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Hydrolink

RESERVOIR SEDIMENTATION – NEED FOR ACTION AT GLOBAL, REGIONAL, CATCHMENT AND LOCAL SCALES

BY HELMUT HABERSACK & CHRISTOPH HAUER

Sediment surpluses and deficits following the interruption of sediment flow continuity through the river system by the construction of dams are growing in almost all river basins. Land use changes and climate change intensify this tendency. Consequences are reservoir sedimentation and river bed erosion in the free flowing river sections, leading ultimately to significant coastal erosion. Examples of international activities at global, European, regional and catchment scales demonstrate the increasing importance of reservoir sedimentation and associated research and management challenges.

According to Syvitski *et al*.[1] the pre-development (*i.e*. prior to any anthropogenic influence) sediment flux delivery of all rivers around the world was estimated to be 14 Gt/year. According to Walling[2], due to human activities the total flux in the absence of reservoir trapping would be 36.6 Gt/year, of which 24 Gt/year are trapped in reservoirs. This is approximately a 160 % increase in the sediment flux delivery compared to the undisturbed system (*i.e*. 14 Gt/year) and approximately a 66 % reduction due to reservoir sedimentation. The management of these quantities without working "with the rivers" would not be technically, economically, and ecologically possible[3].

World's Large Rivers Initiative and Selected Projects

Climate and land use changes affect soil erosion and sediment transport. It is therefore important to start studying rivers in a joint effort between nations to develop a global assessment of the present status of the world's large rivers. Sediment transport is an integral part of the UNESCO IHP World's Large Rivers Initiative (WLRI) (http://worldslargerivers.boku.ac.at/wlr/), coordinated by the Austrian UNESCO Chair on Integrated River Research and Management (http://unesco-chair.boku.ac.at/). The WLRI aims at analysing the status of up to 300 rivers considering different issues (from hydraulics to hydropower) and including sediment transport and reservoir sedimentation. A close cooperation with the UNESCO International Sediment Initiative (ISI) has been established. The International Conference on the Status and Future of the World s Large Rivers is organised every three years and is co-sponsored by IAHR (2011 in Vienna, Austria, 2014 in Manaus, Amazonas, Brazil, 2017 in New Delhi, India and the next will take place in 2020 in Moscow, Russia). So far, ten special issues in top Science Citation Index (SCI) journals have been published as the result of the efforts of the WLRI, which include a total of 143 articles by 554 authors.

In general reservoir sedimentation is a key topic for integrated, sustainable river management, which is affected by climate and intensive land use changes (*e.g*. glacier retreat, deforestation, intensification of agriculture) increasing soil erosion and therefore sediment delivery, nutrients and contaminants into reservoirs[4, 5]. In this context the European Sediment Network (SedNet: https://sednet.org/) aims at integrating sediment transport issues in European Strategies to meet the goals of the EU Water Framework Directive and the EU Floods Directive. This includes the development of new tools and strategies to support and guide reservoir sedimentation management[6].

At regional scale, the EU Alpine Space projects SedAlp and HyMoCARES can be mentioned. The SedAlp project (www.sedalp.eu) made recommendations for sediment management in Alpine basins with a focus on integrating sediment continuum, risk mitigation and hydropower production. Methodologies, tools and field monitoring techniques are recommended for effective reduction of sediment related risks, while improving the aquatic ecosystem and reducing the impact of hydropower plants on sediment continuity. The HyMoCARES project (www.alpine-space.eu/

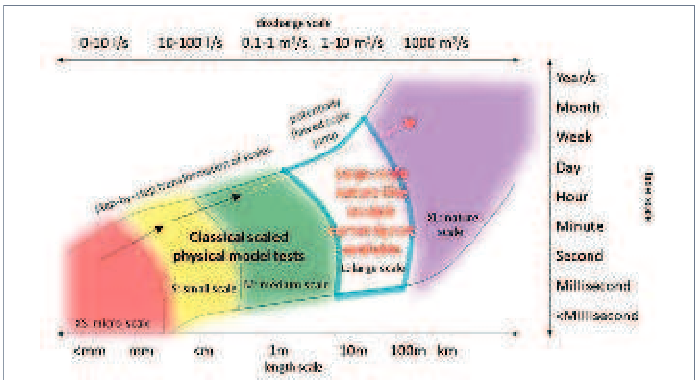

Figure 1. Time and length scales in physical models and real-world situations (nature scale); potentially flawed scale jump from small and medium scale models to nature scale

Figure 2. Experimental research channel at BOKU University, Vienna, being used for 1:1 scale sediment transport tests

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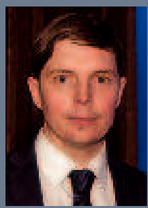

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projects/hymocares/en/home) deals with hydromorphological assessment and management at basin scale for the conservation of Alpine rivers and related ecosystem services over which hydropower and reservoir sedimentation exert a significant influence.

Examples for catchment sediment related activities are the EUSDR PA7 Flagship Project Danube River REseArch and Management (DREAM), the INTERREG Danube Transnational Programme (DTP) Project DanubeSediment and several bilateral INTERREG projects on the Danube basin. The project DREAM aims at fostering cooperation between research organisations working on the Danube basin. Besides flow and morphodynamic numerical models and field monitoring, research vessel infrastructure is of central importance.

Sediment transport scaling issues limit, however; the applicability of empirical formulas[7] which yield sediment transport rates that are often off by orders of magnitudes from field measurements[7, 8]. Thus, there is great need for collecting field data to improve the theoretical concepts forming the basis of numerical models. However, boundary conditions (discharge, water level, turbidity, bedload, biofilms) cannot be controlled during field measurements and deploying instruments under flood conditions is dangerous. Therefore experiments form the basis for understanding complex phenomena. To avoid or minimize scaling errors large-scale experimental facilities have been designed in several hydraulic laboratories[9] (Figure 1). As an example, a research open channel (5 m wide, up to 3 m water depth) with a 10 m^3/s free flowing discharge (using the water level difference between the Danube and the Danube canal) was constructed at the University of Natural Resources and Life Sciences (Universität für BOdenKUltur, or BOKU), Institute of Hydraulic Engineering and River Research, where no scaling of sediment was anymore needed (Figure 2). There are plans to construct a new Hydraulic Engineering Laboratory at BOKU, where it will be possible to use a discharge of 10 m^3/s inside the laboratory.

Another example is the EU DTP Project DanubeSediment – Danube Sediment Management - Restoration of the Sediment Balance in the Danube River. Between 1950 and 1980 a total of 69 large reservoirs were constructed. In 1998 the Freudenau reservoir was constructed in Vienna. Depending on the type, size and location of the run-off-river hydropower plants significant sedimentation has occurred in these reservoirs. Today only less than half of the former annually transported suspended sediment in the Danube reaches the Black Sea, where significant coastal erosion with a maximum of 20 to 25 m/year is observed[10]. During floods significant remobilisation of sediments from reservoirs of run-of-the-river dams can occur, leading to sedimentation in the floodplains downstream. Similar problems can be found in the Rhine (https://www.iksr.org/de/) and the Elbe (https://www.ikse-mkol.org/) rivers, where sediment transport is as well crucial for the functioning of the river systems.

Christian Doppler Laboratory "Sediment Research and Management"

The ongoing reservoir sedimentation related problems suggest that there is a need for further research activities to improve understanding of physical processes at various scales and to develop robust tools for sediment transport management. The Christian Doppler (CD)-Laboratory at BOKU University has a seven-year program (from 2017 to 2024) to address these needs. This program has been motivated by the fact that 60% of all new energy investments over the next 20 years will be in renewable energy systems and that new hydropower production will represent 25% of all new renewables, mainly due to high hydro potential in China, Africa, Latin America and South-East Asia. In the European Union, the growth of hydropower production aims to support achieving the set emission reduction targets by 2050. Some of the key economic, technical and ecological challenges in this context are the deposition, the treatment, and the dynamics of disturbed sediment in river catchments, which can reduce significantly the future market potential of hydropower due to reservoir sedimentation[11] (Figure 3).

The CD-Laboratory "Sediment Research and Management" aims at establishing and preserving the long-term use of reservoir storage capacity, and ensuring a long technical lifespan of various hydropower plant components, such as the intake channels, pumps and turbines. The CD-Laboratory is organized into three Modules. Module 1 aims at improving the economical, technical and ecological standards for hydropower use. Module 2 focuses on the improvement of sediment management for industrialised rivers, and Module 3 targets ways to achieve a long technical lifespan of hydropower plant components. All these issues will be addressed within the framework of the overall aim of minimising costs in the future by improving sediment management in river catchments.

Based on the state-of-the-art of engineering practice, basic research activities will be conducted on erosion, sedimentation and remobilisation of bedload and suspended load. A combination of laboratory (*e.g*. flume experiments, physical models) and field studies (*e.g*. monitoring of reservoir sediment flushing) at different scales (from mm to catchment) is expected to improve understanding of the relevant physical processes. Moreover, based on the development or adaptation of hydrodynamic-numerical models and monitoring techniques (*e.g*. seismic profiling), advanced tools will be developed for use by hydropower companies.

The CD-Laboratory is based at the Institute of Hydraulic Engineering and River Research, Department of Water – Atmosphere – Environment, BOKU University of Natural Resources and Life Sciences, Vienna. The laboratory was established in 2017 with four industrial partners (VOEU, viadonau, Andritz AG and Voith GmbH): VOEU (Verein für Ökologie und Umweltforschung) for studies on hydropower technologies and management (Module 1), viadonau participating in studies on sediment management in large rivers (Module 2), and the companies Andritz AG and Voith GmbH as contributors to Module 3 (sediment turbine research). One additional

Figure 3. Sedimentation in an Austrian reservoir after a controlled reservoir level drawdown (courtesy: Gökler)

module (abrasion studies) is scheduled to be launched at a later stage of the CD-Laboratory. The CD-Laboratory will provide new standards for technological, ecological and economical optimisation of hydropower management and novel aspects for sustainable sediment management in rivers based on (i) advanced understanding of physical processes, (ii) environmental impact assessments, and (iii) development of new monitoring and modelling technologies. The implementation of the results in strategy plans, guidelines, manuals, natural water safety plan and into laws is expected. A significant contribution to a consistent Austrian strategy concerning the future sediment management in surface waters is planned, in cooperation with all federal groups working in the field of mountain and hydraulic engineering.

The first phase of the CD-laboratory research activities focuses on small-scale experiments. For instance, Lichtneger *et al*.[12] investigated locally velocities, turbulence and shear stresses over a fixed non-porous rough bed to characterise the hydraulic conditions for the initiation of motion of natural sediment. In the work of Schobesberger *et al*.[13] the 3D coherent flow structures during incipient particle entrainment under 2D flow conditions and behind vertical cylinders (3D flow) with different diameters were investigated. Time-resolved 4D Tomographic - Particle Tracking Velocimetry (4D-PTV) and Shake the Box (STB) algorithm were applied for measuring the 3D velocities. The 4D-PTV method is well suited to shed light on the interaction between coherent structures and incipient conditions for sediment motion.

The goal of the CD-Laboratory is to improve the description of sediment transport mechanisms in numerical models. Tritthart *et al*.[15] presented a small-scale model reproducing turbulent flow structures and the associated pressure field using the high-resolution Large-Eddy Simulation (LES) method and describing their effect on a single spherical grain. This model contributes substantially to the future development of more advanced bedload transport models. The need for an integrated ecological impact assessment of specific sediment management measures, such as sluicing and flushing, has to be addressed. High-suspended sediment concentrations are known to be harmful to biota in downstream river reaches. It is common to set legal sediment concentration limits for reservoir management operations. However, there is considerable spatiotemporal variability of suspended sediment concentrations along both the longitudinal and cross-sectional profiles of rivers. To consider this variability in reservoir management operations, a 3D modelling approach based on the BOKU iSed-Model was developed[15].

Assessing whether the concentration of fine sediments in the aquatic environment is excessive is important because they can have an adverse effect on the habitat of both macroinvertebrates and fish, especially on their spawning sites. Research work has been undertaken at the CD-Laboratory to quantify the vertical distribution of fine sediments in river systems during hydropeaking flow regimes[16]. A repeated survey of fine sediments infiltrating a gravel matrix revealed the general importance of de-clogging caused by flooding and the role of fine sediment infiltration in the aquatic environment, especially during the initial stages of riparian vegetation establishment. Based on these findings it is clear that both coarse and fine sediments are ecologically relevant, and turn-overs reflected in the morphodynamics are targets for future sediment management in river systems.

Conclusions

The socio-economic, technical and ecological problems caused by mismanagement of sedimentation issues or by the lack of understanding of the underlying processes are a call for better management based on science. As stated in the World Congress of Hydropower in Kyoto 2003, the last century was the time of building (large) dams, while in the 21st century hydropower reservoirs will be focusing on sediment management. Research and engineering activities must be coordinated adequately at both local and global scale. Sediment is a resource which is fundamental for ecosystem services and has to be considered in a development framework considering changes in natural systems during the Anthropocene, as well as the future challenges arising from climate and land use changes.

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