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State of the art, shortcomings and future challenges for a sustainable sediment management in hydropower: A review

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ABSTRACT

It is predicted that 60% of all new energy investments over the next 20 years will be in renewables. The estimation for new hydropower production is 25% of all new renewables primarily due to potential in China, Africa, Latin America and South-East Asia. Also in Europe a growth of hydropower production is aimed to achieve emission targets within the European Union by 2050. However, one of the main economic, technical and ecological challenges in future are the deposition, the treatment, and the disturbed dynamics of sediments in river catchments, which reduce the future market potential of hydropower substantially. Due to a lack in awareness of those sedimentological challenges (e.g. lack of process understanding), various huge economical, technical and ecological problems emerge with an increasing relevance for hydropower industry, water management authorities and the society in future. Based on a substantial literature review, (i) legal frameworks and (ii) reservoir management techniques including (iii) process understanding and numerical modelling are addressed in this article. Moreover, the relevant cost-effective aspects of abrasion are worked out for (iv) turbine runners and (v) sediment bypass systems as well as the (vi) the ecological relevance of sediments and possible disturbances are described in this manuscript to open a future discussion on technical opportunities. It was concluded, that all these issues should be addressed within the framework of the overall aim to minimize the costs under consideration of ecological requirements and standards by an improved sediment management in terms of hydropower use. Moreover, it was stated that trans- and interdisciplinary research is required, to achieve those aims in future.

1. Introduction

IEA World Energy Outlook predicts that 60% of all new energy investments over the next 20 years will be in renewables [1]. The prediction for new hydropower production is 25% of all new renewables primarily due to potential in China, Africa, Latin America and South-East Asia. The estimated market potential for economically feasible hydropower projects is 9500 TWh [2]. Assuming development costs of at least 200 million €/TWh, a future market potential for hydropower development should amount to more than 2000 BN €. Also, the European organization Eurelectric, increased its focus on hydropower in 2013 and predicted a growth of hydropower production from 550 TWh to 1000 TWh to achieve emission targets within EU by 2050 [2].

While water resources are important for the production of climate-neutral energy (Directive, 2009/28/EC) [3], watersheds also provide important ecosystem services such as irrigation, drinking water, biodiversity and recreation [4]. Upcoming revision of hydropower licenses, implementation of the European Water Framework Directive (Directive, 2000/60/EC) [5] and new water management strategies (e.g. national river management plans) exert pressure on the hydropower industry by establishing targets for improved environmental conditions in regulated watercourses, potentially at the expense of power production. These drivers and pressures call for knowledge based solutions [6,7] and address the societal concerns [8,9].

One of the main economic, technical and ecological challenges in future, however, are the deposition, the treatments, and the disturbed

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dynamics of sediments in river catchments, which reduce the future market potential of hydropower substantially. Summarizing studies on these issues are missing up to now. Exemplarily, Basson [10] summarized and predicted in his work the loss in reservoir capacity for the different continents. He predicted that 80% of the reservoirs capacity (in average) will be filled up with sediments in (i) 2100 for Africa, (ii) 2035 for Asia, (iii) 2080 for Europe and Russia, (iv) 2060 for Central East and (v) 2060 for North America. Thus, due to a lack in awareness of those sedimentological challenges (e.g. lack of process understanding) various large economical, technical and ecological problems emerge with an increasing relevance for hydropower industry, water management authorities and the society in future. Here, previous studies estimated e.g. the annual sediment replacement costs for the US with six billion US $ [11].

The major technical challenges related to sediments in reservoirs are decrease of storage volume, loss of energy production [12] and technical issues such as clogging of bottom outlets or water intakes. Moreover, coping with the abrasion of turbines (e.g. Francis or Pelton runners) or the construction of sediment bypass systems are also key challenges of hydropower use in river systems with high suspended loads. In addition, sediment depositions in backwaters of run-of-river hydropower systems may cause problems concerning flood protection (e.g. due to the reduction in the hydraulic effective width). Due to the remobilization of fines out of the reservoirs in terms of floodings, other technical problems occur, and thus increase the potential damage downstream (prosecution from agriculture industry in terms of overbank deposition). In future, challenges are given as well by the impacts of global warming on an increase in sediment production due to glacier melting and changes in run-off-regimes [13] and river bed incision due to reduced sediment supply. No summarizing technical papers dealing with these challenges are published yet.

Ecological problems in hydropower use occur due to mid- to long term shortcomings in sediment management, the interruption of the sediment continuum (sediment deficit) and the subsequent impacts in downstream river sections (Fig. 1). Moreover, river sediment accumulation poses a challenge towards increased flood risks (reduces channel discharge capacity), instream biological impacts (e.g. degradation of fish spawning areas/rearing habitats and biodiversity) and robustness of various implemented river restoration means (e.g. spawning gravel etc.). Furthermore, accumulation of sediments upstream of dams, reduces downstream fertilization (e.g. aquatic organisms and irrigation) due to lack of sediments and nutrients, and poses a downstream pollution risk or even release of anoxic water (black water) if flushed. In terms of flushing (surplus of fines), however, local fishing companies

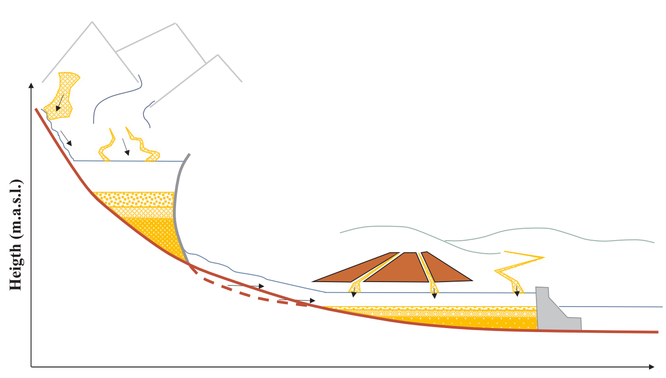

Fig. 1. Schematic overview of sedimentation in hydropower reservoirs, including high-head storage power plant (sediment sources from torrents, unregulated tributaries and glaciers) and low-head run-of-river hydropower plants (sediment sources from industrialized landscape); dashed red line = continuous river bed incision due to lack of sediment supply from upstream reaches. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

and non-governmental ecological organizations claim for additional costs (e.g. required stocking of fish due impacts of flushing on instream population) or try to stop the (technically required) reservoir flushing by law. Now, there is a discussion on objectively investigated (laboratory or field studies) thresholds for federal institutions provided by the scientific community (e.g. for harmful turbidity rates). Moreover, as hydrological regulation has a dampening effect on natural flood dynamics it is important to understand the level of residual (flood) flows that are needed in order to flush and clean sediments (reduce embeddedness). Here, the interaction of instream hydraulics, sediment transport, river morphology and ecology are not adequately understood (from a process perspective), and thus implementation of sustainable sediment mitigation measures in river management plans are missing. Furthermore, there is a lack in standardized evaluation methods for detecting disturbances in the sediment regime.

Aim of the presented review paper is to describe in a comprehensive way the state of the art, shortcomings and future challenges for global sediment management in terms of hydropower use. The content, novelty and research aims are based on a substantial literature review, addressing (1) legal frameworks with a focus on European Union policies and (2) reservoir management techniques including (3) process understanding and numerical modelling. Moreover, the relevant cost-effective aspects of abrasion are worked out for (4) turbine runners and (5) sediment bypass systems as both are important components in reaching sustainability of hydropower techniques. Finally, (6) the ecological relevance of sediments and especially the disturbance in sediment dynamics due to hydropower use are described in this manuscript to open a future discussion on technical opportunities to guarantee both, sustainability in hydropower production and ecological integrity of river systems.

2. Legal frameworks related to sediments in Europe

2.1. Water Framework Directive

A milestone for all European Rivers was determined with the political decisions to implement European Directives to fulfil objective management criteria for all member states of the European Union. Starting with the European Water Framework Directive (WFD) (Directive 2000/60/EC) [5] in 2000, a focus was given on the preservation or recovery of the "good ecological status" (GES) of the aquatic environment (Article 3) until 2015 (Article 4) (Fig. 2). In waterbodies with significant socioeconomic other uses (Heavily modified waterbodies, HMWB), such as hydropower, the target is a "good ecological potential". The WFD, however, does not specifically deal with sediments or sediment processes in riverine systems although sediments are a natural and essential part of the aquatic environment in which management plays an important role in water legislation [14]. Especially, for the required "good ecological status" the preservation and achievement of a sediment continuum in river systems is not targeted (Directive 2000/60/EC) [5]. Only for the "very good status" (not targeted by the WFD) the sediment continuum in a river corridor is targeted as an aimed quality criterion. Instead of a holistic view and integrative catchment scale approach about sediment dynamics to establish the "good ecological status" [15], the focus of the WFD is on e.g. harmful impacts in terms of reservoir flushings (e.g. various thresholds in suspended load concentration discussed) or water quality issues. Nevertheless, the latter point may be influenced by fine sediment transport and accumulation (e.g. [16,17]) and thus may give quality restriction for sediment (re-) use [18] in terms of e.g. reservoir dredging. On the other hand, the WFD handles sediment issues indirectly. If the indicator species, e.g fish are not in good status, the causes have to be addressed, including sediment issues. The current position of the Commission is, that it is left to the member states to identify sediment issues and problems where remedial action is needed underlined by the ecological monitoring of the WFD [14]. If the sediment quality is too