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ORIGINAL ARTICLE

A method for assessment of sediment supply and transport hazard and risk in headwater catchments for management purposes

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Abstract

Headwater streams play an essential role in catchment hydrogeomorphology while supplying water and sediment to downstream reaches along the channel network. Adaptive management strategies which require ecological rehabilitation and natural hazards prevention methods are increasingly needed to sustain ecological services provided by headwater streams. However, environmentally sound and economically effective stream management techniques depend on relevant information on boundary conditions, operating processes and evolutionary trajectories of a river system, which are often unavailable. Therefore, it is desirable to provide river managers with scientifically rigorous, yet easy to apply tools (methods) to assess channel and catchment conditions. The present paper focuses specifically on the sediment supply and transport (SST) regime, a crucial component of the fluvial system and a source of significant hazard to people and infrastructures. The SST hazard and risk assessment procedure was developed for small headwater streams with a catchment area of up to ca. 50 km^2. The method comprises two core modules. *Module 1* is designed to rapidly evaluate susceptibility to SST hazard based on four catchment variables (relief, lithology, erosion-prone surfaces, and connectivity). *Module 1* is intended primarily for river managers to differentiate between catchments and identify those with the highest probability of SST hazard. *Module 2* comprises a detailed evaluation of channel and catchment variables; thus, it is to be conducted applying basic training in fluvial geomorphology and GIS skills. *Module 2* includes five successive steps: channel network segmentation, identification of segments with vulnerable and hazardous anthropic elements, determination of the dominant mode of sediment transport, determination of SST hazard category, and calculation of SST risk score. The method was designed to balance the present-day understanding of sediment flux in the catchment-scale sediment cascades and applicability for target end-users, mostly technically educated professionals and research scientists in river mechanics and erosion and sedimentation.

Keywords Headwater stream · Sediment supply and transport · Hazard and risk assessment · Stream management

Introduction

The headwater streams play a crucial role in the sediment budget of the overall river basin. Sufficient sediment supply from headwater streams was identified as a critical variable to ensure the downstream river reaches' physical integrity and ecological functions (Gomi et al. 2002; Benda et al. 2005; Freeman et al. 2007). On the other hand, the processes related to sediment flux (e.g. debris flows, floods, floodplain erosion and aggradation) are often a source of serious hazard endangering human lives and infrastructures (Brierley et al. 2008). Although the headwater streams make up most of the river network length, their importance is often overlooked in river management. Reconciling the often-conflicting goals of sustaining an environmentally sound sediment regime and protecting the population and infrastructure from

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sediment-related hazards requires adaptive management based on a comprehensive evaluation of the source-to-sink relations in the catchment sedimentary cascade (Brierley et al. 2006; Poeppl et al. 2020).

We use the term sediment supply and transport (SST) regime to express the spatiotemporal dynamics of processes delivering sedimentary material to stream channels and transporting sediment within the stream network. Risk arises when people and infrastructures are exposed to these processes, which is a product of SST hazard and vulnerability of elements at risk. The SST hazard should not be viewed as linked solely to excessive sediment transport and deposition during flood events. Adverse effects of SST regime include processes connected with both intensive sediment transport and limited sediment availability in the channels (Fig. 1). A marked example of channel instability related to sediment scarcity is the "hungry water" phenomenon caused by valley closures and/or sediment dredging (Kondolf 1997; Kondolf et al. 2014). Yet another management issue is the gradual siltation of engineered channels with sediment in urban areas, causing lowered channel conveyance for flood flows (Shi 2005; Lane et al. 2007).

The main objective of this paper is to present a method of SST hazard and risk assessment developed for the Forest of the Czech Republic, state enterprise, which is an important river manager in Czechia. The company manages almost 38,500 km of small headwater streams, largely in forested hilly to medium–high mountain catchments. River managers often lack the appropriate tools to assess the hazard and risk associated with the sediment flux on a catchment scale. They frequently adopt a local or reach scale perspective connected to the location of endangered/vulnerable infrastructures. They dismiss the need for a holistic approach to assessing catchment-scale connectivity of hydrogeomorphic processes (Fryirs et al. 2007).

The headwater streams have been conceptualised as complex systems that evolve in response to the operation of natural and anthropogenic drivers (Knighton 1998; Wohl 2000). They are characteristic with a high degree of slope-channel coupling, diverse hillslope and in-channel sediment sources, and fluvial and non-fluvial modes of sediment transport, resulting in various SST hazards (e.g. floods with bedload deposition, hyperconcentrated flows, debris flows). In Czechia, the risk associated with debris flows is relatively low, but intensive bedload transport and significant morphological changes of channels during severe floods are relevant for this area (Bíl et al. 2015; Brázdil et al. 2019). The degree of risk associated with SST processes is enhanced by the concentration of settlements in narrow floodplains in the medium–high mountains of central Europe.

Unlike processes like flash floods or debris flows, much less attention was paid to assessing hazard and risk related

Fig. 1 Examples of critical issues associated with sediment transport management in mountain streams in Czechia. Conditions of sediment excess (photos **A**–**D**) and sediment scarcity (photos **E**–**F**). **A** Severe sediment accumulation during floods in inhabited areas, **B** jamming of culverts and flooding of roads during flood events, **C** supply of fine sediments from agricultural land to coarse-bedded streams and rivers, loss of physical habitats (e.g. fish-spawning gravels), **D** sediment deposits stabilised by vegettaion, which decreases flow capacity in inhabited areas, **E** channel incision due to the presence of impermeable barriers for sediment transport (e.g. dams or jammed culverts), **F** degradation of habitat heterogeneity due to missing coarse fractions (caused by sediment trapping by barriers and artificial bank stabilisations preventing from lateral sediment supply), loss of natural bedforms (bars, pools, riffles)

to fluvial sediment transport and deposition in headwater streams. Moreover, attention was mainly paid to high-mountain areas rather than highlands or medium–high mountains. Adopted approaches included the detection of susceptibility to sediment transport hazard by the analysis of catchment morphology (Wilford et al. 2004; Marchi and Dalla Fontana 2005), analysis of spatiotemporal variability in costs of bedload transport damages (Badoux et al. 2014), quantifying the vulnerability of buildings to fluvial sediment transport (Totschnig et al. 2011; Holub et al. 2012; Sturm et al. 2018) or analyses and simulations of individual sediment transport events (Theule et al. 2012; Liu et al. 2013; Rickenmann et al. 2016). A few approaches for sediment flux quantification and active and passive mitigation strategies have also been proposed in the past decade (Mazzorana et al. 2011, 2013; Rickenmann 2016; Hübl 2018).

The method presented here was designed as a supporting tool for identifying catchments susceptible to SST hazard and associated risk to vulnerable human infrastructures. The susceptibility to hazard and the degree of risk are classified on ordinal scales underlain by the scoring the set of variables derived by GIS analyses and field surveys. The procedure includes two basic modules. *Module 1* is intended to rapidly assess geographical setting and identify catchments with natural and anthropogenic prerequisites of SST hazard occurrence. In contrast, *module 2* is designated for a detailed evaluation of sediment sources, boundary conditions of fluvial sediment transport and existing technical measures implemented by the river managers. This paper presents constituent steps of the proposed assessment method and a case study from the Satina catchment (Outer Western Carpathians, Czechia).

Sediment supply and transport regime evaluation procedure

The proposed method of SST regime assessment was designed primarily for forested headwater streams in hilly lands to medium–high mountains with catchment areas smaller than ca. 50 km^2. These streams are characterised mainly by coarse sediment (bedload) transport. However, the high variability of environmental conditions and land use types in Czechia, spanning from agricultural lowlands to forested mountains, necessitated fine sediments (suspended load) to be considered as well. Since the method is based on GIS analyses supplemented with field surveys, it is not suitable for large catchments where personnel and/or financial constraints may limit field assessment of stream conditions.

The proposed assessment procedure consists of two interrelated modules, which differ in their purpose and degree of detail. *Module 1* is to be used by personnel of river management agencies for rapid assessment of susceptibility to SST hazard and identification of prevailing sediment transport regime (either bedload, mixed load or suspended load). *Module 1* is intended to support decision-making processes, whether the catchment needs a more detailed evaluation of the SST regime and perhaps the implementation of additional mitigation measures. *Module 1* has been designed relatively simple and not excessively time-consuming for personnel lacking a background in fluvial geomorphology.

Module 2 was designed as a supporting tool for consultant companies, which will perform detailed surveys of sediment flux conditions and evaluate the efficiency of existing measures in the catchment. The application of *Module 2* is to be carried out by personnel with the appropriate expertise in fluvial geomorphology and sufficient skills in GIS software. While *Module 1* requires only a combination of data extracted from online databases, *Module 2* includes field evaluation of channel forms and processes.

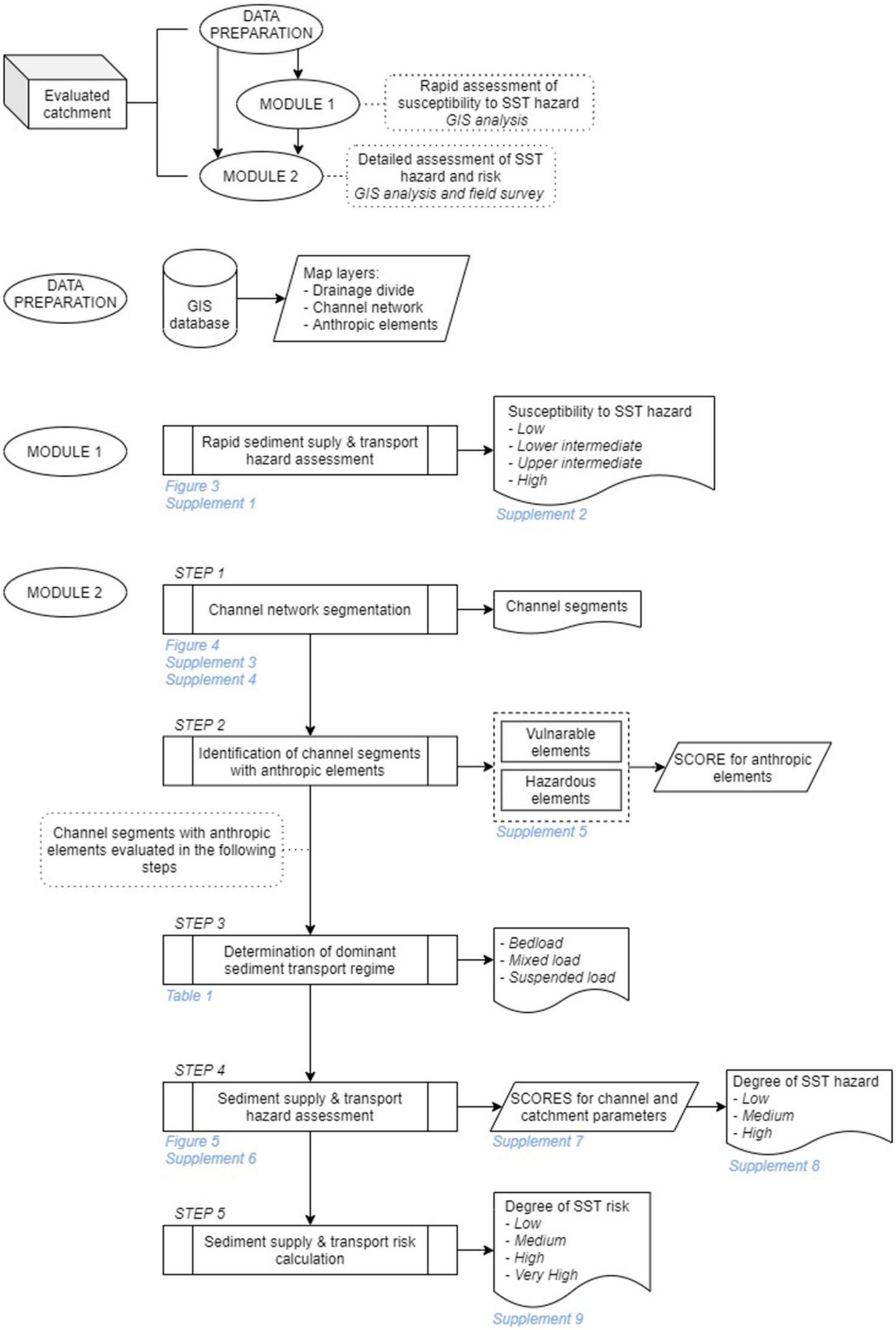
Major steps of the procedure are reported in Fig. 2 and synthetically described in this section. The assessment of susceptibility to SST hazard based on analysis of catchment relief, lithology, land cover and connectivity of erosion-prone surfaces to channel network is performed in *Module 1*. *Module 2* includes five consecutive steps: channel network segmentation, identification of vulnerable channel segments with anthropic elements, determination of dominant sediment transport regime in vulnerable channel segments, assessment of SST hazard degree, and calculation of risk arising from SST hazard.

Module 1: rapid assessment of susceptibility to SST hazard occurrence

Module 1 is an optional step in the proposed procedure, which includes the evaluation of environmental prerequisites governing the SST regime (Fig. 3). An analysis of general catchment properties precedes the detailed assessment of SST hazard and risk. The overview survey among a large number of managed catchments may serve river managers to better allocate the catchments with the enhanced sediment flux and the highest probability of SST hazard occurrence. Relative relief, lithology, and land cover are generally accepted variables governing the sediment production in river basins (Richards 2002; Liébault et al. 2005). Additionally, active hillslope sediment sources may also be identified (e.g. debris flows, arable land affected by water erosion connected adjacent to streams). These catchment characteristics are primarily responsible for the character of sediment load in streams, whether bedload, suspended load or mixed load (Schumm 2007).

Basin relief is a variable dictating the intensity of hydrogeomorphological processes (Slaymaker 2006). Dimensionless Melton ruggedness number (Melton 1958) was used to characterise the dissection of basin relief.

Fig. 2 Workflow of the procedure of sediment supply and transport hazard and risk assessment in headwater catchments



Lithology is a crucial factor affecting the amount and properties of solid load in stream channels (Lecce 1991; Bloomfield et al. 2011). The definition of lithological control over the SST regime was based on rock genesis, strength (degree of lithification), and grain size. Land cover was categorised according to the relative proportion of erosion-prone surfaces (mainly arable soils affected by heavy water erosion) connected to the channel network. The presence of active landslides, debris flows or gullies physically connected to the channel network may be withdrawn and analysed from the existing databases (e.g. field mapping campaigns, aerial images, DEMs). For a detailed description of basin relief, lithological, land cover and connectivity categories, see Supplement 1.

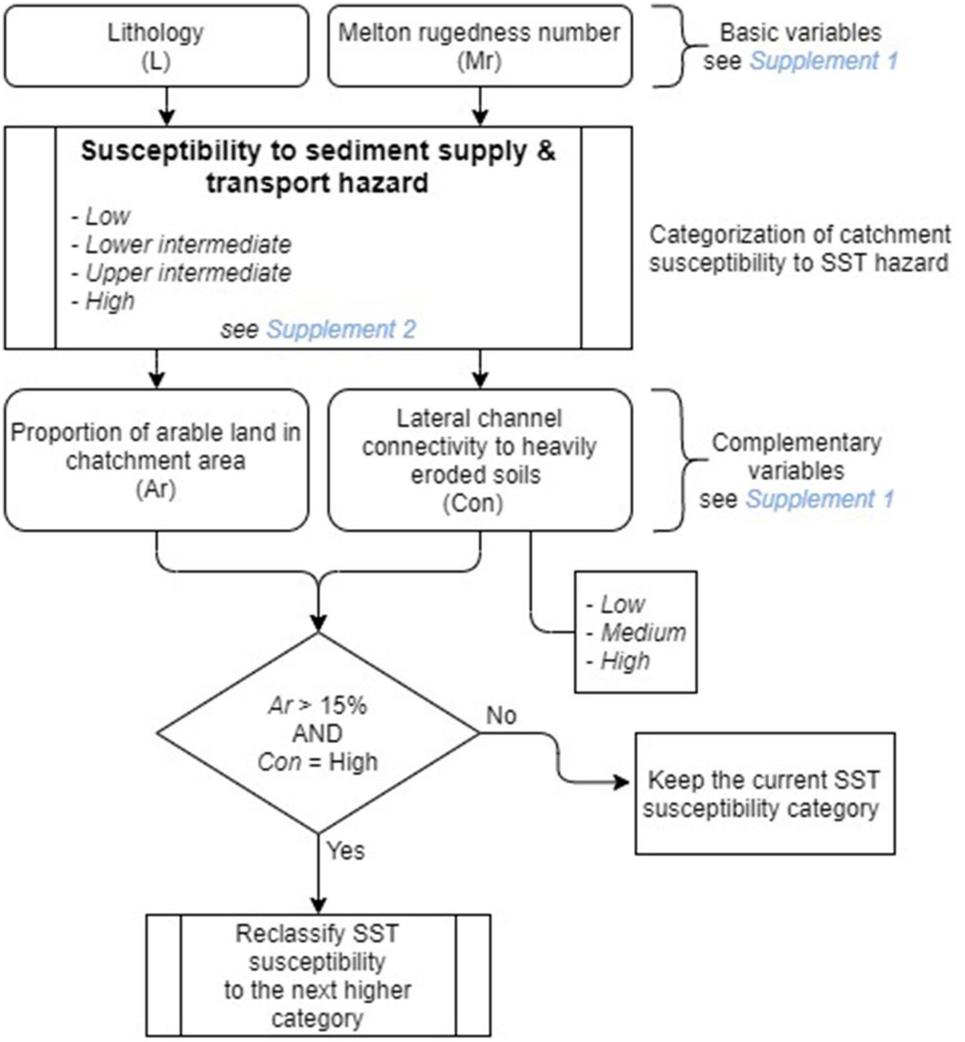


Fig. 3 Workflow for rapid assessment of catchment susceptibility to sediment supply and transport hazard within *Module 1*

The interpretation of these variables in relation to the potential sediment production and susceptibility SST hazard is included in Supplement 2. In the first step, each catchment is classified into four categories according to Melton ruggedness number and lithological class. In the second step, catchment land cover and connectivity of erosion-prone surfaces to the channel network are evaluated. If the area of arable land exceeds 15% of the catchment area and the connectivity of erosion-prone surfaces to the channel network is determined as high, the catchment is reclassified to the next higher category. The high proportion of arable land and its physical connectivity to streams may also indicate a potential problem with the siltation of channels and floodplains with fine sediment. Evaluation of the land cover and connectivity of arable land to streams is indicative of whether bedload or suspended load dominates the stream transport regime. The catchments most susceptible to SST hazard (categories 3 and 4) are to be the subject of detailed assessment within *Module 2*.

Module 2: detailed assessment of SST hazard and risk

Step 1: segmentation of the channel network

In step 1, the channel network is subdivided into relatively homogeneous segments, along which the determining boundary conditions do not change significantly (i.e. channel confinement by valley slopes, channel gradient and dimensions, water discharge, channel bed grain size etc.). The identified channel network segments serve as elementary spatial units for assessing SST hazard. The segmentation is based on information derived from the DEM and field surveys integrated into the GIS database.

The segmentation is a hierarchical process including three consecutive levels of channel network fragmentation with a different degree of detail (Fig. 4):

Level 1 division according to the lateral channel confinement by valley slopes.

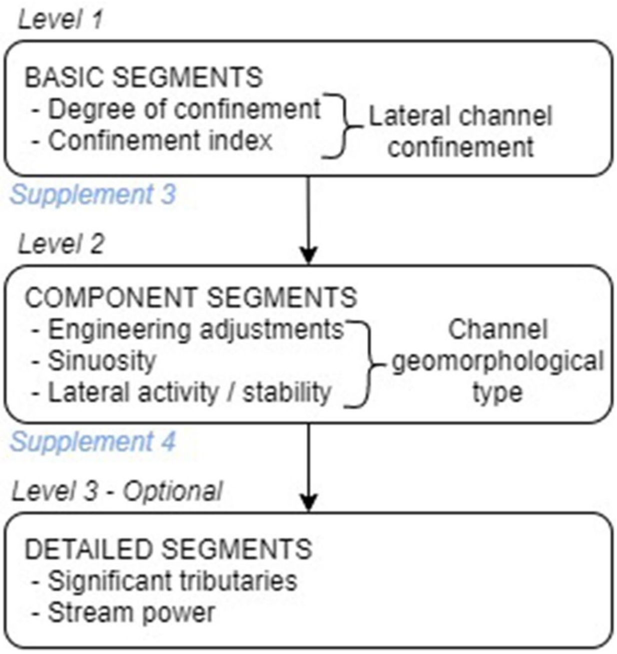


Fig. 4 Overview of the method for channel network segmentation

Level 2 division according to the channel pattern, at this level the influence of both engineering modifications and natural channel structures are taken into consideration.

Level 3 division is applied if high internal variability of level 2 segments is apparent; a set of the predefined channel and floodplain parameters is used for the segmentation.

At level 1, three categories of lateral confinement are differentiated: channels confined, partly confined, and unconfined by valley slopes (Brierley and Fryirs 2005). The modification of the method described in Rinaldi et al. (2013) is followed for channel confinement classification. Channel confinement is defined by the combination of the "degree of confinement", that is, the proportion of the channel length with the direct contact with hillslopes or river terraces (O'Brien et al. 2019), and "confinement index", which is defined by the ratio between the floodplain width and the channel width (Nagel et al. 2014). Therefore, the resulting channel confinement category integrates the longitudinal extent of the contact between channel banks and hillslopes and the lateral extent of the floodplain (see Supplement 3).

As the channel network in Czechia shows a considerable degree of human modification, the initial division into engineered and natural sections is conducted at level 2. Different guidelines are followed for the classification of engineered and natural sections of channels. While engineered sections are divided into three categories according to the character and extent of channel modification, natural sections are classified according to channel pattern and lateral channel instability (Supplement 4).

At level 3, the detailed division of the channel network may be conducted according to significant discontinuities in channel forms and processes. As discontinuities in the functioning of stream channels are brought about primarily by changes in discharge and sediment load, the junctions with significant tributaries and the location of closure dams are used for a division at level 3. Only tributaries with considerably large catchment areas or high expected sediment loads should be considered for the division of a channel to separate segments. The actual effect of tributaries upon the trunk stream forms and processes should be verified in the field.

Step 2: delimitation of anthropic elements at risk

In step 2, vulnerable and hazardous human anthropic elements along the river network are defined and delimited. The definition of vulnerable anthropic elements endangered by SST hazard depends on societal priorities (Murphy and Gardoni 2007; Hewitt 2013). Furthermore, we define hazardous anthropic elements, which are poorly designed human infrastructures (e.g. non-capacity culverts and bridge profiles, piped stream reaches), which become barriers to sediment transport during floods (cf. Fig. 1). Within the presented assessment method, the urbanised areas (municipalities) are considered the primary anthropic elements at risk, representing large concentrations of residential, recreational and commercial areas, transport infrastructures, and other public utilities. As a rule, the extent of urbanised areas located along the channel network needs to be defined. Fewer anthropic elements may be found in rural areas. However, features like scattered residential or commercial buildings, transport corridors, and electricity lines aligned with stream channels are other examples of endangered infrastructures outside of municipalities. At this step, each delimited segment is assigned a vulnerability score according to the presence or absence of the vulnerable and hazardous human infrastructures (Supplement 5).

Step 3: determination of dominant sediment transport regime

When the identification of channel segments containing anthropic elements at risk is completed, the assessment of SST hazard for those segments follows in step 3. Here, we define SST hazard as an excessive, unwanted sediment deposition in a section of the stream channel. This situation occurs when the sediment supply exceeds the stream transport capacity. Since the different approaches to evaluating sediment sources and transport conditions for coarse and fine sediments are required, identifying the dominant character of the sediment transport regime (either bedload, mixed load or suspended load) is performed before SST hazard assessment (Table 1).

Step 4: assessment of SST hazard

The SST hazard classification is designed as a three-level: low, medium and high degree of hazard. The classification is based on the evaluation of the set of variables related to the assessed channel segment and the adjacent segment located upstream. These variables reflect sediment sources, channel morphodynamics, stream power, and engineering adjustments; the selection of variables differed between streams transporting prevailingly bedload or suspended load (Fig. 5, Supplement 6). A matrix of possible combinations of the variable's status values in the lower and upper segments is created for all evaluated variables. Each combination in the matrix is assigned a numerical score (Supplement 7). The degree of SST hazard is then calculated as a sum of partial scores of individual variables (Supplement 8).

Step 5: assessment of risk arising from SST hazard

Finally, segments with anthropic elements at risk are ranked according to the degree of SST risk. Risk is generally defined as the product of interference of natural hazard with vulnerable human infrastructures (Panizza 1996). Processes related to the SST regime become a risk when their economic and/or social impacts exceed a certain threshold. The degree of risk may be calculated according to the general equation:

$$R = pL^x,$$

where R is the degree of risk, p is the probability of the hazard occurrence, and L is the potential damage caused by the hazard. Greater weight is usually assigned to the vulnerability parameter (L) in the equation; the weight is then given by the value of the exponent ($x > 1$). The exponent x may be changed flexibly according to the value assigned to vulnerable infrastructures affected by the SST hazard. Lower values of R represent a lower degree of risk and vice visa. In our approach, the resulting risk is the simple product of the

Table 1 Guidelines for the evaluation of the prevailing transport regime (bedload, mixed load and suspended load) of the evaluated stream channel segment

Bedload transport regime	> 3/4 segment length show > 90% proportion of coarse-grained sediments on the wetted perimeter (> 0.250 mm grain size fractions; medium, coarse and very coarse sand, gravel, pebbles, cobbles, boulders)
Mixed load transport regime	The segment shows 10–30% proportion of fine-grained sediments on the wetted perimeter
Suspended load transport regime	> 3/4 segment length shows > 30% proportion of fine sediment on the wetted perimeter (< 0.250 mm grain size fractions; fine and very fine sand, silt, clay)

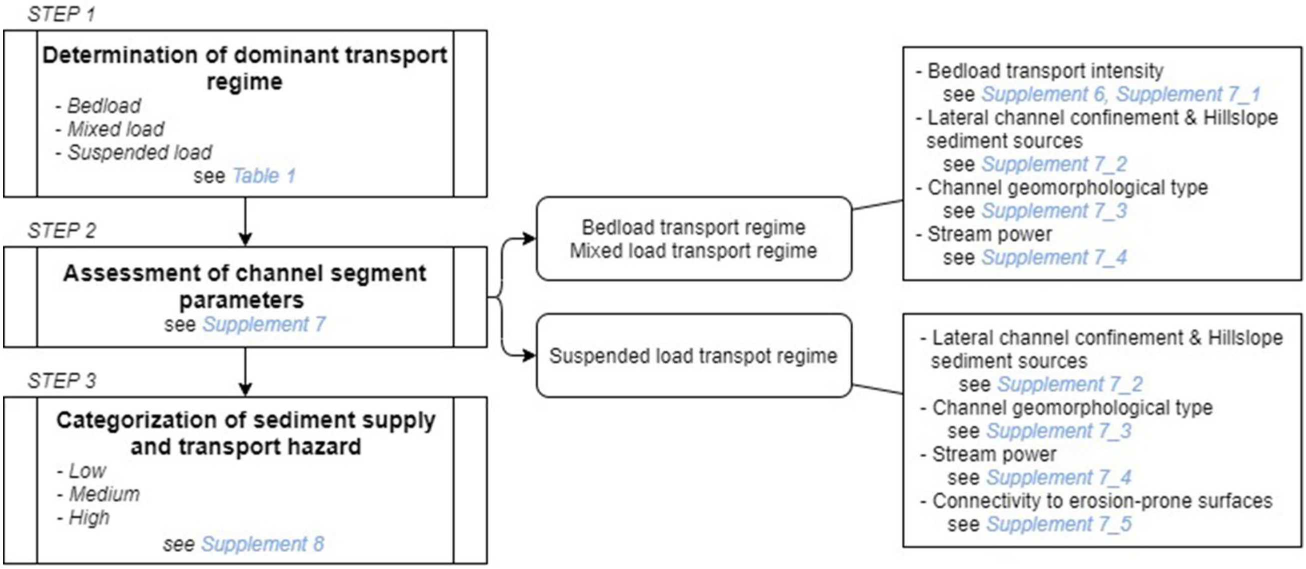


Fig. 5 Overview of catchment and channel variables used for sediment supply and transport hazard assessment in streams with bedload and suspended load transport regimes

scores assigned to SST hazard in step 2 and scores assigned to elements at risk in step 3 (Supplement 9).

Since the method is designed for catchment-scale surveys rather than for local risk studies, the exact calculation of potential economical/societal damages expressed in monetary units is not incorporated in order to maintain reasonable simplicity and time efficiency. An example of the procedure applied in the Satina catchment located in the Beskydy Mts. (Outer Western Carpathians) may be found in Fig. 6.

Discussion and conclusions

The proposed sediment supply and transport assessment method was designed to support the practical management of small headwater streams in hilly land to medium–high mountain landscapes of Czechia. However, since the proposed method is not a rigid set of rules but rather a flexible procedure, it may be applied and tested in other countries with a similar geographical setting. The overall design of the method follows a series of consecutive steps, including the rapid identification of catchments with potentially high sediment production and susceptibility to SST hazard (*Module 1*), followed by a detailed assessment of sediment supply and transport conditions in the catchments with the highest susceptibility to SST hazard (*Module 2*).

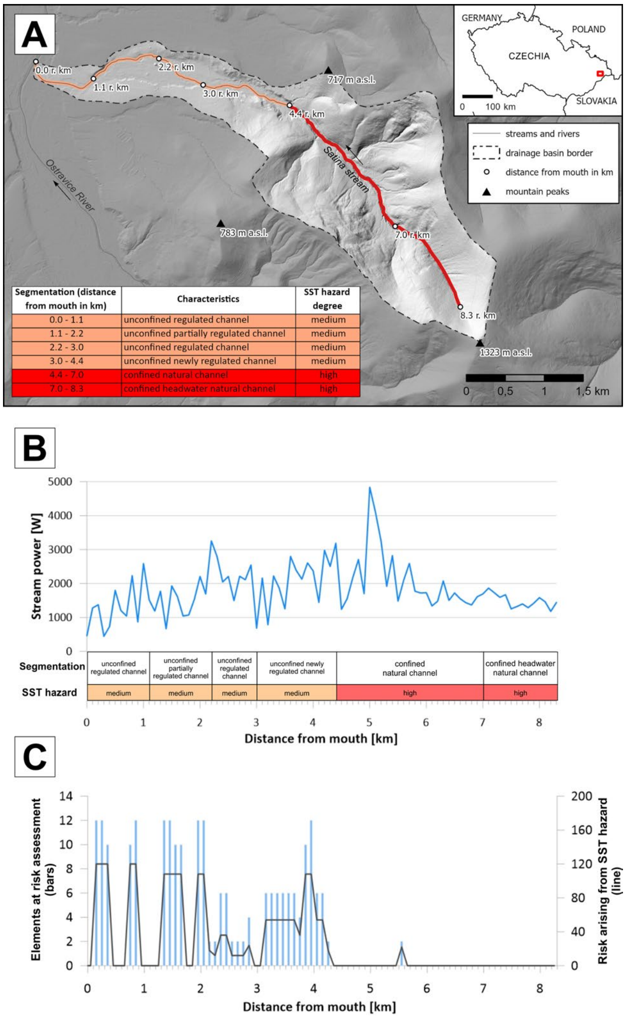


Fig. 6 An example of channel network segmentation in the Satina catchment (the Beskydy Mts., Outer Western Carpathians) with hazard and risk assessment

The method is based on an expert judgement of the set of catchment and stream channel variables and delimitation of anthropic vulnerable and hazardous infrastructures. The elementary spatial unit used for the SST hazard assessment is a channel network segment along which hydraulic, geomorphological, and sedimentological variables do not change significantly. A similar procedure of hazard assessment based on the evaluation of homogeneous channel segments was used by Hooke (2003), Parker et al. (2015) and Wohl (2016).

Since channel reaches are open entities functioning within the river continuum, the damage related to sediment transport hazard results from both processes operating in the stream reach itself and processes operating in the adjacent reaches further upstream. That is why the controls of the SST regime (sediment sources, stream power, and engineering adjustments) are assessed not only in the evaluated channel segment itself, but also in the adjacent segment(s) located farther upstream. Here we follow the approach adopted by Bizzi and Lerner (2015) and Parker et al. (2015), who evaluated the sensitivity of stream channels to erosion and deposition by analysing the upstream–downstream changes in stream power.

The application of the method (at least *Module 2*) is to be carried out by personnel with the appropriate expertise in fluvial geomorphology and sufficient skills in GIS software. That is not always the case for river management authorities and consultancy companies, in which professionals with technical education still prevail. As a result, present-day engineering adjustments of headwater streams in Czechia often represent an immediate response to extreme hydrogeomorphological events rather than the outcome of a conceptual catchment-scale assessment of sediment sources and stream channel morphodynamics.

An inadequate understanding of source-to-sink relations in the catchment sediment cascade often results in sediment control measures (e.g. retention check dams, embankments) implemented even in stream reaches with limited sediment sources and low intensity of sediment transport. Engineering adjustments constructed at the turn of the nineteenth and twentieth centuries are still repaired and maintained in some places despite the shift towards the condition of limited sediment supply (Galia 2021). Therefore, the proposed SST assessment method based on the holistic understanding of the catchment sediment cascades will hopefully stimulate the prolific knowledge exchange between river managers, consultancy companies, and academic experts on practical issues of fluvial sediment transport management. From the river authorities' point of view, the main issue is that the scientifically sound SST regime assessment may substantially reduce the financial costs of stream management targeted to reduce risk related to fluvial sediment transport.

The limitation of applying the holistic approach to SST risk management may also be a lack of expertise in fluvial geomorphology among technically educated river managers. For example, the current management of headwater streams in Czechia focuses on mitigation against hazards connected with intensive sediment transport and rapid morphological changes. In contrast, consequences related to sediment deficit are somewhat overlooked. Moreover, on some occasions, sediment deposition during a flood outside inhabited areas is technically considered "flood damage", which should be "repaired", and prevention measures (e.g. construction of check dams or embankments) should be implemented. As a result, technical measures causing unwanted off-site responses (e.g. upstream knickpoint migration, downstream sediment starvation) are frequently introduced in the natural stream reaches (Galia and Hradecký 2014; Galia et al. 2016, 2017).

The method was designed to balance the present-day academic understanding of solid load flux in the catchment-scale sediment cascades and applicability for target end users, mostly technically educated professionals from river authorities and consultancy companies. As a result, the presented procedure is a compromise between scientific rigour and practical applicability. Some indicators of sediment supply and transport processes may thus appear to be too simplified. Mainly, *Module 1* is based on a limited number of catchment variables considered critical for sediment production and supply to stream channels. *Module 1*, therefore, may be used with caution only for the rapid prioritisation of catchments with a potentially high level of sediment production and sediment transport hazard. Similarly, *Module 2* is not designed for an in-depth quantification (modelling) of the sedimentary budget and its temporal evolution. Instead, it relies on expert evaluation of GIS or field-based indicators of current conditions of sediment supply and transport. Despite its relative simplicity, the presented method may serve as a supporting tool for more environmentally sound and economically effective decisions on the management of headwater streams in hilly to medium–high mountain environments.

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Author contribution All authors contributed to the conception and design of the proposed sediment supply and transport hazard assessment method. Václav Škarpich and Tomáš Galia performed the case study in the Satina catchment. The first draft of the manuscript was written by Zdeněk Máčka and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability All data generated or analysed during this study are included in this published article (and its Supplementary Information files).

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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