC-GeoRAS outputs

The HEC-GeoRAS model was used to simulate changes in water velocity and discharge for various channel and riparian zone conditions (Fig.7). The model runs for flood stages with a return period of 2, 10, 20 and 100 years show that the larger the flood, the greater the impact of channelisation on flow velocity (Table 2). For the 2 year flood, the modelled flow velocity in a completely channelised stream increases by 28% compared to a natural stream. During a 100 year flood, this increase in flow velocity rises to 41% (Table 2).

Changes in flow velocity can also be observed along the longitudinal profile of the river. In the most upstream sections of the river, where discharge is low, the change in water velocity is much smaller when the state of the channel and riparian zone is changed from natural to channelised (Fig. 8). With increasing catchment area, the modelled velocities straddled the measured velocity profile with higher flow rates attributable to channelised flows. At the outlet, the measured average flow velocity of 1.6 m/s lies between the channelised average velocity of 1.8 m/s and 1.4 m/s for a natural channel (Fig. 8).

Discussion and conclusions

A simple field survey approach to assess the current state of the river channel, riparian zone morphology and vegetation

To assess the state of a channel in terms of its ability to retard sediment and water can be done in various ways. However, some channel assessment methodologies are very crude or extremely detailed (e.g. Church, 1992) and do not give the required information for a river reach. The development of a simple survey approach has the benefit of being time and data efficient. Very detailed mapping techniques are used largely for reach scale research and originate from fauna and flora focused-based research (e.g. Maddock et al., 1995; Hogan et al., 1996). These surveys are used as the basis of most restoration projects, but

Table 1. Characteristics of the typical locations.

Site	Channel form description	Bank height	Floodplain	Vegetation	Other
A	Symmetric, natural	<1 m	Undeveloped	Herbs, few trees	
B	Symmetric, natural, straight	<1.5 m, erosive gravel/bedrock banks	Well developed	Dense herbs and trees, no shrubs	
C	Symmetric, natural	<1.5 m steep, vegetated		Herbs/shrubs / young trees	5-10% LWD
D	Asymmetrical, natural	~1.5 m, varying steepness, steep bank: bare/eroding, gentle sloped bank: vegetated		Dense herbs/shrubs, trees on top of banks	
E	Channelised, rectangular	2 m, granite blocks		Herbs on bars	Cobbles on channel bed
L	Meandering natural, asymmetrical	One steep, erosive, one gentle vegetated	Wide, natural on one side of channel	Dense trees and shrubs	
M	Symmetric	<0.5 m, vegetated, in outer bends undercut	Well developed	Dense herbs, few trees	
N	Natural, straight	<1 m, erosive due to undercutting and livestock	Wide, densely vegetated		Herbs and shrubs
O	Natural, straight	<0.5 m		Low Herbs/shrubs	
P	Semi-natural, next to road	~2 m, erosive		Mainly shrubs	
Q	Channelised, trapezoidal, granite blocks	~2 m		Poor, few herbs	Natural/gravel channel bed
R	Natural, straight	<2 m, erosive, partly in bedrock		Forest, dense shrubs and trees, few herbs	Bed rock channel forming cascades
S	Semi-natural, symmetric	Stable banks <2 m slope 35°		Dense herbs and shrubs on upper banks	

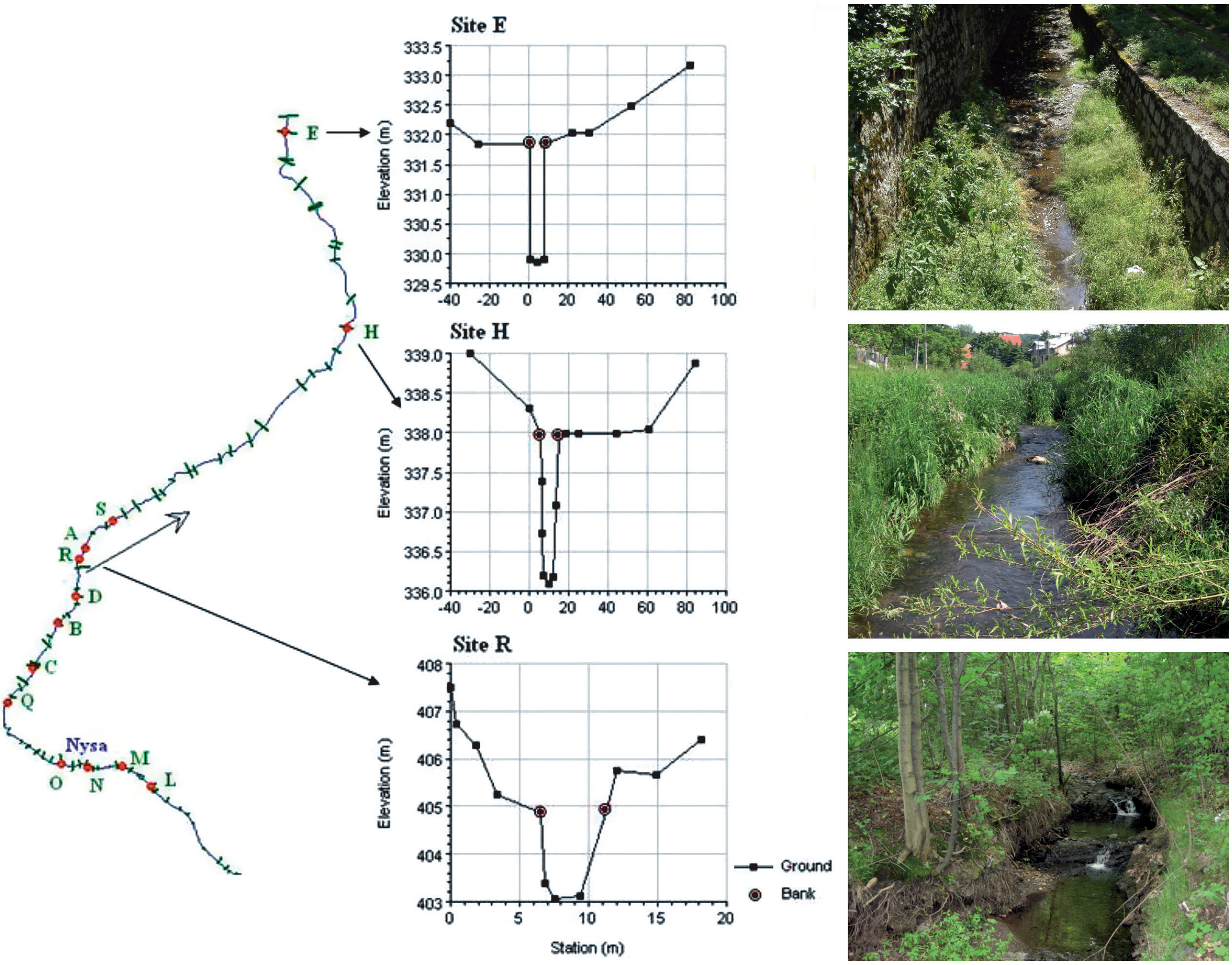


Fig. 7. Example of 3 cross-sections with accompanying pictures (Sites E, H and R) for use in the HEC-GeoRAS model. Large arrow indicates flow direction downstream. Bold arrow shows flow direction of river.

the role of sediment transport in determining stream morphology is mostly not taken into account (e.g. WDFW, 2004). Therefore, river restoration and catchment managers are advised to consider watershed conditions and plan, construct and assess river restoration (Sudduth et al., 2007; Kondolf et al., 2007; Rosgen, 2006, FISRWG, 1998, Florsheim et al., 2008; Sear, 2009) and river management projects on the scale of the watershed and to include the up and downstream areas, specifically channel and riparian zone characteristics, in order to improve the project effectiveness.

Table 2. Results of the steady flow HEC-GeoRAS model runs.

Return period of flood	**Change in water velocity comparing a natural state with a channelized state of the channel and riparian zone**
100 year	+41%
20 year	+37%
10 year	+36%
2 year	+28%

Mapping the entire river in detail is not normally feasible in most projects. However, a detailed description of the whole river channel with its riparian zone based on characteristics relevant for sediment and water transport, is presented here. The methodology used in this study has the benefit of being both detailed (describing river depth, width, channel morphology, erosive features and vegetation types), but also practical in terms of time management. Thus making a survey of both the geomorphological and sedimentological and vegetational characteristics possible. Each characteristic site in the study reaches can then be used as a benchmark. After this intensive fieldwork phase, the remaining larger sections of the river are classified according to the attributes of the benchmark site. Using this method, large river sections can be assessed relatively quickly. Furthermore, the information obtained for the entire river is of high quality. Thus models (in our case the HEC-GeoRAS model), with high density data requirements for the condition of the river, can be parameterised without high investments in field surveys.

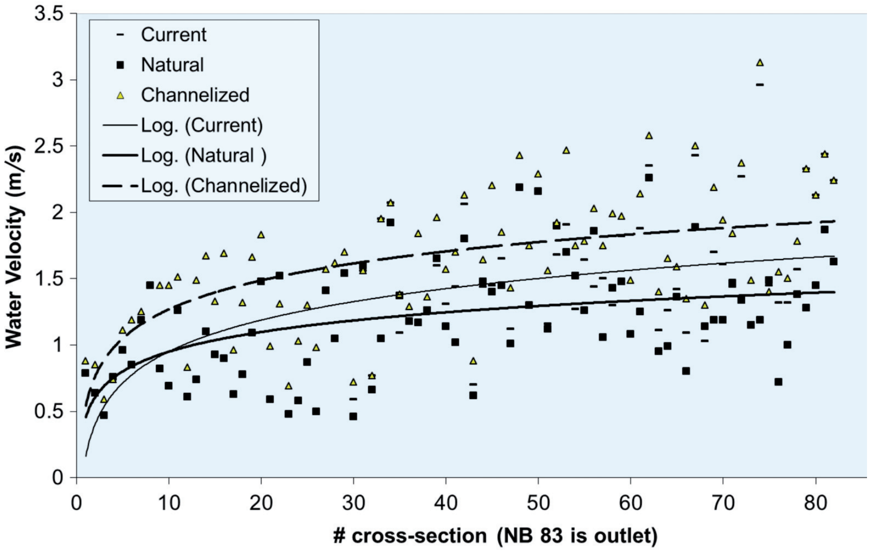


Fig. 8. Comparison of the relation between simulated water velocity and the longitudinal profile, for the current (measured) cross-sections and the two studied scenarios (fully natural and fully channelised).

Modelled impact of riparian and channel vegetation and channel management on stream flow velocity

Based on previous research, there are strong correlations between water velocity in a channel, the geomorphology of a stream, and the roughness of a channel due to vegetation in the bed and along the channel in the riparian zone (Ghadiri et al., 2000; Steiger et al., 2001; Nicholas, 2003). Furthermore, natural streams in terms of morphology and vegetation, constrain water passage (cf. Parkyn et al., 2005; Zaimes et al., 2006; Keesstra, 2007) as channel roughness and flow obstructions are generally more prevalent. The effects of slowing flow rates results in greater opportunities for sediment deposition on the adjoining channel floodplains, and a reduction in the overall sediment yield from the catchment. In contrast, a fully channelised channel generates a significant increase in sediment yield (cf. Brooks, 1985; Nagle et al., 2007). However, these previous studies did not provide any data as to the degree of catchment sediment yield change. The simulated results in this study also do not reflect those processes described in these studies. The possible reasoning for this difference can be found within the model as it does not take into account channel flow, as sediment is routed to the river, and once it reaches the channel, it is immediately transferred to the outlet. The channel flow model HEC-GeoRAS was designed to determine the impact of channel morphology and in-channel and riparian vegetation on stream flow and sediment transport. Previous studies (e.g. Wiles & Levine, 2002; Horritt and Bates, 2002; Maingi & Marsh, 2002) have demonstrated this models effectiveness in simulating flooding events and flow velocities during peak flow events.

Modelling shows that an increase in the effect of riparian vegetation/geomorphology results in an increase in return period of the modelled peak discharge. The impact of riparian vegetation causes drag thereby reducing flow velocity. Unlike channelised flows, the floodplains of natural reaches with their broad riparian zone, has a retarding effect on stream flow (Table 2). Furthermore, the higher the flood water stage, the greater the drag due to vegetation on the floodplains of natural river reaches compared to channelised sections (Table 2). Furthermore, the natural channel cross-section can also cause a reduction in flow velocity relative to channelised sections. Slower flow rates have an impact on sediment mobilisation and transport in the river. However, determining sediment discharge (as both suspended load and bed load) is not straight forward as exactly how much sediment will be carried downstream is difficult to determine especially as the modelling depends on several sediment transport equations. The amount of sediment transported is also dependant on whether the riverine flow characteristics are transport or detachment limited. In a transport limited context, sediment and water discharge are more strongly correlated than in a supply/detachment limited system (cf. Seeger et al., 2004; Keesstra, 2007; Keesstra et al., 2007, 2009). Sediment yield is also dependant on the amount of sediment available for transport. From field observations in some of the upper reaches (Nup, Fig. 4), sediment was stored in the channel and floodplain, indicating a transport limited system. However, many downstream partly channelised reaches of the stream were clear of sediment, indicating a supply limited system. Furthermore, in a natural system (non-channelised) it can be expected that in the downstream reaches, sediment would be readily abundant (e.g. Temme et al., 2011; Keesstra et al., 2005), and thus transport limited.

Finally, the HEC-GeoRAS model only uses the impact of channel roughness to calculate river discharge and water velocity from which sediment transport is determined. However, sediment transport and supply limited situations are not taken into account and thus the impact of changing land use / land cover in the catchment cannot be incorporated into the model runs.

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References

Abernethy, B. & Rutherford, I.D., 1997. Where along a river's length will vegetation most effectively stabilise stream banks? Geomorphology 23: 55-75.

Atlas of Lower and Opole Silesia, 1997. Printed by Atlas Research Centre of Wroclaw University *http://openlibrary.org/books/OL18202674M/Atlas_%C5%9Al%C4%85ska_Dolnego_i_Opolskiego*

Arcement, G.J. & Schneider, V.R., 1990. Guide for selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains. US Geol. Surv. Water Supply Pap. 2339, 67 pp.

Brooks, A., 1985. Downstream Morphological Consequences of Rover Channelization in England and Wales. The Geographical Journal 151: 57-62.

Church, M., 1992. Channel morphology and typology. *In:* Callow, C. & Petts, G. (eds): The rivers handbook: Hydrological and ecological principles. Oxford: Basil Blackwell: 126-143.

Ducros, C.M.J. & Joyce, C.B., 2003. Environmental assessment – Field based evaluation tool for riparian buffer zones in agricultural catchments. Environmental Management 2: 252-267.

Fitzgerald, S.A., Klump, J.V., Swarzenski, P.W., Mackenzie, R.A. & Richards, K.D., 2001. Beryllium-7 as a tracer of short-term sediment deposition and resuspension in the Fox River, Wisconsin. Environmental Science & Technology 35: 300-305.

Florsheim, J.L., Mount, J.F. & Chin, A., 2008. Bank erosion as a desirable attribute of rivers. BioScience 58: 519-529. (*www.bioone.org/doi/abs/10.1641/B580608*)

FISRWG, 1998. Stream Corridor Restoration: Principles, Processes, and Practices. By the Federal Interagency Stream Restoration Working Group (FISRWG) (15 Federal agencies of the US govt). GPO Item No. 0120-A.

Gao, P., 2008. Understanding watershed suspended sediment transport. Progress in Physical Geography 32: 243-263.

Ghadiri, H., Hogarth, B. & Rose, C., 2000. The effectiveness of grass strips for the control of sediment and associated pollutant transport in runoff. *In:* M. Stone (ed.): Role of Erosion and Sediment Transport in Nutrient and Contaminant Transfer, Proceedings. IAHS Publication: 83-91.

Ghafari, G., Ghodousi, J., Ahmadi, H. & Keesstra, S.D., 2010. Investigation of the hydrological impact of land-use change in the Zanjanrood Basin, North-West Iran. Hydrological Processes 24: 892-903.

Hogan, D.L. & Bird, S.A., 1995. Channel assessment procedure. British Columbia Ministry of Environment, Lands and Parks and British Columbia. Ministry of Forests, Watershed Restoration Program, Technical Circular No. 7, Victoria.

Horritt, M.S. & Bates, P.D., 2002. Evaluation of 1D and 2D numerical models for predicting river flood inundation. Journal of Hydrology 268: 87-99.

Jones, K.B., Williams, L.R., Pitchford, A.M., Slonecker, E.T., Wickham, J.D., O'Neill, R.V., Garofalo, D. & Kepner, W.G., 2000. A national assessment of landscape change and impacts to aquatic resources: A 10-year strategic plan for the Landscape Sciences Program, U.S. Environmental Protection Agency, Office of Research and Development (EPA/600/R-00/001).

Keesstra, S.D., Van Huissteden, J., Vandenberghe, J., Van Dam, O., De Gier, J. & Pleizier, I.D., 2005. Evolution of the morphology of the river Dragonja (SW Slovenia) due to land-use changes. Geomorphology 69: 191-207.

Keesstra, S.D., 2007. Impact of natural reforestation on floodplain sedimentation in the Dragonja Basin, SW Slovenia. Earth Surface Processes and Landforms 32: 49-65.

Keesstra, S.D., Van Dam, O., Verstraeten, G. & Van Huissteden, J., 2009. Changing sediment generation due to natural reforestation in the Dragonja catchment, SW Slovenia. Catena 78: 60-71.

Kondolf, G.M., Anderson, S., Lave, R., Pagano, L., Merenlender, A. & Bernhardt, E.S., 2007. Two decades of river restoration in California: What can we learn? Restoration Ecology 15: 516-523.

Kreiter, T., 2007. Dezentrale und naturnahe Retentionsmaßnahmen als Beitrag zum Hochwasserschutz in mesoskaligen Einzugsgebieten der Mittelgebirge. (Distributed and natural retention measures as a contribution of flood protection in meso-scaled catchment areas of low mountains). PhD-Thesis from the University of Trier (Trier) Germany.

Kuhnle, R.A. & Wren, D.G., 2005. Breakout Session I, Suspended Sediment Measurement: Data Needs, Uncertainty, and New Technologies. *In:* Gray, J.R. (ed.): Proceedings of the Federal Interagency Sediment Monitoring Instrument and Analysis Research Workshop, September 9-11, 2003, Flagstaff, AZ, U.S. Geological Survey Circular 1276: 8-15.

Lane, S.N., Tayefi, V., Reid, S.C., Yu, D. & Hardy, R.J., 2007. between sediment delivery, channel change, climate change and flood risk in a temperate upland environment. Earth Surface Processes and Landforms 32: 429-446.

Lewis, D.J., Singer, M.J., Dahlgren, R.A. & Tate, K.W., 2006. Nitrate and sediment fluxes from a California rangeland watershed. Journal of Environmental Quality 35: 2202-2211.

Liangang, C., Xin, Q. & Yong, S., 2011. Critical Area Identification of Potential Soil Loss in a Typical Watershed of the Three Gorges Reservoir Region. Water Resources Management 25: 3445-3463.

Maddock, I., Petts, G. & Bickerton, M., 1995. River channel assessment – a method for defining channel sectors on the River Glen, Lincolnshire, UK. *In:* G.E. Petts (ed.): Man's Influence on Freshwater Ecosystems and Water Use. Proceedings of the IAHS Conference, Boulder, CO, July 1995. IAHS Publ. 230, 1995: 219-226.

Maingi, J.K. & Marsh, S.E., 2002. Quantifying hydrologic impacts following dam construction along the Tana River, Kenya. Journal of Arid Environments 50: 53-79.

Mizumura, K., 1989: Hydrological approach to prediction of sediment yield. Journal of Hydraulic Engineering 115: 529-35.

Nagle, G.N., Fahey, T.J., Ritchie, J.C. & Woodbury, P.B., 2007. Variations in sediment sources and yields in the Finger Lakes and Catskills regions of New York. Hydrological Processes 21: 828-838.

Newson, M.D. & Large, A.R.G., 2006. 'Natural' rivers, 'hydromorphological quality' and river restoration: A challenging new agenda for applied fluvial geomorphology. Earth Surface Processes and Landforms 31: 1606-1624.

Newcombe, C.P. & Macdonald, D.D., 1991. Effects of suspended sediments on aquatic ecosystems. North American Journal of Fisheries Management 11: 72-82.

Nicholas, A.P. & Mitchell, C.A., 2003. Numerical simulation of overbank processes in topographically complex floodplain environments. Hydrological Processes 17: 727-746.

Niezgoda, S.L. & Johnson, P.A., 2005. Improving the urban stream restoration effort: Identifying critical form and processes relationships. Environmental Management 35(5): 579-592.

Parkyn, S.M., Davies-Colley, R.J., Cooper, A.B., & Stroud, M.J., 2005. Predictions of stream nutrient and sediment yield changes following restoration of forested riparian buffers. Ecological Engineering 24: 551-558.

Rosgen, D.L., 2006. The natural channel design method for river restoration. *In:* World Environmental and Water Resource Congress 2006: Examining the Confluence of Environmental and Water Concerns, 2006.

Saavedra, C., 2005. Reservoir sedimentation assessment using acoustic geo-referenced sonar sounding and GIS. Estimating spatial patterns of soil erosion and deposition of the Andean region using geo-information techniques: a case study in Cochabamba, Bolivia (PhD thesis). ITC and Wageningen University (Wageningen), the Netherlands: 244.

Sear, D.A., 1994. River restoration and geomorphology. Aquatic Conservation-Marine and Freshwater 4:169-177.

Sear, D., Newson, M., Hill, C., Old, J. & Branson, J., 2009. A method for applying fluvial geomorphology in support of catchment-scale river restoration planning. Aquatic Conservation-Marine and Freshwater Ecosystems 19: 506-519.

Seeger, M., Errea, M.P., Beguería, S., Arnáez, J., Martí, C. & García-Ruiz, J.M., 2004. Catchment soil moisture and rainfall characteristics as determinant factors for discharge/suspended sediment hysteretic loops in a small head-water catchment in the Spanish pyrenees. Journal of Hydrology 288: 299-311.

Simon, A., Doyle, M., Kondolf, M., Shields, F.D., Rhoads, B. & McPhillips, M., 2007. Critical evaluation of how the Rosgen classification and associated 'natural channel design' methods fail to integrate and quantify fluvial processes and channel response. Journal of the American Water Resources Association 43: 1117-1131.

Steiger, J., Gurnell, A.M. & Petts, G.E., 2001. Sediment deposition along the channel margins of a reach of the middle River Severn, UK. Regulated Rivers: Research & Management 17: 441-458.

Sudduth, E.B., Meyer, J.L. & Bernhardt, E.S., 2007. Stream restoration practices in the southeastern United States. Restoration Ecology 3: 573-583.

Temme, A., Peeters, I., Buis, E., Veldkamp, A. & Govers, G., 2011. Comparing landscape evolution models with quantitative field data at the millennial time scale in the Belgian loess belt. Earth Surface Processes and Landforms 36: 1300-1312.

USACE, 2006. HEC-RAS River Analysis System User's Manual. Version 4.0 Beta, Hydrologic Engineering Center, Davis, California, 420 pp.

Vanacker, V., Von Blanckenburg, F., Govers, G., Molina, A., Poesen, J., Deckers, J. & Kubik, P., 2007. Restoring dense vegetation can slow mountain erosion to near natural benchmark levels. Geology 35: 303-306.

WDFW, 2012. Stream habitat restoration guidelines. Sediment transport appendix. Washington Department of Fish and Wildlife. *http://wdfw.wa.gov/publications/01374/*.

Wohl, E., Angermeier, P.L., Bledsoe, B., Kondolf, G.M., MacDonnell, L., Merritt, D.M., Palmer, M.A., Poff, N.L. & Tarboton, D., 2005. River restoration. Water Resources Research 41: W10301, doi: 10.1029/2005WR003985.

Wainwright, J., Parsons, A.J., Michaelides, K., Powell, D.M. & Brazier, R. (eds), 2003. Linking short and long term soil erosion modelling. *In:* Long Term Hillslope and Fluvial System Modelling. Concepts and Case Studies from the Rhine River Catchment. Springer-Verlag (Bonn), Germany.

Wiles, J.J. & Levine, N.S., 2002. A combined GIS and HEC model for the analysis of the effect of urbanization on flooding; the Swan Creek watershed, Ohio Environmental & Engineering Geoscience 8: 47-61.

Zaimes, G.N., Schultz, R.C. & Isenhart, T.M., 2006. Riparian land uses and precipitation influences on stream bank erosion in central Iowa. Journal of the American Water Resources Association 42: 83-97.