EKONOMIA I ŚRODOWISKO • 3 (66) • 2018

Ewa **SZALIŃSKA** • Paweł **WILK**

SEDIMENT QUANTITY MANAGEMENT IN POLISH CATCHMENT-RIVER-SEA SYSTEMS – SHOULD WE CARE?

Ewa **Szalińska,** Prof. – *AGH University of Science and Technology*
Paweł **Wilk,** PhD– *Institute of Meteorology and Water Management, Section of Modeling Surface Water Quality*

Correspondence address:
Faculty of Geology, Geophysics and Environmental Protection
Mickiewicza street 30, Kraków, 30-059, Poland
e-mail: eszalinska@agh.edu.pl

ABSTRACT: The continuity of sediment transport in many catchment-river-sea systems worldwide has been disturbed by anthropogenic interferences. These interferences alter the sediment balance and result either in a surplus or lack of sediment, and with mostly negative, impacts to the economy, development and infrastructure, and environment. The main issues discussed related to surplus or lack of sediment belongs to: i) siltation of reservoirs with negative effects on hydropower production or water storage, and ii) erosion at downstream reaches where sediments are essential for channel formation and aquatic habitats. Both problems are recognized in Poland, however, only dealt with when they cause local economic problems. The paper focuses on examples of sustainable sediment managements in catchment-river-sea systems, and presents the idea of combining the Macromodel DNS with the SWAT module. The resulting modelling and analytical tool can be considered very valuable in sediment quantity management.

KEY WORDS: sediment, quantity, management, catchment

No. 3(66) 2018 • pages: 25-37

JEL: Q25, Q57

Introduction

Recent years have brought about a gradual change in the approach to sediments and a growing understanding of their role in aquatic environments. Not more than two decades ago, the sediment research and management efforts were mainly site-specific, undertaken when sediment quality or quantity posed a nuisance forbeneficial uses, or risk to health or the environment (Apitz, 2012). Coarse and fine sediments are natural and essential components of ecosystems, providing habitat and substrate for a variety of organisms. They are also considered as a dynamic component of the hydrologic cycle which links terrestrial, freshwater and marine ecosystems. Sediments also play a role in a wide range of human activities within aquatic systems, including flood protection, water resource management, as well as the maintenance of navigability, and the protection of coastlines.

Natural and anthropogenic disturbances in sediment balances can result either in a surplus or lack of sediment, with large-scale mostly negative impacts to the economy, development, infrastructure, and environment. Therefore, estimating and predicting suspended sediment load in catchment systems has long been a goal for sedimentologists, hydrologists, hydraulic and environmental engineers, and many other earth specialists. Both, in Poland and globally, there are currently no comprehensive systems for monitoring of the transported sediments quantity and quality. Since, knowledge about sediment in surface waters usually comes from single computational profiles, where single measurements of low frequency are made, modeling and estimation have become key elements in global water resources and environmental policy and management (Olyaie et al., 2015; Suedel et al., 2015).

A somewhat disregarding approach to the sediment problem in Poland, observed in various management documents, is somehow undermining research in this field of knowledge. As consequence of this situation we still have many river basins where strong erosional processes induced by human activity are observed, but their extent and impact on ecosystems is not estimated and discussed. The problem becomes even more exacerbated in systems where sediment continuity is altered by dam construction. In this case, we should be concerned not only about how much sediment is being delivered and trapped in the reservoir, but also how much of the sediment is being released to the downstream reaches of the river. Such data is almost completely nonexistent for Polish dam reservoirs, especially for the outflow parts of such systems. Since, the surplus or lack of sediment in its budget may have serious consequences to the ecosystems, the issue of sediment quantity management shall be recognized and discussed more extensively in Poland. Following this idea, the paper discusses its importance, and provides examples of sustainable sediment management. Taking into consideration shortages in the existing monitoring data, the Authors propose also a modelling tool to overcome this problem. This tool combines possibilities offered by environmental models and field studies based on the sediment fingerprinting method. Such a combination provides optimal opportunities to estimate the quantity and quality of suspended sediment in the whole catchment, and also assess the impact of climate change and land use on sediments.

Importance of sediment quantity management

In natural and non-altered anthropogenic intervention environments, sediments are usually not considered a stressor, and do not need to be managed, neither in terms of quality nor quantity (Apitz, 2012). However, since natural and non-altered conditions in aquatic environments become more and more rare, we shall mostly deal with results of human activity, additionally amplified in recent years by climate change. In case of sediments, rate and magnitude of input changes, alterations of hydromorphological conditions of water courses, intensive use of catchments and water bodies are only a few reasons to be concerned about their management.

The role of sediments in ecosystems has been discussed in countless publications. They have often been referred as “sink and source” for or a wide variety of organic and inorganic pollutants (e.g. Perelo, 2010), a “vital link between terrestrial and aquatic environment” (e.g. Likens, Bormann, 1974), or a “global problem” (Chapman, Smith, 2010). Originating from various processes and sources in the catchment, sediments are transported in form of fine (suspended sediment) and coarse (bedload) particles. Both types of sediment particles are of a crucial importance for aquatic systems, equally in terms of quality and quantity. They serve, among the others, as: a habitat for aquatic organisms (fish, macroinvertebrates, diatoms, and macrophytes), a key component of pollutant fate and transport (sorption and release of substances), and as a major factor shaping riverbeds, floodplains and estuarine mudflats (e.g. Kondolf, 1997; Kondolf et al., 2014). The rate of the sediment transport and its continuity in catchment-river-sea systems have been severely altered in many places, through implementation of different arrangements and structures to intensify or protect beneficial uses of watercourses by humans. The most common discourse on sediment transport interruption has been focused on trapping of sediment in dam reservoirs. Reservoirs serve different purposes (i.e. flood control, water supply, and power production), and their trap efficiency is frequently reported as 50-80% of the sediment volume delivered from the watershed (Sundborg, 1992; Vorosmarty et al., 2003). The obvious consequence of sediment deposition is depletion in reservoir capacity, and accumulation of contaminants associated with sediment particles. An equally important consequence, however, definitely less frequently discussed in Poland, is observed in downstream reaches of dammed rivers. There is an increasing evidence of ecosystem effects resulting from sediment starvation downstream of dams, often called "hungry water" (Kondolf, 1997), including channel incision, coastal erosion, and delta drowning (e.g. Schmitt et al., 2017).

It should also be noted, that these results of human interventions can be additionally amplified by the impacts of climate change. Most of the currently available climate models, clearly indicate a warming trend of the Earth's surface, resulting from increased greenhouse gas concentrations (Errico et al., 2013; IPCC, 2014). According to the Fifth IPCC Assessment Report (AR5) conclusions, and the National Oceanic and Atmospheric Administration (NOAA) findings, climate change has an impact (with a different probability) among others on: the global water cycle, changes in precipitation distribution, and its intensification over land areas, as well as frequency of extreme weather events (NOAA, 2017). On a catchment scale, climate change can lead to alterations in water quantity reaching the soil, and thus to disturbances of natural processes like: increased weathering, increase of erosion rate and denudation, and increased surface runoff. Since, these processes are responsible for sediment delivery from catchment areas to surface waters (Middelkoop et al., 2001; Li et al., 2009), therefore, global climate change has the potential to modify suspended sediment quantity, and quality. This clearly indicates the need for development of comprehensive catchment-river-sea sediment management strategies, and accurate sediment quantity monitoring.

Examples of sustainable sediment management

Since, the erosive power of rainfall is expected to grow due to increase of precipitation intensity (e.g. Burt et al., 2016; Panagos et al., 2017), the increased erosion rates can elevate the sediment delivery from catchments to water bodies. Indeed, such phenomena has been observed in many lakes and reservoirs, especially in upland and mountain areas (e.g. Marziali et al., 2017). The reduction of reservoir storage capacity due siltation causes necessity of undertaking various management actions, such as dredging, flushing, sluicing, or hydropeaking (Kondolf et al., 2014). Some of these actions are highly expensive and time consuming (i.e. dredging), and can additionally increase economic and ecological costs due to the requirement of disposal sites. However, some of them can be considered as a means to reestablish sediment continuity (i.e. sluicing), as proposed by the EU Water Framework Directive (2000/60/EC) (Fremion et al., 2016).

Process of bed erosion occurring downstream of dams, resulting from sediment entrapment in reservoirs, is well recognized and described in multiple publications (e.g., Babiński, 2007; Kondolf et al., 2014). Although the majority of dam management planning and operational documents take into account solutions counteracting erosion impacts, there is growing awareness that such solutions are not always effective. Some of the downstream reaches of dammed rivers require sediment augmentation or sediment replenishment, and such actions of riverbed "feeding" with sand and gravel deposits are undertaken for various reasons (table 1).

Table 1. Selected examples of sediment augmentation projects

Localization	Year	Action	Reasons	Source
Isar River (Germany)	since 1995	artificial sediment (re-)insertion	channel incision, groundwater table lowering, subsequent ecological consequences to floodplain	Heckmann et al., 2017
Trinity River (California, USA)	since 2000	supplementation of coarse sediment (gravel/cobble bars), improvement of its transport	reduced gravel bar deposits, and reduced salmon spawning and rearing habitat	http://www.trrp.net/
Mokelumne River (California, USA)	2003-2004	placement of cleaned floodplain gravel	protection of salmonids and their spawning grounds and benthic organisms	Merz et al., 2005
Yodo River system (Japan)	2004-2009	sediment replenishment	restoration of bed load transport and the associated habitat	Kantoush, Sumi, 2010
Lower American River (California, USA)	2011-2012	gravel augmentation	improvement of salmon spawning sites	Zeug et al., 2014
Wisłoka River (Poland)	2011-2015	gravel augmentation, large-scale boulders placement	reconstruction of gravel habitats of fish	http://www.krakow.rzgw.gov.pl/

Source: author's own work.

Most projects are undertaken to restore aquatic habitat, especially for fish, with gravels artificially added to enhance available spawning supply below dams (e.g. Kondolf, 1997; Kondolf et al., 2014), beginning with the creation of riffles for salmon spawning on the Trinity River below the Lewiston Dam in California. However, in the last couple of decades the increased use of sediment augmentation has been observed to support restoration of geomorphological processes, such as channel migration, or formation of bar features (Gaeuman, 2014), and to restore sustainable sediment management (Heckman et al., 2017). Gravel augmentation is also implemented for non-ecosystem purposes, such as damage to downstream infrastructure (bridges, pipeline crossings, and embankments), with the largest ongoing project on the Rhine River below the Barrage Iffezheim (Kuhl, 1992).

Also, in Poland such operations are discussed more and more frequently. The first gravel feeding concept in Poland was proposed by Parzonka (Parzonka et al., 2010) for the Odra river below the Malczyce barrage (300 km). Since then, such projects are undertaken occasionally when river bed erosion induces local economic or ecological problems. For example, in 2010-2015 two projects of patency restoration for the Wisłoka and Biała Tarnowska rivers and their tributaries have been executed, which also included gravel supplementation to restore structure of fish habitats and spawning sites (Bartnik et al., 2015). Also, sediment augmentation has been proposed for the Vistula river downstream from the Włocławek reservoir since, the river is not able to autonomously recreate the transport of its deposits in the eroded sections of the river (Habel et al., 2017). Despite the research efforts, the sediment quantity issue seems to be neglected in the official management documents. It should be noted, that in the water management plans for the Vistula and Odra catchments adopted in 2016, the term of “sediment” (“rumowisko”) has been mentioned only once, precisely in the context of expected increase of sediment transport in the upland parts of these catchments (Dz.U.2016.1911; Dz.U.2016.1967). In light of construction plans of new weir on the Vistula river (Siarzew, 706 km) these issues should be discussed and deal with more repeatedly.

Tools in sediment quantity monitoring

Research on sediment quantity, transport and fate is of crucial importance, not only from academic reasons to understand better geomorphological forms and processes, but also to provide assistance in engineering and management operations in riverine environments. The choice of the most accurate measuring systems, both for bedload and suspended matter, is often difficult and depends on many parameters, and can be broadly divided into direct and indirect techniques. The direct ones commonly use a variety of samplers, traps or slots allowing data collection in selected locations and time intervals (e.g. Habersack et al., 2017). While indirect (surrogate) monitoring systems are based on instruments operating mainly on bulk optic (turbidity), laser optic, pressure difference, and acoustic backscatter for suspended sediments (Lin et al., 2016) and acoustic Doppler current profilers (ADCPs), sonar, radar, and smart sensors for bedload measurements (Grey et al., 2010). In any case, quantifications of sediment volumes are time consuming, some of which are very expensive, and usually pose difficulties due to significant spatio-temporal variability of the sediment transport.

When monitoring data is limited, which is a common situation for many catchments, it becomes essential to use supplemental tools such as mathematical models. They provide an opportunity for the complementing of spatial and temporal resolution data, and simulation of interactions with various elements of the environment, also under forecasted climate changes. The proper choice of a modelling tool is crucial to incorporate necessary information from the field of hydrology, geology, and environmental engineering, and to integrate existing research data. Almost from the moment of its first creation, the SWAT model (Soil and Water Assessment Tool) (Neitsch et al., 2011) was used to simulate the intensity of water erosion occurring in river catchment areas and suspended sediment movement in the water column. Generally, it is a continuous long-term yield model, where processes associated with water and nutrient cycles are directly modeled by internal algorithms to describe the relationship between input and output variables. Physical processes are simulated within hydrologic response units (HRU), which are designed as land areas within a sub-basin that are comprised of unique land cover, and soil and management combinations. Although the SWAT module is most often used to simulate the transport of biogenic compounds in the catchment, it can also be used to simulate water erosion and suspended sediment transport in rivers and reservoirs. This possibility is provided by the built-in USLE module (Universal Soil Loss Equation) and its modifications R-USLE and M-USLE (Bagarello et al., 2010), which is an empirical, probabilistic equation developed for calculating the amount of soil loss in areas used for agriculture. This tool allows one to very precisely estimate the amount of suspended sediment on any number of calculation profiles on the river according to the following formula:

$$Sed = 11.8 \cdot (Q_{surf} \cdot q_{peak} \cdot area_{hru})^{0,56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG$$

where:

Sed – is the sediment yield on a given day [metric tons],

Q_{surf} – is the surface runoff volume [mm/ha],

q_{peak} – is the peak runoff rate [m^3/s],

$area_{hru}$ – is the area of the HRU [ha],

K_{USLE} – is the soil erodibility factor,

C_{USLE} – is the cover and management factor,

P_{USLE} – is the support practice factor,

LS_{USLE} – is the topographic factor,

CFRG – is the coarse fragment factor.

The SWAT modelallows also for conducting analyses of the river load time variability with the sediment load and the annual sediment production in each selected catchment area limited by calculation profiles (Peraza-Castro et al., 2014; Duru et al., 2017), and helps to understand soil erosion mechanisms (Li et al., 2017; Melaku et al., 2017). Currently, many publications describe calibration methods and obtained results for suspended sediment for catchments of various sizes located in different climatic zones (Vigiak et al., 2015; Rodríguez-Blanco et al., 2016). However, it should be noted that SWAT simulations of runoff discharge often have problems with showing any good fitting in suspended sediment concentrations (Mizugaki et al., 2014; Haregeweyn et al., 2017; Shivhare et al., 2017). In any case, the SWAT module works well in simulating phenomena related to suspended sediment transport both on natural and strongly altered basins. The use of this module on rivers with water dams also produces good results, especially when combined with radionuclide dating of sediment cores and bathymetric survey methods (Alighalehbabakhani et al., 2017). The built-in meteorological module also allows understanding the impacts of projected climate change on the hydrological processes. Simulations of the impact of climate change on water erosion and the amount of suspended sediment in surface waters using the SWAT module are used to prepare action programs aimed at reducing their negative impact on the environment (Verma et al., 2015; Nerantzaki et al., 2015; Li et al., 2017).

The Polish modelling tool, Macromodel DNS (Discharge-Nutrient-Sea) (Wilk et al., 2017) created at the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) allows analyzing of the processes which take place in catchments related to water and matter cycles. This macromodel combines existing and verified mathematical models and equations of hydrological transport process units. It allows the simulation of long-term impact of land use on water quality and the impact of pollutant such as suspended sediment discharges to surface waters. It is a combining of data processing modules, data replenishment modules, water quantity models and water quality models. The Macromodel DNS contains also theSWAT model as an integral module, and the resulting DNS/SWAT Macromodel has been successfully used for analyzing nutrient and suspended sediment transport, and also preliminary analysis of climate change in six catchments (Wilk, 2015).

The SWAT model can estimate soil erosion from the landscape and in-stream depositional and degrading processes during sediment routing. Therefore, the Macromodel DNS/SWAT will be able to accurately determine both the amount of sediment flowing into the river, as well as the amount of sediment on all designated calculation profiles. The important feature of this model is the fact that the data only from two monitoring profiles localized in the catchment area (with a minimum of two years of monitoring activity) is required for its correct calibration, verification, and validation. Based on such data, the model will be able to simulate results for all other computational profiles determined at any place in the catchment. The model is able to simulate the movement of suspended particles from the moment of release, up to the closing profile of the catchment even when the dam reservoir is located along the way. Moreover, it makes possible simulations of phenomena occurring in water reservoirs while analyzing water level fluctuations, sedimentation, median particle diameter of the suspension, bank erosion and many others.

Due to the fact that the DNS/SWAT simulations requires validation, and also quantitative analyses of suspended sediment should be supported by the qualitative information, combining this model with meta-aids, such as radioisotopes, or sediment fingerprinting is necessary. Combination of hydrological observation and natural radionuclide investigations enables to estimate the suspended sediment yield for each lithological source area within the watershed(s), relating them with potential factors such as erosion represented by steep slopes, landslides, and bare surface of slope failures. The use of the fingerprinting technique allows also to discriminate between potential sources of suspended sediment and to provide reliable estimates of the relative contribution of these sources. Therefore, a conceptual model combining Macromodel DNS/SWAT with other research and monitoring tools has been proposed by the Section of Modeling Water Quality of the Institute of Meteorology and Water Management and the AGH University of Science and Technology. Figure 1 presents a schematic diagram showing the concept of the proposed tool. Enabling precise analysis of quantity and quality for suspended sediment in the selected river catchment. Using such a tool also provides other significant benefits, like the possibility of considering climate change andland use scenarios.

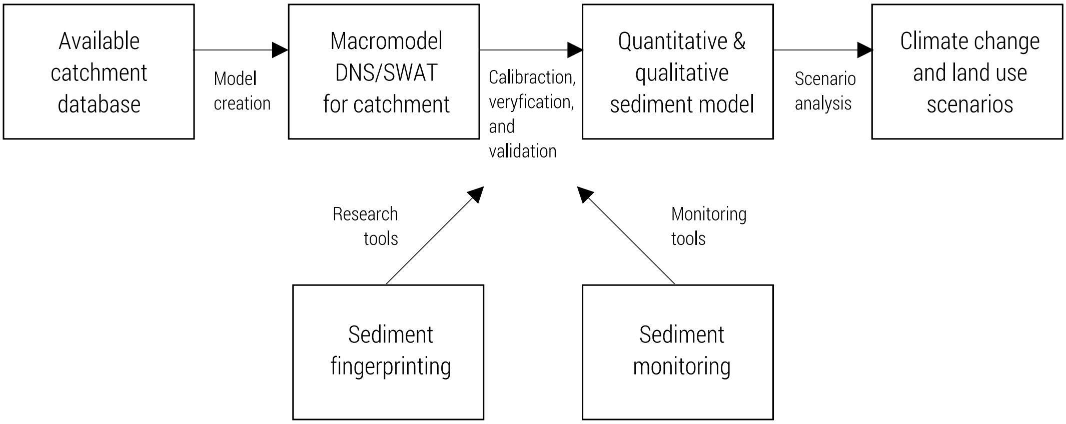

Figure 1. Conceptual model of suspended matter quantity and quality analytical tool

Source: author's own work.

Macromodel DNS/SWAT allows for the development of a baseline scenario reflecting the actual state of land use or meteorological conditions, and then comparing it with selected variant scenarios, which would take into account forecasted changes in the type of land use or climate change. The use of this tool is also possible for river catchments where the dam reservoir is situated. In such cases, monitoring data are particularly important because currently in Poland there are practically no measurements on suspended sediment quantity released from a dam. Lack of data results in possible errors in simulation results for individual calculation profiles downstream from the dam. The use of the proposed analytical tool allows to solve this problem to a large extent since, this model treats the river basin comprehensively, analyzing water erosion and suspended sediment in a watercourse as well as in a possible dam reservoir located in this watercourse.

Conclusions

Maintaining sediment transport continuity is crucial importance for important environmental and economic reasons. It has only recently begun that such a problem need be discussed for the whole catchment-river-sea system. Since monitoring data on sediment is far from being exhaustive there is an urgent need to employ different modelling tools. Despite invaluable advantages of these tools, there is still a requirement for the quantitative and qualitative data to validate and verify these model simulations. River basins where dam reservoirs are located, still pose the biggest challenge for researchers using modeling and analytical tools. Whilst the data on the quantity and quality of sediment from the source to the inflow to the reservoir can be relatively easily obtained and reproduced, the same data at the outflow from the reservoir remains thus, unattainable. The analytical tool proposed by the Authors, should help to overcome these obstacles, however, more attention to sediment monitoring is highly postulated.

Acknowledgements

This research has been supported by the Ministry of Science and Higher Education within the statutory research AGH WGGiOŚ No. 11.11.140.017.

The contribution of the authors

Ewa Szalińska – 60%
Paweł Wilk – 40%

Literature

Apitz S.E. (2012), *Conceptualizing the role of sediment in sustaining ecosystem services: Sediment-ecosystem regional assessment (SEcoRA)*, "Science of the Total Environment" No. 415, p. 9-30

Alighalehbabakhani F. et al. (2017), *Forecasting the remaining reservoir capacity in the Laurentian Great Lakes watershed*, "Journal of Hydrology" No. 555, p. 926-937

Babiński Z. (2007), *Deep erosion downstream of reservoirs on the example of selected dams in the world*, "Nauka Przyroda Technologie" No. 1(2), p. 11 (in Polish)

Bagarello V. et al. (2010), *Testing alternative erosivity indices to predict event soil loss from bare plots in Southern Italy*, "Hydrological processes" No. 24(6), p. 789-797

Bartnik W. et al. (2015), *Warunki przywracania struktury siedlisk dla ryb na odcinku Wisłoki w km 73+200 – 42+600*, "Gospodarka Wodna" No. 5, p. 147-152 (in Polish)

Burt T. et al. (2016), *More rain, less soil: Long-term changes in rainfall intensity with climate change*, "Earth Surface Processes and Landforms" No. 41, p. 563-566

Chapman P.E., Smith M. (2010), *Assessing, managing and monitoring contaminated aquatic sediments*, "Marine Pollution Bulletine" No. 64(10), p. 2000-2004

Duru U. et al. (2017), *Modeling stream flow and sediment yield using the SWAT model: a case study of Ankara River basin, Turkey*, "Physical Geography", doi.org/10.1080/02723646.2017.1342199

Errico R.M. et al. (2013), *Development and validation of observing-system simulation experiments at NASA's Global Modeling and Assimilation Office*, "Quaterly Journal of Royal Meteorological Society" No. 139(674), p. 1162-1178

Fremion F. et al. (2016), *Impact of sediments resuspension on metal solubilization and water quality during recurrent reservoir sluicing management*, "Science of the Total Environment" No. 562, p. 201-215

Gaeuman D. (2014), *High-flow gravel injection for construction designed in-flow channel features*, "River Research and Applications" No. 30(6), p. 685-706

Gray J.R. et al. (2010), *Bedload-Surrogate Monitoring Technologies*, U.S. Geological Survey Scientific Investigations, Report 2010-5091

Habel M. et al. (2017), *Issues related to renewal of the bed load downstream of dams. Assessment of the possibility to artificially rebuild the load downstream the Włocławek dam*, "Gospodarka Wodna" No. 11, p. 361-363 (in Polish)

Habersack H. et al. (2017), *Integrated automatic and continuous bedload monitoring in gravel bed rivers*, "Geomorphology" No. 291, p. 80-93

Haregeweyn N. et al. (2017), *Comprehensive assessment of soil erosion risk for better land use planning in river basins: Case study of the Upper Blue Nile River*, "Science of the Total Environment" No. 574, p. 95-108

Heckmann T. et al. (2017), *Feeding the hungry river: Fluvial morphodynamics and the entrainment of artificially inserted sediment at the dammed river Isar, Eastern Alps, Germany*, "Geomorphology" No. 291, p. 128-142

IPCC (2014), *Climate Change 2014*, Synthesis Report, Core Writing Team, R.K. Pachauri, L.A. Meyer (eds), Geneva, p. 151

Kantoush S.A., Sumi T. (2010), *Geomorphic response of rivers below dams by sediment replenishment technique*, in: Dittrich et al. (eds), *River Flow*, Bundesanstalt für Wasserbau, p. 1155-1163

Kondolf G.M. (1997), *Hungry water: effects of dams and gravel mining on river channels*, "Environmental Management" No. 21(4), p. 533-551

Kondolf G.M. et al. (2014), *Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents*, "Earth's Future" No. 2, p. 256-280

Kuhl D. (1992), *14 years of artificial grain feeding in the Rhine downstream the barrage Iffezheim*, Proceedings of the 5th International Symposium on River Sedimentation, p. 1121-1129

Li P. et al. (2017), *Comparison of soil erosion models used to study the Chinese Loess Plateau*, "Earth-Science Reviews" No. 17, p. 17-30

Li Z. et al. (2009), *Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China*, "Journal of Hydrology" No. 377(1), p. 35-42

Li Y. et al. (2017), *Assessing the impacts of climate and land use lane cover changes on hydrological droughts in the Yellow River Basin using SWAT model with time-varying parameters*, Proceedings of Agro-Geoinformatics 6th International Conference, p. 1-6

Likens G.E., Bormann F.H. (1974), *Linkages between terrestrial and aquatic ecosystems*, "BioScience" No. 24(8), p. 447-456

Lin CP. et al. (2016), *Extensive Monitoring System of Sediment Transport for Reservoir Sediment Management* in: L. Wang et al. (eds) *Natural Resources and Control Processes*. "Handbook of Environmental Engineering" Vol. 17

Melaku N.D. et al. (2017), *Prediction of soil and water conservation structure impacts on runoff and erosion processes using SWAT model in the northern Ethiopian highlands*, "Journal of Soils and Sediments" No. 1, p. 13

Merz J.E. et al. (2005), *Effects of gravel augmentation on macroinvertebrate assemblages in a regulated California river*, "River Research and Applications" No. 21(1), p. 61-74

Middelkoop, H. et al. (2001), *Impact of climate change on hydrological regimes and water resources management in the Rhine basin*, "Climatic change" No. 49(1), p. 105-128

Mizugaki S. et al. (2014), *Interpreting runoff process of suspended sediment at the watershed scale by observation and fingerprinting for improvement of model*, in: American Geophysical UnionFall Meeting Abstracts H23L-1047

Neitsch S.L. et al. (2011), *Soil and water assessment tool theoretical documentation version 2009*, Texas Water Resources Institute

Nerantzaki S.D. et al. (2015), *Modeling suspended sediment transport and assessing the impacts of climate change in a karstic Mediterranean watershed*, "Science of the Total Environment" No. 538, p. 288-297

NOAA (2017), *National Centers for Environmental Information, State of the Climate: Global Climate Report for Dec. 2016*,https://www.ncdc.noaa.gov/sotc/global/201612

Olyaie E. et al. (2015), *A comparison of various artificial intelligence approaches performance for estimating suspended sediment load of river systems: a case study in United States*, "Environmental Monitoring and Assessment" No. 187(4), p. 189

Panagos P. et al. (2017), *Global rainfall erosivity assessment based on high-temporal resolution rainfall record*, "Scientific Reports" No. 7, p. 4175

Parzonka W. et al. (2010), *Estimation of the degradation of the middle Odra river bed and programme of the restoration works*, "Infrastructure and Ecology of Rural Areas" No. 8(1), p. 59-68 (in Polish)

Peraza-Castro M. et al. (2015), *Modeling environmental services in rivers at catchment scale*, "Annales de Limnologie, International Journal of Limnology" No. 51(1), p. 59-70

Perelo L.W. (2010), *Review: In situ and bioremediation of organic pollutants in aquatic sediments*, "Journal of Hazardous Materials" No. 177(1-3), p. 81-89

Rodríguez-Blanco M.L. et al. (2016), *Sediment yield at catchment scale using the SWAT (Soil and Water Assessment Tool) model*, "Soil Science" No. 181(7), p. 326-334

Schmitt R.J.P. et al. (2017), *Losing ground – scenarios of land loss as consequence of shifting sediment budgets in the Mekong Delta*, "Geomorphology" No. 294, p. 58-69

Shivhare N. et al. (2017), *Identification of critical soil erosion prone areas and prioritization of micro-watersheds using geoinformatics techniques*, "Ecological Engineering", doi.org/10.1016/j.ecoleng.2017.09.004

Suedel B.C. et al. (2015), *The effects of a simulated suspended sediment plume on eastern oyster (Crassostrea virginica) survival, growth, and condition*, "Estuaries and coasts" No. 38(2), p. 578-589

Sundborg A. (1992), *Lake and reservoir sedimentation. Prediction and interpretation*, "Geografiska Annaler" No. 74A, p. 93-100

Vorosmarty C.J. et al. (2003), *Anthropogenic sediment retention: major global impact from registered river impoundments*, "Global Planet Change" No. 39, p. 169-190

Wilk P. (2015), *Method of calculating river absorption capacity (RAC) as a tool to assess the physicochemical state of surface flowing waters*, PhD thesis, IMGW-PIB (in Polish)

Wilk P. et al. (2017), *The flattening phenomenon in a seasonal variability analysis of the total nitrogen loads in river waters*, "Czasopismo Techniczne" No. 11, p. 137-159

Verma S. et al. (2015), *Climate change impacts on flow, sediment and nutrient export in a Great Lakes watershed using SWAT*, "CLEAN–Soil, Air, Water" No. 43(11), p. 1464-1474

Vigiak O. et al. (2015), *Adapting SWAT hillslope erosion model to predict sediment concentrations and yields in large Basins*, "Science of the Total Environment" No. 538, p. 855-875

Zeug S.C. et al. (2014), *Gravel augmentation increases spawning utilization by anadromous salmonids: a case study from California, USA*, "River Research and Applications" No. 30(6), p. 707-718