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A TOOLBOX FOR SEDIMENT BUDGET RESEARCH IN SMALL CATCHMENTS

ABSTRACT. Sediment monitoring and assessment remain one of the most challenging tasks in fluvial geomorphology and water quality studies. As a response to various environmental and human disturbance effects, the main sources and pathways of the sediments transported within catchments, especially most pristine small one, may change. The paper discusses state-of-the-art in the sediment budget research for small catchments. We identified nine independent approaches in the sediment transport assessment and applied them in 11 catchments across Eurasia in the framework of an FP – 7 Marie Curie – International Research Staff Exchange Scheme in 2012-2016. These methods were classified as: i) Field-based methods (In-situ monitoring of sediment transport;– Soil morphological methods and dating techniques; Sediment source fingerprinting; Sediment-water discharge relationships), ii) GIS and remote sensing approaches (Riverbed monitoring based on remote sensing/historical maps; parametrization of the channel sediment connectivity; Sediment transport remote sensing modeling), and iii) Numerical approaches (Soil erosion modeling and gully erosion (stochastic and empirical models); channel hydrodynamic modeling). We present the background theory and application examples of all selected methods. Linking field-based methods and datasets with numerical approaches, process measurements as well as monitoring can provide enhanced insights into sediment transfer and related water quality impacts. Adopting such integrated and multi-scale approaches in a sediment budget framework might contribute to improved understanding of hydrological and geomorphological responses.

KEY WORDS: sediment budget, suspended sediment, erosion processes, erosion modeling

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INTRODUCTION

Sediment monitoring and redistribution assessment for the different parts of fluvial systems remain one of the most challenging tasks in fluvial geomorphology and water quality studies. As a response to various environmental and human disturbances, the main sources and pathways of sediments transported through a catchment, especially small ones which are regarded to be the most pristine, may change. Sediment transport in and to river channels is strongly influenced by climatic conditions, particularly when heavy precipitation and warmer climate triggers fluvial processes.

Even though the importance of sediment budgets as a universal conservation law modification has been widely accepted (Alexeevsky et al. 2013), there are still no generally applicable procedures to establish a comprehensive sediment budget for a catchment (Walling and Collins 2008). Ongoing work by the authors has focused on the developing and testing of various methods and integrating them in a general approach («integrated») (Walling et al. 2001). This «integrated» approach combines some complementary techniques. They have been properly analyzed and classified according to the available tools, spatial resolution, and methodological steps, as well as in respect to an acceptable range of results.

The recent studies were carried out within an EU FP-7 project entitled: «Fluvial processes and sediment dynamics of slope channel systems: Impacts of socio economic-and climate change on river system characteristics and related services, (FLUMEN)». The project was aimed at setting up empirical experiments and modeling tests in various catchments and environments distributed over Eurasia to understand the contemporary landform evolution and sediment redistribution within river basins up to the sediment transport from the land to the ocean (in relation to mountain areas). Therefore, we identified commonly used techniques based on a detailed literature review. Moreover, we applied some of these methods and present the results achieved in the case study catchments. Generally, we provide a comprehensive classification of the available methods and techniques namely the sediment budget toolbox.

METHODS AND FLUMEN CASE STUDY CATCHMENTS

This paper intends to give an overview of complementary and comparative tools and techniques that can be used as a toolbox for future studies in various environments of Eurasia. We aimed at identifying applicable techniques that can be jointly used as a toolbox in different environmental situations. We selected the following catchments representing different environmental characteristics: i) Mongolian steppes (Kharaa), ii) volcano region at Kamchatka peninsula (Sukhaya Elizovskaya), iii) tundra of Koryak Mountains at Kamchatka (Vetvey), iv) periglacial environment on the Scandinavian peninsula (Tarfalajokk) and v) North Caucasus mountains (Dzhankuat), vi) Ukrainian Carpathian flysch mountains (Black Tisza), vii) dry and wet subtropics (San-Leonardo) and viii) Tsanik rivers, ix) arid Zagros mountains in Iran (Mazayjan), x) Sakhalin island (Langeri) and xi) Intra-Apennine Central Italy (Mugello) (Fig. 1). Implications of applying different available tools to understand the sediment budgets of a particular catchment are explored using data from these 11 catchments across Eurasia. All available tools can be split into three main groups according to the data types:
i) field-based and monitoring methods;

ii) geographic information system (GIS) and remote sensing analysis
iii) numerical approaches (catchment and in-channel modelling)
Among them, the following 11 tools will be discussed in detail (Table 1):
(i) Field based methods
1 – In-situ monitoring of sediment transport;
2 – Soil morphological method and dating techniques;
3 – Sediment source fingerprinting;
4 – Sediment-water discharge relationships;
(ii) GIS and remote sensing analysis
5 – Riverbed monitoring based on remote sensing/historical maps;
6 – parametrization of channel sediment connectivity;
7 – Sediment transport remote sensing modeling;
(iii) Numerical approaches
8 – Soil erosion modeling and gully erosion (stochastic and empirical) models;
9 – channel hydrodynamic modeling.

Field-based and monitoring methods

In-situ monitoring of sediment transport

In-situ sediment monitoring remains the main method to characterize erosion within catchments as well as sediment transport in

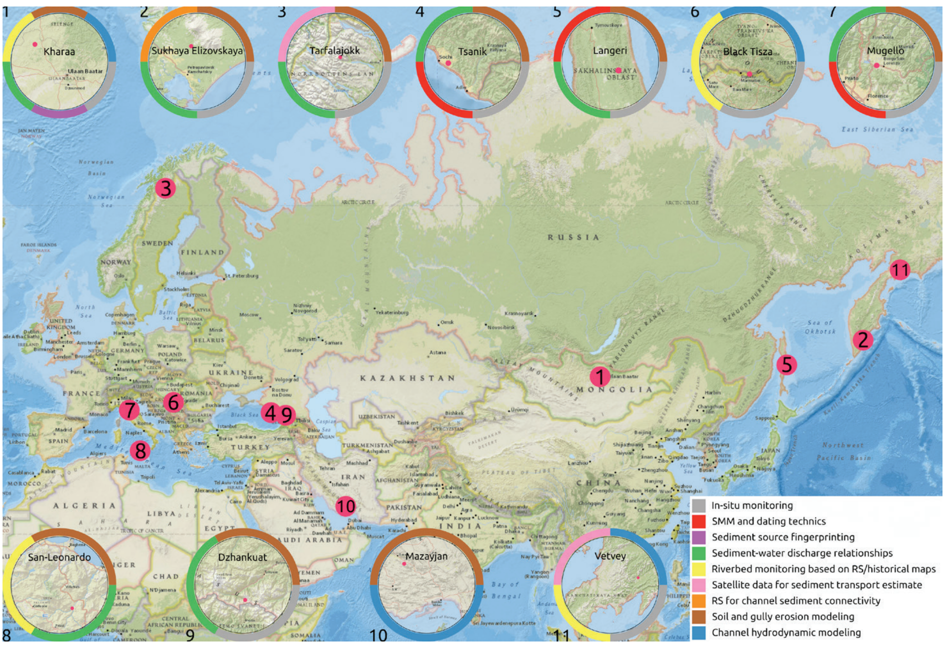

Fig. 1. Map of case study sites and used methods

the river network. The recent technologies have been drastically improved and this leads to the relatively wide range of direct and surrogate technologies for In-situ monitoring of sediment transport. Various approaches have been tested in the case study catchments (Kharaa, Sukhaya Elizovskaya, Vetvey, Tarfalajokk, Tsanik, Langeri, Black Tisza, Mugello and Dzhankuat river basins). Based on this, we developed a classification of approaches of sediment load (suspended and bed) monitoring including acceptance criteria for Suspended-Sediment Concentrations (SSC) (following (Gray and Gartner 2010)), accuracy and monitoring strategy (Table 2).

Suspended load monitoring is based both on traditional gravimetric analyses as well as advanced technological capabilities where bulk optic (turbidity), laser optic and acoustic backscatter principles are widely used and applied in the present study (Table 2). In all cases, the usefulness of the surrogate information obtained depends heavily on the existence of a close relationship between fluctuations in SSC and surrogate parameters and the calibration procedure that relates SSC to the used variable. Turbidity is an expression of the optical properties of a sample that causes light rays to be scattered and absorbed

Table 1. Case studies and used methods

River	Area	Watershed area, km^2	Methods applied (according to the text)								
			1	2	3	4	5	6	7	8	9
Kharaa	Mongolia. Selenga River basin	11 345	+	-	+	+	+	-	-	+	+
Sukhaya Elizovskaya	Russia, Southern Kamchatka, Avacha riv. Basin	174	+	-	-	+	-	+	-	+	-
Tarfalajokk	Sweden, Scandinavian mountains, Kebnekaise massif	6.7	+	-	-	+	-	-	+	+	-
Tsanik	Russia, Black sea coast, Sochi	12.1	+	+	-	+	-	-	-	+	-
Langeri	Russia, Sakhalin island	1 343	+	+	-	+	-	-	-	+	-
Black Tisza	Ukrainian Carpathia	965	+	-	-	-	+	-	-	-	+
Mugello	Italy, Florenze	375	+	+	-	+	-	-	-	+	-
San-Leonardo	Italy, Sicily	253	-	-	-	+	+	-	-	+	-
Dzhankuat	Russia, Northern Caucasus, Terek riv. basin	9.1	+	-	-	+	-	-	-	+	-
Mazayjan	Iran, Zagros Mountains	900	-	-	-	-	-	-	-	+	+
Vetvey	Russia, Norten Kamchatka, Koryak Plateau	181	+	-	-	-	+	-	+	-	+

rather than transmitted in straight lines through the sample. Turbidity is a measurement unit for quantifying the degree to which light is penetrating through a water column that in turn is scattered by the suspended organic (including algae) and inorganic particles. Laser diffraction instruments exploit the principles of small-angle forward scattering. Pressure differential instruments measure mass density in a water column, thus integrating substantially more streamflow than a point measurement. Acoustic Doppler profilers use acoustic backscatter to measure suspended sediment concentrations in much higher stream orders than do instruments that rely on point measurements.

Bed load still remains one of the most poorly explored components in the fluvial system. Monitoring approaches consist of direct and surrogate measurements. In our study, different types of bedload samplers were used to characterize bed load in small mountain streams (Table 2): Box or basket samplers, pan or tray samplers, pressure-difference samplers, and trough pit samplers. Box samplers intercepted particles due to a reduction in flow velocity (Gray et al. 2010). Pan or tray samplers retain the sediment that drops into one or more slots after the sediment has rolled, slid, or skipped up an entrance ramp. Pressure-difference samplers are designed so that a sampler's entrance velocity is about the same as the stream velocity. Additionally, acoustic Doppler current profiles (ADCP) were used to estimate apparent bed velocities and ultimately to infer bedload-transport rate according to a method described by (Guillermo et al. 2017).

Soil morphological methods and data techniques

Quantitative assessment of soil losses and sediment deposition can be evaluated based on a comparison of soil profiles of undisturbed soil, that formed under given climate conditions with soil profiles after the beginning of cultivation. Erosion and deposition processes lead to soil profile transformations and detailed descriptions of soil profiles allow to quantitatively evaluate the soil losses or gains. Depending on the soil type the decrease of thickness in the A_{plough}, A_1, AB and/or B horizons in cultivated areas can be used to estimate the total soil loss or gain for the entire period of cultivation for different positions along the slope (Belyaev et al. 2005; Larionov et al. 1973; Olson et al. 2008; Rommens et al. 2005). The accuracy of the method, also called as soil morphological method (SMM), can also be refined by choosing different geomorphic locations for the survey pits (Kiryukhina and Serkova 2000; Rommens et al. 2005).

Limitations of this approach are often associated with variations in natural soil horizon thickness in particular for mountain conditions because of microclimatic and lithology differences. However, it has been shown that in case of severe soil losses this variation is less than that due to erosion (Belyaev et al. 2005; Larionov et al. 1973; Rommens et al. 2005). Besides, it is necessary to know the total duration of cultivation for a particular site in order to correctly calculate the mean annual soil loss or sediment gain for the entire period of cultivation. In case of areas with a relatively short history of intensive cultivation, like the Great Plains in the USA, the southern part of the Russian Plain or Australia information might be available in form of archive data. It is more difficult to identify the period of cultivation for a site with a longer history of anthropogenic influence. In this case, some archeological methods and dating techniques are helpful. The buried soil method is widely used for the evaluation of total deposition for a given agriculture period, in particular in case of dry valley bottoms or river floodplains (Alexandrovskiy et al. 2004; Knox 2001). The applicability of this method considerably increases during last decades because of serious progress in dating techniques (Notebaert and Verstraeten 2010).

Most sediment dating techniques were initially elaborated for the evaluation of sedimentation rates in lakes, reservoirs and sea bottoms (Appleby 2008). However, they are also applied for the evaluation of contemporary sedimentation rates of other terrestrial sediment sinks (cones, dry valley bottoms, river floodplains).

There is a range of dating techniques available, but the most widely used can be split into two groups: i) application of fallout radionuclides and ii) substances contained in the sediments (Table 3). Radionuclides, such as Lead-210 (210Pb, $t½=22.3$ y) and Cesium-137 (137Cs, $t½=30.2$ y), are the most widely-used and reliable methods employed to calculate short-term (years to decades) sediment deposition and accumulation rates in fluvial environments (Appleby and Oldfieldz 1983; Belyaev et al. 2011; Belyaev et al. 2013; Du and Walling 2012; Golosov 2009; Golosov et al. 2010; He and Walling 2003; Mizugaki et al. 2006; Owens and Walling 2002; Ritchie et al. 2004; Ritchie and McHenry 1990; Walling 1999). Generally, 210Pb dates are confirmed using 137Cs profiles, when the 137Cs profiles are sufficiently intact (Appleby and Oldfieldz 1983; Du and Walling 2012).

Recently it is possible to use bomb-derived 137Cs as a tracer for the identification of sedimentation rates since 1963 (maximum fallout) and in some cases between 1959-1963, because in particular in 1958-59 a second maximum of bomb-derived 137Cs fallout was observed. In addition, for the most parts of Europe it is possible to use Chernobyl-derived 137Cs for dating (Golosov 2000; Leenaers 1991; Walling et al. 1998). So, recently in case of using both bomb-derived and Chernobyl-derived 137Cs it is possible to evaluate e.g. overbank sedimentation dynamics for relatively homogeneous time intervals (1963-1986 and 1986-sampling time) (Du and Walling 2012; Golosov et al. 2010). However, in areas with very high Chernobyl contamination levels usually it is not possible to identify any bomb-derived peak. Also, the 1986 peak can not

Table 2. Sediment monitoring approaches applied for different fluvial systems of the FLUMEN project

Approach	Suggested acceptance criteria and measurement requirements	Suggested monitoring strategy	Advantage	Disadvantage	Examples of application (Reference)	Example of application among case studies (according to Table 1)
Suspended load (SSC)						
Gravimetric analyses	The mass of the filtered sediment should be comparable with filter mass	Used for calibration of surrogate technologies	Direct parameter of SSC	routine collection and analysis of water samples	(Minella et al. 2014; Piper et al. 2006)	Kharaa, Sukhaya Elizovskaya, Tarfalajokk, Tsanik, Langeri, Black Tisza, Mugello, San-Leonardo, Dzhankuat
Bulk optic (turbidity), backscatter	SSC acceptance criteria range from ±50% uncertain-ty at lowest SSCs to ±15% uncertainty for SSC's exceeding 1 g/L.	affordable time series data		existence of a close relationship with fluctuations in SSC which are differed between rivers and in time	(Göransson et al. 2013; Gray and Gartner 2010)	Kharaa, Sukhaya Elizovskaya, Tarfalajokk, Tsanik, Langeri, Black Tisza, Mugello, San-Leonardo, Dzhankuat
Laser optic		affordable time series data	Obtaining both suspended concentrations and grain sizes		(Gray and Gartner 2010)	Sukhaya Elizovskaya, Tarfalajokk

Acoustic backscatter		SSC distribution at the reaches of high probability of local (profile) spatial variability	Provide a profile (vertical and horizontal) of the	Applicable only for large rivers, requires existence of a close relationship with fluctuations in SSC	(Chanson et al. 2008)	Kharaa
Bedload						
Box or basket samplers			Easy field installation	Influenced by flow fields		Sukhaya Elizovskaya, Dzhankuat
pan or tray sampler			Easy field installation	Influenced by flow fields		Sukhaya Elizovskaya
pressure-difference samplers			Easy field installation	Influenced by flow fields		Kharaa, Sukhaya Elizovskaya, Tarfalajokk, Tsanik, Langeri, Dzhankuat
ADCP	apparent velocity of particles at the bedload layer as resulting by comparing the ADCP's velocity from its capability to acoustically track the bottom and from accurate GPS recording			Dependence on instrument frequency, acoustic pulse length used and site-specific properties, such as riverbed composition and bedforms presence	(Guillermo et al. 2017).	Kharaa

Table 3. Dating techniques used for evaluation of sedimentation rates in different fluvial sinks

Dating technique	Decay	Age range	Advantage	Disadvantage
fallout radionuclides				
^{7}Be (0.14 yr)	63 days	<0.6 yr	Event base, easy to measure	Need to measure reference systematically, to be collected very soon after deposition event
Fukushima-derived ^{137}Cs	30.2 years	Peak March 2011	Clear peak with fix time	Local scale, can be applied only in Japan
Chernobyl-derived ^{137}Cs	30.2 years	Peak May 1986	Clear peak with fix time	Regional scale, can be applied in parts of Europe
Bomb-derived ^{137}Cs	30.2 years	Peaks 1958/59 and 1963/64	One clear peak, distribute across the Earth	Now low value in Southern Hemisphere, difficult to identify
^{241}Am	432.6 years	Peaks 1963/64	Allows to identify bomb-derived ^{137}Cs peaks from others	Precision has still to be improved, expensive
^{238}Pu	87.74 years		Can be used instead bomb-derived ^{137}Cs	It still need to improve the precision, expensive
$^{239+240}Pu$	$2.411 \cdot 10^{4}$ and 6 564 years	Peaks 1963/64		
$^{210}Pb_{ex}$	22.3 year	1-130 years	Useful for identification of deposition rate dynamics for the last 130 year in case of application with other FRN	Improvement of measurement accuracy is still needed
material in deposits				
^{14}C	5.7 kyr	100 yr–50 kyr	Relatively simple to collect	insufficient accuracy for the assessment of contemporary sedimentation rates, expensive
Optically simulated luminescence	-	50 yr–100 kyr	Detail dating of sedimentation rates for few time intervals	It is necessary to have quarzitic sand deposits, expensive
Fly ash	-	100-150 years	Cheap analytical equipment	labor-intensive and time-consuming method of analysis

be determined in case of very low fallout of Chernobyl-derived 137Cs even in the North of the European part of the Russian Plain.

The application of the SMM in the Langeri river for floodplain in the downstream part of the basin allows to evaluate the mean annual net accumulation for the last 50 years in the range of 2.3±0.6 mm/year (≈200 t/year), that are in fitting well with assessments of sediment budget using other methods (Chalov and Tsyplenkov 2016).

SEDIMENT SOURCE FINGERPRINTING

Another tracing technique capable of providing useful information to assess catchment sediment budgets is the fingerprinting approach. Sediment source fingerprinting can generate valuable information on the relative importance of individual potential sources contributing to the downstream suspended sediment flux of a river. Such information is clearly of considerable value both providing information on the linkages between upstream sediment sources and downstream sediment yield. It allows sediment budgeting and a more precise sediment control as well as related measures and thus optimizing the effectiveness of such work in reducing downstream sediment fluxes. Moreover, the source fingerprinting technique has been successfully deployed to investigate spatial sediment sources, classified in terms of discrete geological zones (Collins et al. 1998) or tributary sub-catchments (Collins et al. 1996). Information on individual source types e.g. surface soils characterized by different land use and eroding channel banks (Collins et al. 1997; Motha et al. 2004; Walling 1999) are valuable especially in a management context. The fingerprinting approach is based on the link between geochemical properties of sediment and those of its sources. The assumption is that the potential sediment sources can reliably distinguish by their geochemical properties «fingerprints». Thus, the provenance of the sediments can be established by comparing its properties with those of the sources, using a numerical mixing model coupled with uncertainty analysis.

This method was successfully adopted to the Kharaa river basin, where the identification of the contributing sources showed a dominance of riverbank erosion to the total suspended sediments at the outlet. Riverbank erosion contributed 74.5% to the total load, whereas only 21.7% originated from surface erosion and 3.8% from gully erosion (Theuring et al. 2013). By the way, in the upper parts of the catchment in average 63.8 % of the SS originated from riverbank erosion and 36.2% from surface erosion. However, in spring 2011, when snowmelt occurred in combination with strong precipitation, surface erosion contributed with 53.9% (Theuring et al. 2013). This indicates that an elevated contribution of suspended sediments from surface erosion to the sediment load was mainly associated with increased precipitation.

Sediment – water discharge relationship

In natural river systems, sediment transport hysteresis can be observed to varying extents (Fan et al. 2012; Lawler et al. 2006); thus, sediment discharge is variable for similar or equivalent water discharges. Furthermore, sediment concentration (SC) – water discharge (Q) hysteresis loops can vary from clockwise to anti-clockwise. Clockwise hysteresis loops occur when the SC peak arrives before the Q peak. The SC is then generally greater during the rising limb of a flow hydrograph than during the falling limb. Clockwise hysteresis loops are often related to the depletion of readily available sediment sources and the associated dilution of suspended sediment concentrations (Bača 2008). High SC-Q skewness can occur when the bed load constitutes a considerable portion (>30%) of the total sediment load (Alexeevsky 1998), such as in the presence of large in-channel sediment sources (e.g., submerged bars). Anti-clockwise hysteresis loops occur when the sediment delivery to the river channel is limited at the beginning of an event. These loops can, for instance, be associated with catchment processes that delay the sediment delivery from the upper portions of a river basin (Hughes et al. 2012). For instance, anti-clockwise loops can be a result of the delivery of fine-grained material from disturbed floodplains, including mining sites (Chalov 2014).

The SC–Q relations in rivers are typically governed by multiple and relatively complex processes (Hudson 2003; Lawler et al. 2006; Lefrançois et al. 2007), such as hillslope erosion within catchment areas (Nadal-Romero et al. 2008; Runkui et al. 2010), sediment wave dispersion (Bull 1997), upstream floodplain sedimentation (Asselman and van Wijngaarden 2002) or an abrupt erosion of river banks (Lefrançois et al. 2007). In many cases, the net effect of such varied processes is quantified empirically based on historical observation data. Commonly, these relations take the power law form:

$$SC = aQb \qquad (1)$$

where a and b are regression coefficients (Asselman 2000). However, the above-mentioned hysteresis effects cause scatter in the empirical datasets, which must be understood and considered to enable dependable predictions for river system management. A primary challenge is therefore to identify key governing processes and their relative contribution to such hysteresis, particularly at large-catchment scales, where many of the processes are less well investigated or understood than at smaller scales (Alexeevsky 1998; Williams 1989).

The SC–Q relations built for the Sukhaya Elizovskaya river show different types according to the location of the gauging station. For example, in the upper stream where the river characterizes by incised channels with rifles and waterfalls the SC-Q relation type is taking the form of a simple linear regression. However, in the middle reach where channel type changes to wandering the SC-Q relation changes to figure-to-eight hysteresis pattern. Downstream, in the lower part of the basin due to the flattening of a longitudinal profile (Chalov et al. 2017) the channel as such disappears and the water flows in a laminar way like a sheet erosion. In this area, the SC-Q relation has an anti-clockwise pattern with a rapid rise event, with a slight sediment lag resulting in a narrow anti-clockwise loop.

GIS ANALYSIS, REMOTE SENSING AND HISTORICAL MAP ANALYSIS

Channel planform dynamics based on remote sensing/historical maps

A widely accepted approach for assessing the role of in-channel processes in sediment transport is related to the evaluation of channel planform dynamics based on remote sensing/historical maps. The approach based on a detailed reconstruction of channel changes requires a significant number of measurements of one or more channel features (e.g., channel width, bed elevation, sinuosity, braiding intensity) over a specific time period. The number of measurements generally depends on available data (e.g., aerial photos, topographic data, data from gauging stations) and defines the quality of reconstruction, which is the temporal detail of the evolutionary trajectory.

To identify the main morphological changes of Black Tisza River and also to assess the most unstable river reaches, remote sensing data and detailed topographical maps were used for a time period that covers more than 100 years. The research time frame goes back to 1869, when during the third military survey detailed maps on a scale of 1:75 000 were obtained. These maps are indicating the closest natural conditions of the river without a significant anthropic intervention. Other maps used were the result of geodetic surveys during the Soviet Union period: scale 1:100 000 (edition 1976), scale 1:10 000 (edition 1992) and satellite data from 2013. Using ArcGIS analysis, main hydrographic, geomorphologic and morphometric characteristics of Black Tisza and its tributaries were obtained based on ASTER Global Digital Elevation Model (DEM) (NASA LP DAAC 2015). The resolution of the DEM (30 x 30 m/pixel) was not detailed enough to identify the precise location of the main channel that is why it was not taken into account for the channel morphologic dynamics.

A comparison of WorldView 2 and Landsat 7ETM+ satellite images in the downstream part of Langeri river for 2012 (WorldView 2, 2012-06-16) and 2015 (Landsat 7ETM+, 2015-07-20) years made it possible to assess channel planform dynamics. As a result, we got total

Fig. 2. Landform dynamics of the Langeri River in 2012-2015

erosion area that amounts to 0.145 km^2 for a period from 16.06.2012 to 20.07.2015. This corresponds to a streambank erosion rate of 1 593 060 kg/year.

Parametrization of in-channel sediment connectivity

The mentioned approach (6) is closely related to the understanding of structural and functional sediment connectivity in a long time span for the migrating river channels via remote sensing applications. The methodology consists of and represents the identification of flood periods as well as data processing (e.g. (Kidová et al. 2016)) and is based on different steps. First of all, it is a discrimination of bank-attached and mid channel gravel bar areas as potential sediment sources and stores in GIS. Secondly — we estimated the potential connection links between bars based on the Euclidean distance in GIS and the calculation of probabilities. Then we identified the type of connectivity based on an estimation of balance between accreted and eroded areas of bars or floodplains followed by a process-based interpretation of structural connectivity for different flood periods as well as for single channel reaches.

In case of braided and anabranching channels the identification of the main processes that are conditioning different forms of the sediment connectivity is based on the assessment of the balance between accreted (ΔS_2) and eroded (ΔS_3) areas by overlaying the braidplain components polygons in two consecutive time horizons t–1 and t.

$$K_1 = \frac{\Delta S_1}{S_{t-1}} \qquad (2)$$

$$K_2 = \frac{\Delta S_2}{S_{t-1}} \qquad (3)$$

$$K_3 = \frac{\Delta S_3}{S_t} \qquad (4)$$

where $K_{1\text{-}3}$ – and additionally ΔS^1 represent unchanged area within floodplain polygons (Fig. 3).

The application of the approach revealed spatial discrepancies of the connectivity patterns in different river systems. Such methodology was applied to the Sukhaya Elizovskaya river which has an anabranching channel in the upper reach (Fig. 3). Rapid filling and release of the shallow underground aquafers of the lahar deposits induce such

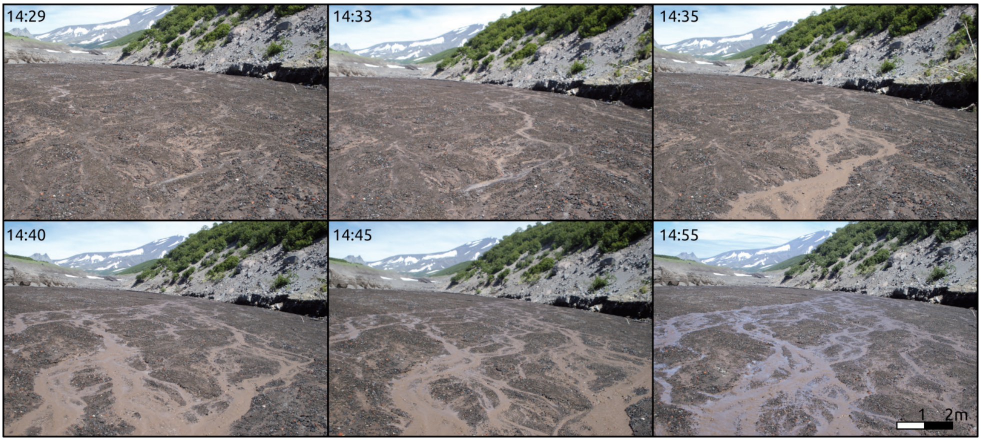

Fig. 3. Short-term planform changes of the Sukhaya Elizovskaya river

branches (Chalov et al. 2017). This short-term changes in water and consequently sediment discharges are common within river sections of lahar valleys (Mouri et al. 2014). They represent most unstable and highly dynamic types of channel planforms.

Sediment transports remote sensing modeling

Using of satellite images for SSC assessment presents a new way to study flow and sediment dynamics. Only a few works have been done yet about the application of the remote sensing for SSC in streams. Most of them deal with reservoirs, estuaries and seas. Experiments in the estuary of the Pearl River (China) (Chen et al. 2009) found negative regression model between water turbidity and reflectance at 570 nm (maximum correlation spectral band between 350 and 2500 nm) $R_{570.}$ The best fit relationship was

$$T = -439.52 \times R_{570} + 22.9 \qquad (5)$$

where T, R_{570} are the degree of turbidity (in Nephelometric Turbidity Unit, NTU), surface water reflectance at 570 nm, respectively. It resulted from an increase of organic matters in the suspended solids. The best model for water turbidity in the Guadalquivir River explained 78% of variance in ground-truth data and included as predictors band 3 (630–690 nm), band 5 (1550–1750 nm) and the ratio between band 1 (450–520 nm) and band 4 (760–900 nm) (Bustamante et al. 2009). For the Tawa Reservoir (Choubey 1997) simple linear regression analyses shows that LISS-I band 3 (0.62±0.68 mm) is the best for correlations of turbidity and radiance values:

$$T = -078 \times band3 + 5.73 \qquad (6)$$

Multiple regression equations have higher correlations (r = 0.91):

$$T = -42.82 + 1.79 \times (band1 + 2 + 3) + 3.67(band1 + band3) \qquad (7)$$

In our experiments in the rivers of the Vetvey basin it was found that even raw data DN (pixel values in bands measured in digital number, dn) could be used to estimate SSC. That suits necessity to expand data on unstudied rivers, which are taken by the same image with rivers covered by field measurements. According to differences in SSC=f(DN) variables we classified streams with low (light color) and high (dark color) human impact. Even low-quality images are a useful instrument for stream monitoring providing the information on larger areas. The general range of digital numbers for clear streams was found from 1 to 120 dn, for streams polluted by mining activity – >120 dn.

We estimated the limits of the streams that could be studied through remote sensing application. 5.8 m resolution of the ISR-P6 images provides necessary information to study streams with a width not less than 10 m (5 pixels per channel width). For the narrow creeks (1-2 pixels per channel width) a quantitative calculation of SSC is impossible because of reflectance intensity transformation caused by the morphology of shallow streams. The problems to make

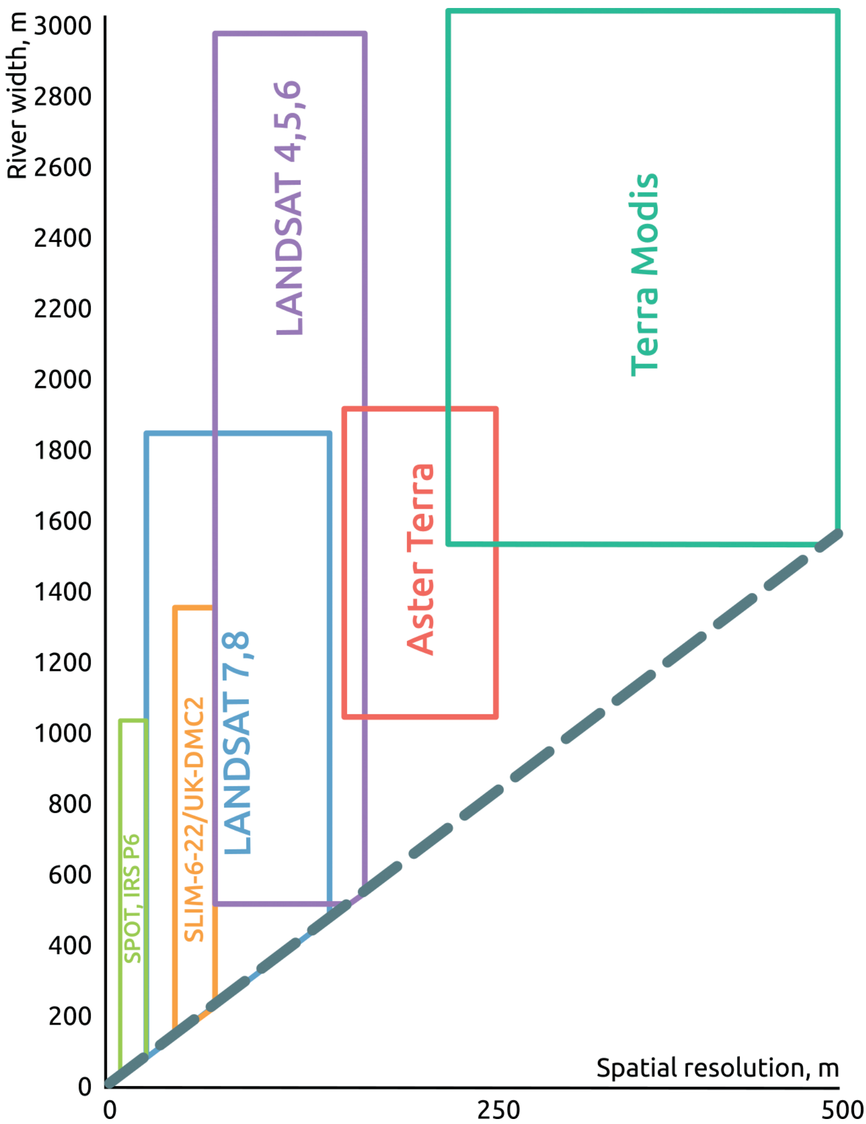

Fig. 4. Spatial limits of RS application in sediment concentration analyses

a calculation of water turbidity occur also at shallow braided reaches especially those characterized by alluvial fans. The suspended load monitoring of small rivers should be provided by higher resolution remote sensing.

NUMERICAL APPROACHES (CATCHMENT AND IN-CHANNEL MODELING)

Soil and gully erosion modeling

In the last decades, significant progress has been made to understand water erosion in general and gully erosion in particular in terms of the controlling factors and associated processes. However, many research questions remain, concerning the most predominant type of water erosion and/or the role of the human impacts and climate change on soil loss in different landscapes or modeling units. Hence, the prediction of areas with higher susceptibility to specific types of water erosion, and in particular gully erosion, is crucial and a key information for a proper land use management in many parts of the world. However, the quantitative and qualitative assessment of gully features has been widely neglected and thus, the estimation of erosion and quantification of sediment production is always limited (Kumar and Kushwaha 2013).

Although there are many models for evaluating water erosion rates (Flanagan and Nearing 1995; Merritt et al. 2003; Poesen et al. 2003), most of these models are physical based that need detailed input data and are difficult to apply on large areas. The application of different soil erosion models and soil conservation methods varies in their context, purpose, and degree of detail and therefore, the most suitable model depends on the proposed use, and the characteristics of the basin being considered. The numerical models for the assessment of water erosion can be classified in physically based models, stochastic models and empirical models. According to the different model approaches, users have to select specifically the relevant input data and processing techniques, depending on their expertise, local conditions and data availability (Conoscenti et al. 2008; Karydas et al. 2013).
In the Mazayjan catchment of Central Zagros Mountains we applied different approaches to identify and quantify especially gully erosion processes and their contribution to the general sediment budget. Using the Erosion Response Units (ERU) concept (Märker et al. 2001) we generated a susceptible map for the entire Mazayjan catchment area based on a detailed terrain analysis and a stochastic approach. We used the Maxent model (stochastic mechanics) (Zakerinejad and Märker 2014) to identify gully susceptible areas that later on were used in the quantitative approach. For this study 12 topographic indices that included: elevation, slope, aspect, analytical hillshading, plan and profile curvature, curvature classification, convergence index, altitude above channel network, catchment area, stream power index, length-slope factor have been used to predict gully erosion applying the Maxent model. As depended variable gully areas mapped in Google Earth were used. The approach allows the assessment of the potential spatial distribution of gullies in the Mazayjan catchment. We applied a combined approach using the USPED (Mitasova et al. 1996) model together with a SPI (Stream Power Index) index based approach to assess the gully areas in the Mazayjan catchment in the southwest of the Zagros Mountains in Iran. We show that sediment production and transport by gully erosion is not considered in traditional «sheet erosion» models like RUSLE, USPED or WEPP. However the proposed approach allows for a detailed quantification of sediments produced by gully systems.

For the Tsanik and San-Leonardo river basins the erosion rates have been computed through an indirect assessment based on the application of the Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1997). In both basins the most eroded land use/land cover type are agricultural lands. During wet years the San-Leonardo erosion rates are twice as high as the Tsanik basin but in dry years these difference is lower or inverse – The Tsanik basin erosion rates are 9% higher. The same situation appears in forested areas - in wet years in Sicilian basin erosion rates are 1.5 times higher than in dry years where they are two times lower (Tsyplenkov et al. 2017). The spatial distribution of net annual erosion rates for the San-Leonardo and the Tsanik rivers have been carried out with a RUSLE modeling approach illustrated in Fig. 5.

HYDRODYNAMIC MODELING

According to various observations, the river channel often controls the sediment transport by acting as the main source of the material during high flow events (David et al. 2012; Petticrew et al. 2007). In most river systems, in-channel sediments are stored for a relatively short time in comparison to material accumulated, for instance on floodplains (Walling et al. 1998). On the other hand, in-channel bed storage, which is depleted after even the most extreme flow events, can also be replenished in a relatively short time (Ciszewski 2001). Thus, the exchange of sediments on a channel bed can be very dynamic under transient flow conditions. The dynamics of in-channel storage of sediments control the variability in sediment yield of a catchment. It is because bed erosion/deposition processes within a channel contribute to the evolution

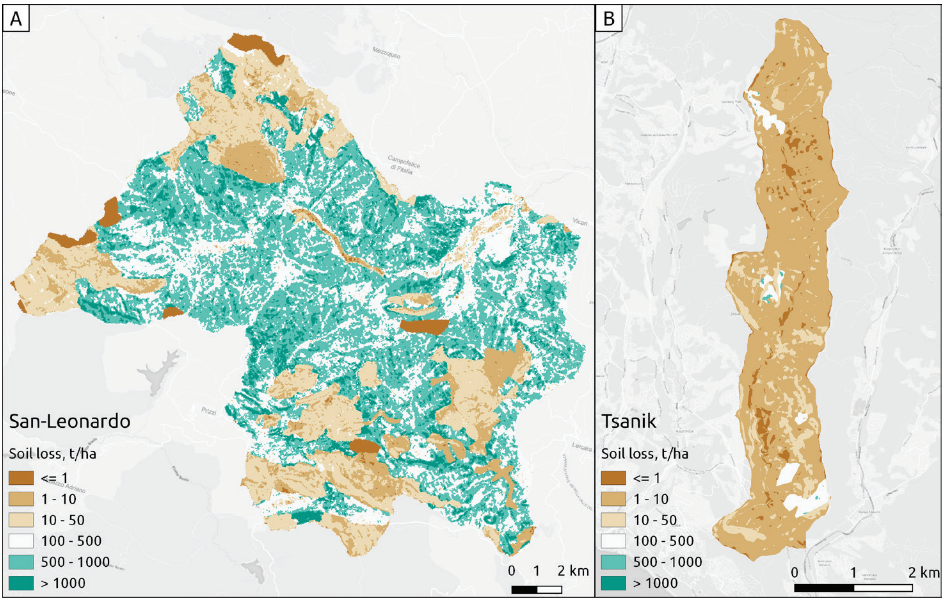

Fig. 5. Application of erosion models for San-Leonardo (A) and Tsanik (B) river basins (net annual soil losses, t/ha)

of the difference between upstream and downstream sediment loads and concentrations (Owens et al. 1999; Smith 2003).

Due to limited information available on the nature of channel changes, numerical simulation remains the main tool providing a certain amount of sediment washed due to in-channel changes or stored in river channels. Flow phenomena in natural rivers are three-dimensional, especially those at or near a meander bend, local expansion and contraction, or a hydraulic structure. Sophisticated numerical schemes have been developed to solve truly three-dimensional flow phenomena.

Most sediment transport models are one-dimensional, especially those used for long-term simulation of a long river reach. However, one-dimensional models are not suitable for simulating truly two- or three-dimensional local phenomena.

In the autumn of 2014 field surveys were conducted along the whole 51 km reach of Black Tisza River. Using modern geodetic (GPS Sokkia GRS 1 and a dumpy level Leica Sprinter 150) and hydrometric equipment (current meter), morphological parameters of the channel-floodplain zone were determined; stream velocity and water runoff measurements were conducted, as well as granulometric analysis (sorting method) of the bed-load was undergone. Hydrological data regarding the water flow was collected from the hydrometric gauging station in Yasynia village. Hydraulic modeling using one-dimensional HEC-RAS software was performed for floodplain delineation and in order to obtain streamflow characteristics during flood peak discharges.

Forecasting assessments in terms of the HEC-RAS hydraulic model for the section of the lower reach of the branched channel of one of the Vetvey tributaries, with complete cessation of placer platinum mining in 2014 taken into account, showed that vertical deformation of the longitudinal profile was responsible for the input of 300 to 1000 t/year to the river channel (Chalov et al. 2015).

Zero-dimensional modeling was performed by using «SedimentLoad» for Langeri and Vetvey rivers. This model builds a SSC longitudinal profile. Based on river morphology obtained from SRTM DEM and field measurements we found that at a distance of less than 2 km from the source (platinum deposit in Vetvey basin) occurs mass deposition with an average accumulation rate up to 3 mm/day.

DISCUSSION: COMPILING THE TOOLBOX

A range of different research methods to investigate and quantify soil erosion, sediment transport and sediment input have been applied to nine case study catchments located over various environments over Eurasia domain. A range of state-of-the-art 11 methodological approaches was tested and compared, resulting in a set of most effective methods that can be used for a reliable and cost-time effective assessment of fluvial sediment transport and sediment sources at the catchment scale (Fig. 6).

Based on the general analyses of deliverables, constraints and experience, we identified schematically the analytical framework of sediment budget tools (conceptual framework). This consists of (a) identification and mapping of catchment sediment sources on the certain sub-basins; (b) quantification of the contribution of sediment source areas by processing remote sensing and auxiliary data in a GIS framework; (c) detailed investigation and processing of the sediment transport data for the evaluation of the contribution of various sub-basins; (d) carrying out the balance calculation and developing the sediment budget. The resulting sediment budget equation consists of 3 independent estimates of catchment, in-channel and delta equations. The delivery from the catchment ΔW is related to the identification of *i* sediment sources, located within the catchment (both slope wash and gullies): $\sum A_i$ or related to the upstream in-channel sources $\sum C_i$ and compared with the sediment load at the sub-basin outlet W_H:

$$\sum A_i + \sum C_1 - W_H = \Delta W \tag{8}$$

In-channel sediment budget is most effectively used for the downstream part of the catchments where the contribution of in-channel sources is of crucial importance. The resulting balance is related to k channel patterns units where due to sediment connectivity increase (erosion) or decrease (channel storage) sediment transport ΔW may occur (Alexeevsky et al. 2013):

$$\left(\sum A_i + \sum C_i\right)_{\Gamma\Lambda} + \sum_{j=1}^{j}\left(\sum A_i + \sum C_i\right) \pm \sum_{k=1}^{k}(\Delta W) - W_H = \Delta W \tag{9}$$

The assessment of significant changes of sediment transport along bifurcation deltaic areas is limited by constraints in monitoring of independent channels and thus, requires additional approaches to test the sediment budget (Chalov et al. 2017). Combination of catchment, in-channel and delta approaches with respect to available tools enables to construct a conceptual framework of a catchment sediment budget toolbox, finally allowing to built a catchment-scale sediment budget model.

The proposed methodology allows the application of field data, collected and provided by the above-mention methods and techniques to assess different erosion types, sediment redistribution, sediment transport and the sediment budget. The selection of an optimal set of methods and approaches for the evaluation of contemporary sediment budgets in river basins, allow for an assessment of extreme events in terms of sediment redistribution and problems like the selection of the appropriate temporal scale to study the evaluation of sediment budgets. It offers a unique possibility to estimate total sediment budget for the catchments. In the case study of Lange River (Russia, Sakhalin island) we applied methods 1, 4 and 8 in order to reveal the contribution of various catchment and in-channel processes in a river network affected (Table 4). In this particular case, the combination of various approaches including soil inventories allows for the classification of mass fluxes based on different grain sizes. We observed a significant increase of sediment delivery from the catchment due to gold mining processing. The results indicate the deposition of around 1000 t/day of sediments during flood events in the downstream section of the river which in turn is described by 137Cs analyses of the floodplain cores with 2.3±0.6 mm/year rates.

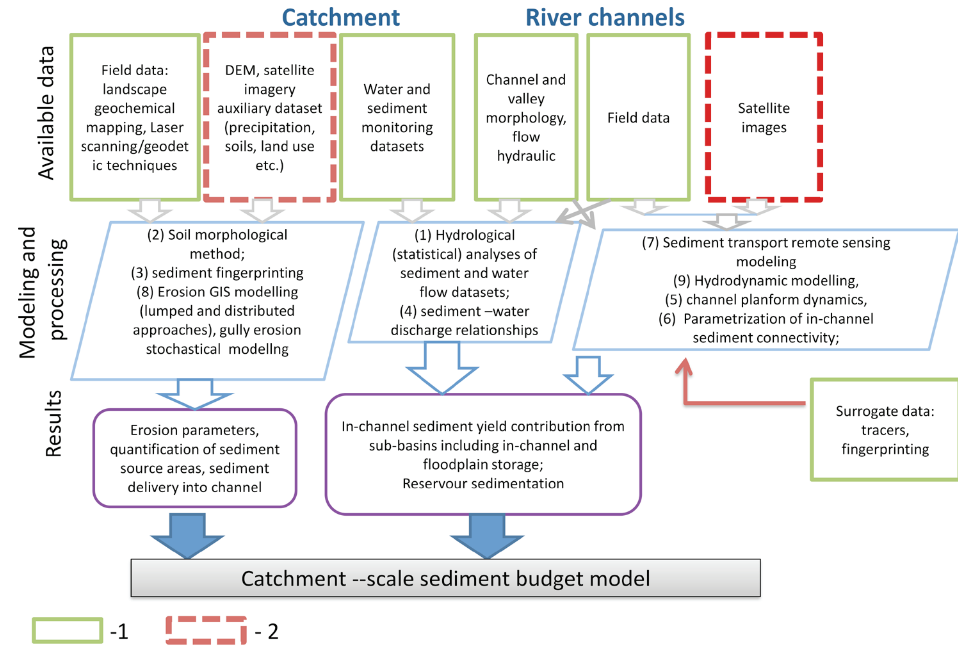

Fig. 6. Conceptual framework of catchment sediment budget toolbox (1 – field-based datasets; 2 – GIS and RS datasets)

Table 4. Integrated sediment budget assessment for Langeri River basin (for the summer period - from June to August)

Grain size class	Sediment discharge at the outlet downstream station, t	Sediment delivery from catchment, t	Sediment delivery from eroded banks, t	Sediment deposition on the floodplain, t
< 0.001 mm	4361	5881	414	43.1
0.001 – 0.5 mm	8722	865	589	61,3
> 0.5 mm	2907	1911	589	61,3
Total	14537	8657	1593	165

CONCLUSION

Between 2012 and 2016 we set up empirical experiments and modeling tests in a various catchment of different scales and environments located over Eurasia to understand i) the contemporary landform evolution and ii) sediment redistribution within the river basins up to iii) the sediment transport from the land to the ocean. The results of the investigations allowed to give an overview of complementary and comparative tools and techniques that can be used as a toolbox for future studies in various environments of Eurasia. In this paper we present the methodologies grouped according to the type of data collection: i) field methods; ii) GIS and remote sensing analysis; iii) numerical approaches. They are integrated within the general framework, that finally allows a comprehensive approach for sediment budget assessment.

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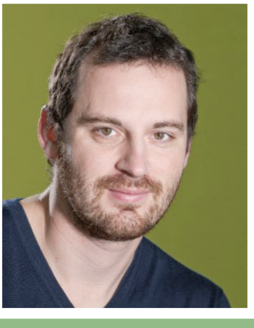

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