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RESERVOIR SEDIMENTATION

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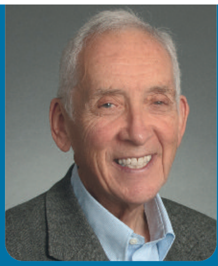
RESERVOIR SEDIMENTATION: CHALLENGES AND MANAGEMENT STRATEGIES

EDITORIAL BY KAMAL EL KADI ABDERREZZAK & ANGELOS N. FINDIKAKIS

Reservoirs formed by dams have been a key part of water resources development for a long time. Today, reservoirs serve one or more purposes, such as flood and drought control, water supply, hydropower, irrigation, groundwater recharge, inland navigation, fish and wild life conservation, and recreation. The International Commission on Large Dams (ICOLD) has estimated that in 2018 there are more than 59,071 large dams, *i.e*. dams higher than 15 m, and several times as many smaller impounding structures; their global gross storage capacity is about 7 trillion cubic meters. However, despite the continuing construction of new dams, the global storage capacity of reservoirs has been declining since around the year 2000, as reservoirs fill with sediments.



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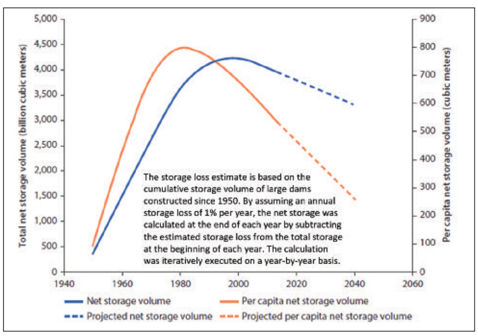
This is the first of two issues of Hyrolink focusing on sediment management strategies aimed at ensuring the sustainability of reservoirs, a subject of increasing interest in the last few years.

As outlined in this issue by Kondolf and Schmitt, despite providing various amenities, dam reservoirs have had a series of detrimental impacts on river systems arising from the regulation of the flow regime, the trapping of sediments, and the interruption of the continuity of sediment routing through the river system. Downstream of dams, the flow is deprived of sediments that are essential for maintaining the channel form and aquatic habitats, thereby transforming downstream channels from dynamically active and spatially complex systems into more static and homogenous, affecting in turn both the flora and fauna of the aquatic environment. The amount of sediment discharging in the oceans from rivers is reduced because of reservoir sedimentation, which has resulted in increasing coastal erosion and the retreat of many river deltas. Finally, reservoir sedimentation upstream of dams poses serious problems, including storage and efficiency losses (*i.e*. less capacity to reduce flooding and to store water for domestic supply and irrigation, lower potential for electricity generation), reduced usable life, dam safely (*e.g*. outlets, turbine intakes) and higher maintenance costs (*e.g.* dredging).

The global storage capacity of reservoirs is diminishing because of sedimentation. The rate of reservoir sedimentation varies across the world and is site specific, ranging from an average annual storage loss of 2.3 % in China to 0.68% in North America[1,2]. Since the late 1990's, the global rate of storage loss due to sedimentation has outpaced the rate of new storage construction, and without further actions, one quarter of all reservoirs will lose their storage to sedimentation in the next 25 to 50 years[3]. The loss of net reservoir storage capacity due to sedimentation can be seen clearly in the Figure below from a recent World Bank report[3].

Combating the storage loss corresponds to adding about 50 billion cubic meters of storage per year worldwide, with a replacement cost of nearly US$18 billion[3].

Global water use and hydropower supply are steadily rising with population and development, requiring construction of new dam reservoirs, particularly in Africa, Southeast Asia and South America. Climate change is projected to increase hydrologic variability worldwide, increasing therefore the need for larger reservoirs to ensure reliable water and power supplies and much-needed flood and drought control. Climate change and deforestation are expected to increase basin erosion and sediment loads in many rivers, exacerbating thus the risk of reservoir sedimentation. These constraints underline the need for improving our understanding of reservoir sedimentation processes (*cf*. Becker *et al.*'s article in this issue), and for developing effective strategies to counter sedimentation in reservoirs while ensuring hydrological and sediment transport processes that support various ecological functions of the river system. Otherwise, after their "design life" is reached, dams and reservoirs would have to be taken out of service, leaving future generations to have to deal with dam decommissioning and the handling of the reservoir sediments.



Net global reservoir storage volume, accounting for storage loss from reservoir sedimentation [3]

There is a considerable body of literature on the methods and techniques that are used to estimate reservoir sedimentation, to manage sediment in reservoirs (*e.g*. flushing, sluicing, dredging, density current venting, bypass tunnels), to reduce the sediment yield into reservoirs (*e.g*. check dams, watershed afforestation), or to reintroduce sediment to rivers whose sediment supply has been reduced or depleted by upstream dams (*e.g*. sediment augmentation/replenishment). In the present and next issue of Hydrolink, examples of operations and strategies are given from China, Japan, India, France, USA, Morocco, Oman and Taiwan, to share experiences and lessons learned. An example of a specific field case is presented in the article of Hussain *et al*. who describe the effect of land use change on the Mangla Reservoir sedimentation in Pakistan.

The consensus now is that proper sedimentation management is key to the sustainable use of reservoirs, as renewable resources, for the benefit of current and future generations. New dam and reservoir projects must be designed, constructed and maintained with the long-term threat of reservoir sedimentation in mind. Existing reservoirs should be converted to sustainable use insofar as is possible. A perfectly sustainable strategy for every situation does not exist, but efforts can be optimized for the particular conditions of each reservoir. In the 1990's, the World Bank initiated the RESCON (REServoir CONservation) research project to develop an approach to the assessment and promotion of sustainable use of reservoirs, with special emphasis on the economic evaluation of reservoir sediment management. The RESCON approach and the associated software was developed to provide a rapid assessment of expected reservoir sedimentation and help identify the optimum sediment management alternative that can transform a reservoir with a finite service life time to one that is sustainable, maximizing this way its net economic benefits. The RESCON tool is described in the present issue by Efthymiou *et al*.

In the United States, the Subcommittee on Sedimentation (SOS) is encouraging Federal agencies to develop long-term reservoir sediment-management plans based on the Lifecycle Management Approach; more details on this effort are given by Annandale *et al*. in the current issue. An example illustrating the promotion of environmental and social sustainability of reservoirs is given by Giri and Narayan for Indian dam reservoirs. In arid or semi-arid countries, afforestation programs have been initiated to protect soils against erosion and preserve the operation efficiency of hydraulic infrastructures. The case of Morocco is described in this issue by Loudyi *et al*.

Reservoir sedimentation is a topic of high interest for IAHR. The topic has often been highlighted in the International Conference on Fluvial Hydraulics (River Flow), organized by IAHR since 2002, and in other events cosponsored by IAHR, such as the River, Coastal and Estuarine Morphodynamics Symposium (RCEM), and the International Symposium on River Sedimentation (ISRS). During River Flow 2014 at the École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, scientists and consultants from all over the world addressed the challenge of reservoir sedimentation in a special session, and selected contributions were published in a book[4]. The increased interest in the subject of reservoir sedimentation and the need to share experiences and lessons learned led to the call for the creation of an IAHR research group focused on the subject. This group will be formally launched in 2019 during the IAHR World Congress in Panama and will be hosted by the "Hydraulic Structures" committee of IAHR.

Following our call for contributions on reservoir sedimentation, 22 articles from different countries have been submitted for publication. This is the proof of the interest of researchers and professionals in sharing their knowledge and experience on such complex, but exciting, topic.

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Cover picture: Paonia Reservoir near Hotchkiss, CO, USA, reached the end of its sediment design life after 50 years when the outlet became clogged with sediment and woody debris (Courtesy of Tim Randle, USBR)

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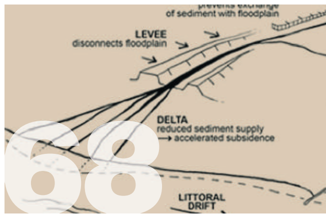
RESERVOIR SEDIMENTATION



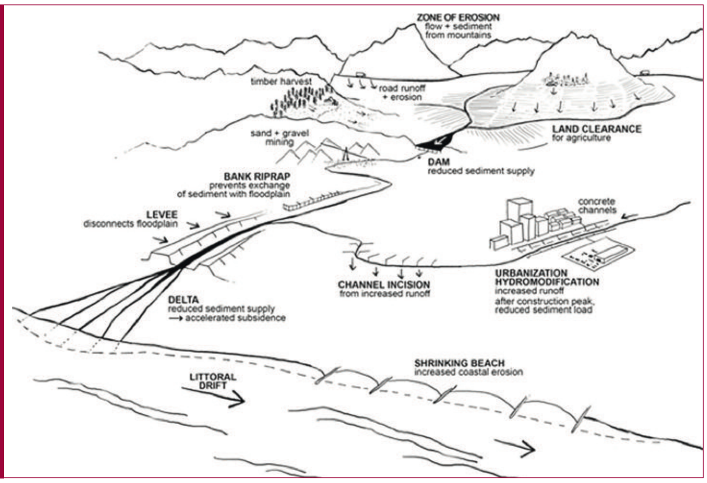
DAMS, SEDIMENT DISCONTINUITY, AND MANAGEMENT RESPONSES

BY G. MATHIAS KONDOLF AND RAFAEL J. SCHMITT

The sediment load of rivers is affected by human alterations, such as increased soil erosion due to removal of native vegetation, road construction, and other land disturbances, especially in steep upland areas (Figure 1). Sediment loads can also be increased by urbanization and the resulting increased runoff. As sediment loads are transported downstream through the water network they can be interrupted by natural and artificial means, including mining of sand and gravel and trapping behind dams. Despite widespread increases in land disturbance and consequent increased sediment yields from upland areas, the sediment loads of most major rivers have decreased in recent decades as a result of extensive sediment trapping by dams. This has led to accelerated coastal erosion and loss of delta lands.

This article focuses on the effects of sediment trapping by dams and planning/management opportunities to minimize these impacts and to restore downstream sediment supply to maintain or restore geomorphic and ecological conditions. It is complementary to other articles in this issue (*e.g*. Annandale *et al*., Efthymiou *et al*.), which explore structural and management approaches to reduce sediment trapping by dams, from a perspective of improving the sustainability of reservoir storage capacity for future generations.

Figure 1. Human alterations increasing sediment yields from the upland landscape, sediment trapping above dams, and consequences of sediment starvation downstream[1]



Sediment trapping by dams

Dams typically store water by design, and store sediment as an unintended consequence, although some dams have been built as debris basins or sediment-control (*sabo*) dams. Dam-induced changes in flow regime are typically accompanied by reductions in the river's sediment load as reservoirs trap sediment, creating conditions of sediment starvation directly below the dam. Reservoirs trap 100% of the river's *bedload* (coarse sediment moving along the channel bed by rolling, sliding, and bouncing, consisting of gravel and sand), and a percentage of the *suspended load* (sand, silt, and mud held aloft in the water column), which depends on the ratio of the reservoir storage capacity over the mean annual inflow of water. Storing water and sediment results in changes in flow and sediment load downstream of dams (*e.g*. incision, narrowing, bed clogging and armoring).

Dams that trap sediment but still release flows that are high enough to transport sediment create sediment-starved, or 'hungry water' downstream[2], so-called because these flows still have energy to transport sediment, but their sediment loads have been trapped in the reservoir. This excess energy is expended downstream on bed and bank erosion, leading to channel incision (downcutting) and consequent undermining of infrastructure (*e.g*. bridges, weirs) and loss of habitats through channel simplification.

However, hungry water does not occur downstream of all dams. It depends on the balance of flow and sediment supply. Reservoirs with large storage (relative to flow in the river), built to redistribute water between seasons or even years, commonly reduce high flows, reducing the dynamism of the river channel downstream. Gravel beds, formerly mobilized every year or two, may go for years without being moved, allowing fine sediment to accumulate within the substrate (so-called clogging process) and riparian vegetation to establish in the active channel. Encroaching woody riparian vegetation can lead to a feedback, where root establishment increases the resistance of the channel banks to erosion, so that dam-modified high flows are ever less likely to result in natural channel morphodynamics.

Large reservoirs may be capable of controlling a wide range of floods, and consequently can reduce the magnitude and frequency of floods experienced by the downstream channel. The reduced flow may not transport sediment delivered to the river below the dam by tributaries, promoting channel aggradation and potentially increasing flooding risk. Thus, depending on the balance between transport energy available and sediment supply, some river reaches below dams are in sediment deficit, some in sediment surplus[3].

The ecological consequences can be profound. The complexity of alluvial channel forms depends upon the availability of coarse material (sand and gravel) that composes bars and riffles. In reaches starved of sediment by upstream dams, gravel is transported downstream without being replaced, resulting in loss of bars, riffles and beds, and with them, loss of channel complexity, resulting in a simplified 'bowling-alley' channel form lacking in habitats needed for fish and invertebrates.

Similar to river channels, also coastal areas and especially deltas depend on a supply of sediment from the river system to maintain their forms against the natural processes of subsidence and coastal erosion[4]. Where the sediment supply to coasts and deltas has been cut off by upstream dams (and/or other activities such as in-channel mining), coastal lands have eroded back and subsided below sea level at increasing rates, as documented for the

Mississippi[5] and the Mekong[6]. For example, the Mekong delta was created by deposition of abundant river sediments, as the coast built out more than 250 km over the past 8,000 years, from the current location of Phnom Penh to its present configuration. After millenia of progradation, however, the delta has begun retreating in the last two decades due to factors such as in-channel mining of sand and accelerated subsidence.

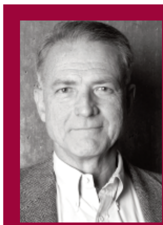
Restoring flow for geomorphic processes below dams

To mitigate dam-induced impacts on sediment transport and channel processes, controlled high-flow releases designed to mimic the action of natural floods are increasingly required in hydroelectric licenses for dams and as part of programs to restore river function. These deliberate, high-flow releases constitute one component of environmental flow requirements for maintenance of aquatic and riparian habitat. They reflect an evolution of environmental requirements from simple minimum flows to include periodic high flows to mimic flood effects on channels or on ecological processes. While terminology varies (*e.g*. "flushing flows", "channel maintenance flows", "morphogenic flows"), the need for periodic high flows to accomplish geomorphic goals has been widely recognized[7].

However, even if a post-dam flow regime was to mimic precisely the pre-dam flow regime, the river system would still be severely altered by the loss of its sediment load. Thus, for the definition of most beneficial morphogenic flows, it is critically important to take into account the sediment load available to the reach downstream of the dam, such as sediment supplied from downstream tributaries. Increasingly, partial restoration of sediment load is prescribed along with morphogenic flows. Coordinating morphogenic flows with sediment augmentations (*i.e*. supply, replenishment) is becoming more common[8].

Managing sediment supply below existing dams

To partially restore sediment loads in a regulated stream, coarse material is most commonly added to downstream channels by mechanical means, and, to less extent, trough induced riverbank erosion and failure[9]. These coarser fractions preferentially deposit in deltas at the upstream end of reservoirs. In some cases, sediment has been mechanically removed from reservoir deltas and placed in the downstream channel[8]. Although this solution replaces the downstream sediment supply with the same sediment transported by the river, it is rarely done because of the costs and of logistical and legal impediments to dredging the deltas and transporting the sediment around the reservoir and dam. Where sediment (usually gravel or gravel-sand mixtures) has been mechanically added to the channel downstream, the sediment has mostly been derived from other sources, such as terrace gravels, floodplain gravel pits, or in some cases, gravel mines on tributary streams.



G. Mathias Kondolf is a fluvial geomorphologist and fellow at the Collegium, Institute for Advanced Studies, University of Lyon, France, and Professor of Environmental Planning at the University of California Berkeley, where he teaches courses in hydrology, river restoration, and environmental science. He researches human-river interactions, including managing flood-prone lands, urban rivers, sediment in rivers and reservoirs, and river restoration (https://riverlab.berkeley.edu) and advises governments and non-governmental organizations on sustainable management of rivers.

Rafael Schmitt is currently a Post Doc at the Natural Capital Project and the Woods Institute for the Environment at Stanford University, and is affiliated with UC Berkeley's Riverlab. His research focusses on numerical modelling of catchment processes with a special focus on sediment connectivity. Schmitt developed the CASCADE model for sediment connectivity, which he has since applied to strategic dam portfolio planning for sediment management in large river basins. His research has been awarded the Chorafas Prize and the International Hydropower Association's Young Researcher Award.

Adding gravel to river channels below dams is commonly termed *gravel augmentation* or *gravel replenishment.* It has been widely undertaken in North America and Europe, in the vast majority of cases to restore spawning habitat for fish, especially salmon or trout. In northern California between 1976 and 2013, over 200,000 m^3 was added to the Sacramento River (Figure 2), 30,000 m^3 to the Trinity River, and over 45,000 m^3 to Clear Creek. On the Trinity River, the first such projects were undertaken in 1976 to create artificial riffles, with lines of boulders across the stream to hold the gravel in place. The river's transport capacity was greatly reduced by Trinity Dam, so the placed gravel did not immediately wash out, as occurred with similarly designed projects on the Merced River[10]. By the early 1990s, releases of morphogenic flows were coordinated with gravel augmentation[11]. Planners have measured the transport of gravel downstream of Trinity Dam by morphogenic flows (and natural floods spilling over the dam) and sought to compensate for these gravel losses from the reach with gravel additions. Thus, the restoration project evolved to have the explicit goal of building of bars and complex channel habitat through addition of coarse sediment and release of flows to transport and redeposit the sediment in natural channel forms; resulting ecological benefits, such as processing particulate organic matter, inducing hyporheic exchange, and creating thermal complexity have been documented[12].

Similarly, on the Uda River below the Murou Dam in Japan, sediment replenishment has been undertaken to restore channel complexity since 2006. In the first five years of the restoration program, natural flows spilling from the dam were sufficient to transport the added sediment in the first year, but in the subsequent four years, morphogenic flows were released to achieve desired sediment mobility[8]. Increasingly, sediment is added to reaches below dams in Japan to support development of gravel bars and other complex channel features[13].

As summarized by Ock *et al*.[13], such restoration efforts require systematic planning that accounts for specific objectives and local restrictions of the river basin, river and reservoir characteristics, and coordinating "*flushing flows (magnitude, frequency, and timing), determining quantity (amount added) and quality (grain size and source materials) of coarse sediment, and selecting an effective implementation technique for adding and transporting sediment…*". Dams vary widely in their settings (*e.g*. flow, sediment load, presence of tributaries downstream, channel slope), in their size relative to the river flow, and in their design and operation (*e.g*. size and location of outlets, reservoir geometry). To assess dam-induced disruptions to a pre-dam sediment balance, a sediment budget[14] can provide a framework within which to analyze information on the sediment transport capacity of the river (with and without "morphogenic flows") and the quantity and caliber of sediment supplied from tributaries and other downstream sources, as a basis for specifying "morphogenic flows" and, if needed, supplying sediment to downstream reaches. Programs of coupled gravel additions and "morphogenic flows" are expensive and consequently not widespread, but prescribing a "morphogenic flow" alone without accounting for sediment supply will usually not achieve ecological goals envisioned for the flows.

Figure 2. Gravel replenishment below Keswick Dam. To balance the sediment starvation created by trapping in Shasta and Keswick Dams, gravel is deposited from dump trucks down the bank of the Sacramento River, creating a cone to be eroded by subsequent high flows. (a) Remote-sensing composite image of site, showing gravel pile emplaced (15 April 2015), and (b) subsequently eroded (24 May 2017) (Google Earth). (c) Gravel augmentation has been ongoing here for decades, as reflected in a much-reproduced photo from January 1989 by Kondolf.

Designing dams to pass sediment

Mechanically adding sediment downstream of dams is expensive. It is more efficient to employ gravity to deliver sediment to the channel downstream of dams by passing sediment through or around dams, for which a range of techniques can be used[15,16,17].

For smaller dams, the most sustainable approach (where feasible) is to pass the sediment load around or through the dam. Water can be diverted to an off-channel reservoir only during lower flows, when water is relatively sediment free, while allowing sediment-laden floodwaters to pass by in the main river. A sediment bypass can divert part of the incoming sediment-laden waters into a tunnel around the reservoir, so they never enter the reservoir at all, but rejoin the river below the dam. Sediment can also be sluiced by maintaining sufficient velocities through the reservoir to let it pass through without allowing it to deposit. Alternately, the reservoir can be drawn down to scour and re-suspend sediment in the reservoir and transport it downstream. This involves complete emptying of the reservoir through low-level gates. Density current venting makes use of the higher density of sediment-laden water. Opening dam bottom outlets when denser turbidity currents pass through the reservoir can maintain them intact and allow them to exit the reservoir via the outlets, carrying most of their sediment with them. Sluicing, flushing, and density current venting pass sediments in suspension, which tend to be the finer fractions of the sediment load but can include significant sand. Sluicing and flushing work best on reservoirs that are narrow, have steep channel gradients, and have storage that is small relative to the river flow. Otherwise, back water zones might form in wider reservoirs where the hydrodynamic forces are insufficient to mobilize sediment. Flushing has been effective on reservoirs that impound less than 4% of the mean annual inflow[18] (Figure 3). Large reservoirs with year-to-year carry-over storage are poor candidates for such sediment pass-through approaches.

It is generally most efficient to take sediment management into account at the outset of the design and planning the operation of dams, so that dams are equipped from the outset to successfully sluice or slush sediment (*e.g.*, with sufficiently large low-level outlets), and the operations are planned to account for some periods of reduced power generation (or other functions) to allow sediment to be passed. Retrofits to allow sediment passing through existing dams may be possible, but often raise safety concerns. Bypasses can be safely built around existing dams without threatening the integrity of the dam.

Minimizing sediment trapping through strategic dam planning

Strategic dam planning at the river basin scale is an often-overlooked opportunity to minimize sediment trapping in dams, with benefits for the

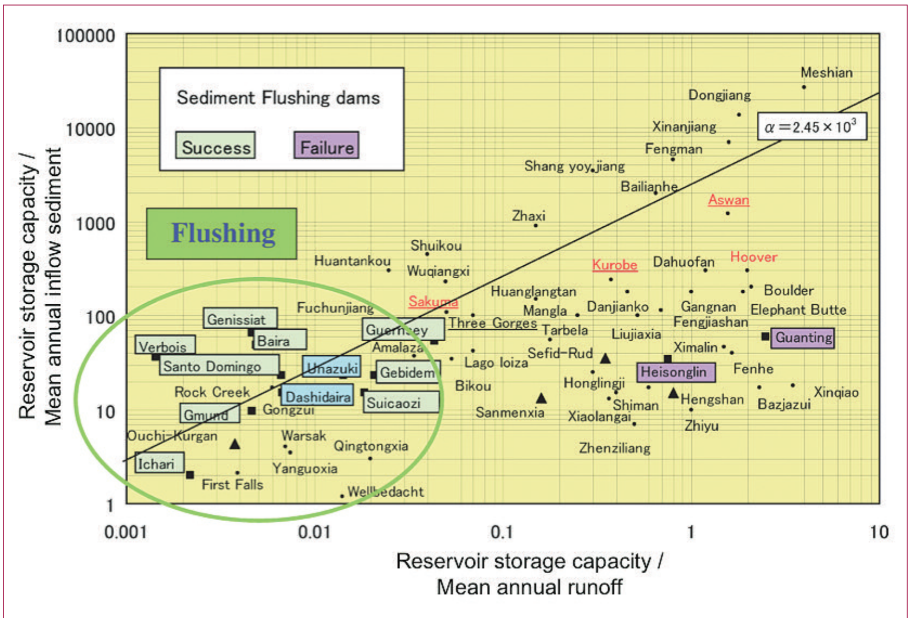


Figure 3. Plot of projects from diverse environments and with different sediment management strategies (flushing (squares), sluicing (triangles), excavation/dredging, check dams or no strategy (circles)). Reservoir life is indicated by the ratio between the reservoir storage capacity and the mean annual inflow sediment to the reservoir. Successful implementation have been in cases characterized by impoundment ratios (reservoir storage capacity divided by mean annual runoff to the reservoir) of 0.04 or less. Using the data, a simple linear regression relates the reservoir life to the impoundment ratio (linearity coefficient $\alpha = 2.45 \times 10^3$). (Figure developed by Tetsuya Sumi, adapted from Kondolf *et al.* [17], used by permission of AGU/John Wiley & Sons)

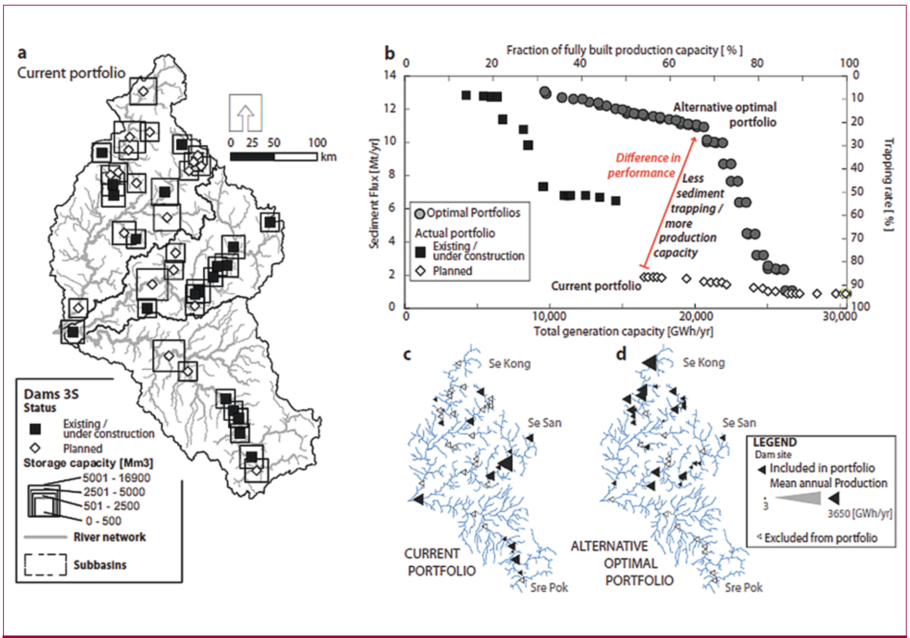


Figure 4. Power generation and sediment trapping from dam building in the Sre Pok, Se San, and Se Kong rivers (the '3S basin'), the largest downstream tributary to the Mekong River. (a) The current 3S dam portfolio includes twenty-one (21) dams built or under construction (black squares), and twenty-one (21) more at various planning stages (white diamonds). (b) Increased power generation capacity and cumulative sediment trapping with construction of the current dam portfolio and alternative portfolios with an optimal trade-off between sediment trapping and power production (grey circles). The arrow indicates a dam portfolio with higher power production but lower sediment trapping compared to the current portfolio (see arrow). Optimal portfolios were identified based on analysis of 17,000 alternative dam portfolios (not shown). The optimal portfolio compares favorably to the currently planned development because of a different spatial configuration of dams in the network. (c) The current dam portfolio includes dams downstream in the Sre Pok and Se San. (d) The alternative, optimal portfolio relies more on dams in the headwaters and on lower sediment-yield portions of the basin. The optimal portfolio greatly reduces environmental impacts and reservoir sedimentation, and also produces higher economic benefits.

dam infrastructure and the downstream rivers and coasts. Such planning should involve recognizing the spatial heterogeneity in natural sediment transport, cumulative effects on sediment supply of multiple dams in a river network and consequent geomorphic impacts[19]. New dams should be located in such a way, that the final dam portfolio minimizes disruption of sediment transport. In addition, each individual dam should be designed to maximize its ability to pass sediment around or through the reservoir[20]. Overall, there is large, but so far mostly missed, potential to develop and manage dams more sustainably for both reservoirs and rivers.

Throughout the developing world there is an explosion of dam building, motivated largely by a push for hydroelectricity, with an anticipated doubling of global hydroelectric capacity within the next two decades. As demonstrated for the major downstream tributary of the Mekong River (the Sre Pok, Se San, and Se Kong system, drainage basins located in Laos, Cambodia, and Vietnam), strategic dam planning could have resulted in a dam portfolio producing 68% of the basin's hydroelectric power potential while trapping only 21% of its sand load. The actual portfolio built to date is the result of project-by-project construction of dams, without a strategic trade-off analysis or planning (Figure 4). As a result, the current dam portfolio produces 51% of the basin's hydroelectric capacity while trapping 91% of its sand load, mostly because of early construction of downstream dams in the Sre Pok and Se San basins[19] (Figure 4), the tributaries contributing most of the basins sand load[20], with high sediment trapping and very little potential for sustainable sediment management. The current portfolio, resulting from project-by-project development, has also similar generation costs than the optimal alternatives[19]. In an effort to preserve remaining connectivity of sediment sources in the basin, the Natural Heritage Institute (as US-based NGO) and the National University of Laos developed a plan (adopted by the Laotian government) to site new hydropower dams in the Se Kong River basin only upstream of existing dams. The plan follows a strategic analysis for planned and built dams to minimize additional sediment trapping in the basin[21]. The example of the lower Mekong tributaries is a call for action for the stakeholders involved in planning and financing the global boom in dam development.

Compared to the current ad-hoc development of individual dams, strategic planning will involve more careful, basin-scale assessments of dam impacts and benefits. It might also result in situations, where different objectives, such as fish-migration and sediment transport, or the national interests of riparian countries to each maximize their generation, are in conflict. However, our increasing ability to model many domains of river ecologic and morphodynamic processes on network scales allows us to evaluate many different planning alternatives and to take informed decisions regarding which project portfolio to develop.

Unfortunately, most dams have been (and continue to be) built on an individual, project-by-project basis, without analysis of cumulative effects of multiple dams on a river network, much less strategic planning to minimize impacts. In these cases, maintaining habitat downstream of dams could involve a combination of morphogenic flows, sediment augmentation, and adding large wood. Especially where new dams are build, decision makers should be aware that such measures can provide some mitigation but will also require continuous investments to provide lasting improvements of ecologic conditions. Strategic planning might hence require to forego developing some projects with the largest short term economic return from a perspective of reducing costs of mitigation measures over the decadal life-time of single dams. For very large rivers, such as the Mekong, cumulative dam sediment trapping and the related impacts on the river system might, however, well exceed what can be possibly mitigated with such approaches mostly tested for smaller rivers in temperate climates. Where mitigation measures are feasible, a simple sediment budget and assessment of geomorphic processes and habitat conditions should be conducted before undertaking restoration actions. The sediment budget should compare downstream sediment supply with energy available to transport it, to ascertain if the reach has a sediment deficit or surplus, and to what degree. Likewise, assessing post-dam channel adjustments and their implications for aquatic habitat will inform potential options for restoration. ■

Acknowledgements
This article is adapted in large measure from parts of the chapter 'Dams and Channel Morphology' by G.M. Kondolf, R. Loire, H. Piégay, and J.-R. Malavoi in the forthcoming

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RESERVOIR SEDIMENTATION MANAGEMENT: A SUSTAINABLE DEVELOPMENT CHALLENGE

BY GEORGE W. ANNANDALE, TIMOTHY J. RANDLE, EDDY J. LANGENDOEN, ROLLIN H. HOTCHKISS, AND THE UNITED STATES NATIONAL RESERVOIR SEDIMENTATION AND SUSTAINABILITY TEAM (NRSST)

Suitable dam and reservoir sites are scarce resources that should be sustainably developed and managed to satisfy the needs of current and future generations. Historic and current dam development approaches do not address the issue of sustainable development (*i.e.* that reservoir water storage is needed for both current and future generations). Figure 1 shows that estimated global net reservoir storage, after allowing for storage loss due to sedimentation, is either stagnating or declining despite continued dam construction worldwide. Average global storage loss due to reservoir sedimentation is estimated to be on the order of 0.8% or 1% per year[1]. Globally, the per capita reservoir storage has been in decline since about 1980, with current per capita storage on the same order as it last was in the late 1950's.

In the United States (US), the nation's 90,000 dams and reservoirs constitute a critical component of the country's infrastructure. These dams and reservoirs serve both to provide fundamental societal needs such as ensuring the stability of water and energy supplies and flood risk reduction. Figure 1 indicates that the trend in net water storage, after allowing for storage loss due to reservoir sedimentation, is negative and that more reservoir storage space is lost each year to reservoir sedimentation in the US than what is being added by construction of new dams. Once a reservoir has completely filled with sediment (Figure 2), the project benefits are lost and it is often cost prohibited to remove the sediment to restore the reservoir storage.

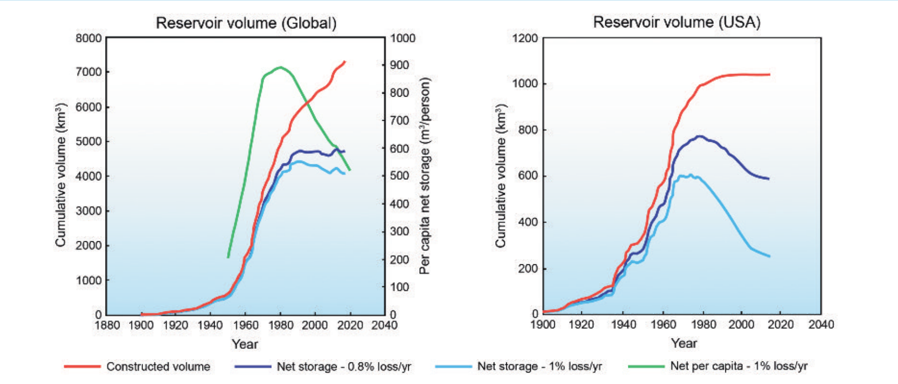

Figure 1. Total and estimated net storage globally and for the USA. Plots are based on the current global database of International Commission on Large Dams (ICOLD)

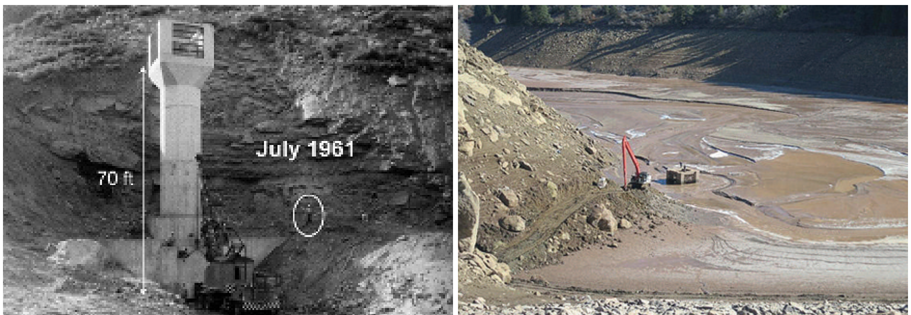

Figure 2. Paonia Reservoir near Hotchkiss, Colorado reached the end of its sediment design life after 50 years when the outlet became clogged with sediment and woody debris. The outlet was constructed in 1961, 21 m above the reservoir bottom (left). By 2014, the sediment level at the dam was 1 m higher than the outlet works (right). Photographs courtesy of Bureau of Reclamation

Concerns about inadequate reservoir sedimentation management activities in the US resulted in the Federal Advisory Committee on Water Information (ACWI), Subcommittee on Sedimentation (SOS) to pass a resolution encouraging Federal agencies to develop long-term reservoir sediment-management plans for the reservoirs that they own or manage. In addition, SOS has formed the National Reservoir Sedimentation and Sustainability Team (NRSST) to provide helpful information on these important topics. This Team, composed of volunteer specialists from Federal agencies, universities, and consultants, is developing an approach towards reservoir sustainability based on the below principles.

Sustainable Development

The principal focus of sustainable development is creation of intergenerational equity, as clearly indicated in one of the most quoted lines in the Brundtland Report[2]: "Sustainable development seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future." Facilitating sustainable development requires reconsideration of development strategies, including approaches to engineering design and operation and economic evaluation of projects. How we view the future determines whether we will be successful in enabling sustainable development. Changing development approaches from a design life to a life cycle management approach can accomplish this goal[3, 4].

Renewable and exhaustible resources

Renewable resources can be sustainably developed, while exhaustible resources cannot. The question then arises whether reservoirs should be designed and operated to be renewable or exhaustible resources. Undoubtedly, in the past and currently, it is assumed that reservoir storage space is an exhaustible resource. General design and development philosophy assumes that reservoirs are exhaustible resources that will be filled with sediment over time, eventually losing all reservoir storage space. Experience on some reservoirs has shown that they can be sustainable and that reservoir storage space can either be completely maintained or its rate of loss significantly reduced[5].

Dual Nature of Reservoir Storage

Dam construction creates water storage space in upstream valleys. The storage space is an enhanced natural resource that can either be an exhaustible or a renewable resource depending on decisions made during investment decision making, design, and operation. If the investor, designer, and operator decide to allow the reservoir to fill with sediment, it is classified as an exhaustible resource. However, if the decision was to implement reservoir sedimentation management approaches to preserve storage space or minimize storage loss due to sedimentation, the reservoir storage may be classified as a renewable resource[4].

Historically, reservoir storage space has mostly been planned, designed, and operated to be exhaustible. To change this, modifications are required to economic evaluation, design philosophy, and operating strategy for dams and reservoirs.

Managing Reservoir Sedimentation

The techniques that are available to manage sediment in reservoirs can be classified in four categories, as shown in Figure 3. The initial selection of appropriate reservoir sedimentation management approaches can be accomplished by making use of prior experience[3]. Figure 4 relates reservoir life (reservoir capacity volume (CAP)/mean annual sediment volume (MAS)) and retention time of water flowing through a reservoir (reservoir capacity volume/mean annual river flow (MAF)) for various projects where different techniques have been implemented, either successfully or not. Generally, implementation of reservoir sedimentation management techniques has been successful for projects located above the black curve, and not successful for projects below the curve; giving rise to the classification of "potentially sustainable" and "non-sustainable". Eight techniques with known performance are labeled and categorized on the graph. The sediment management categories corresponding to these techniques are (1) reduce sediment yield (check dams), (2) route sediments (sluicing and bypassing), (3) remove or redistribute sediment deposits (pressure flushing, drawdown flushing, dredging, and dry excavation), and adaptive strategies (storage operations). Figure 4 only provides an indication of techniques that may be implemented, which should then be further tested at pre-feasibility level with techniques such as the RESCON 2[6] software tool. Once potential solutions have been identified using RESCON 2 more detailed analysis is required through computer model simulation and physical hydraulic model studies.

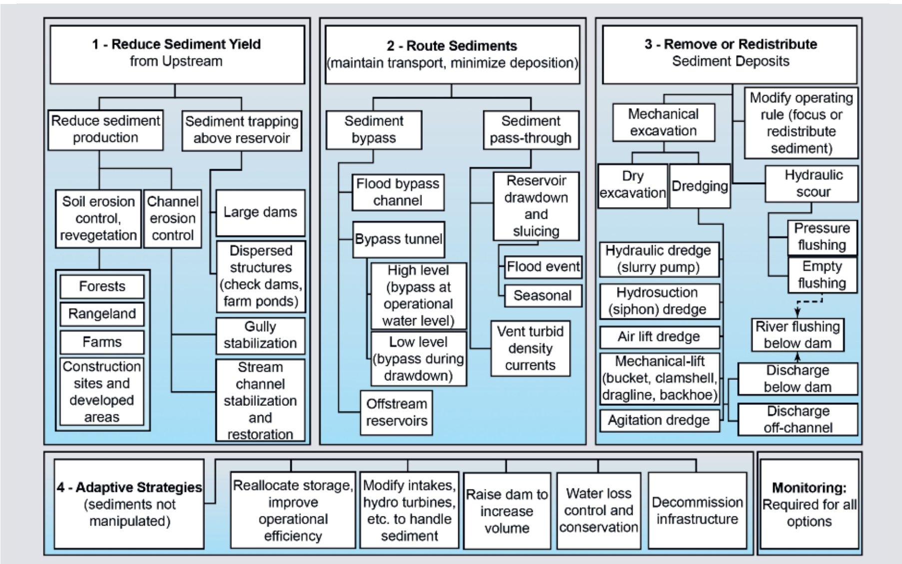

Figure 3. Classification of reservoir sedimentation management techniques[4]

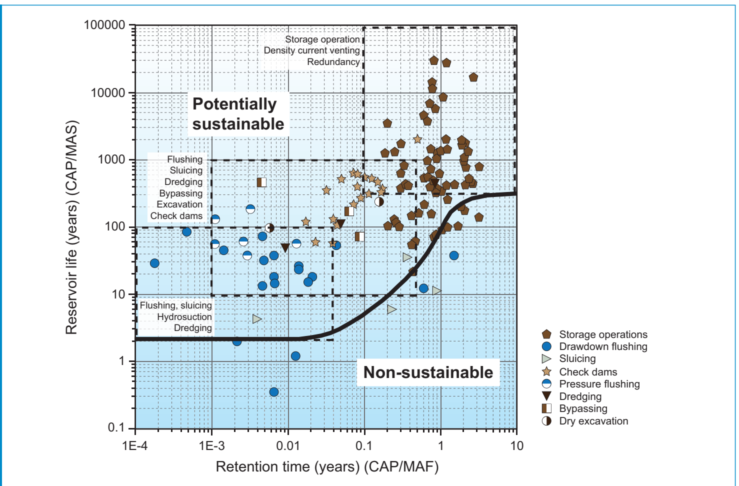

Figure 4. Practical experience with implementing various reservoir sedimentation management approaches[3]

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Rollin Hotchkiss is Professor of Hydraulic & Water Resources, Department of Civil and Environmental Engineering, Brigham Young University, and leads the Reservoir Sediment Management Task Committee of Environmental and Water Resources Institute, American Society of Civil Engineers.

NRSST members are: Mustafa Altinakar, George Annandale, Paul Boyd, Kent Collins, Deborah Cooper, Darrell Eidson, Jon Fripp, Rollin Hotchkiss, Kevin Jensen, Meg Jonas, Kyle Juracek, Sean Kimbrel, Matt Kondolf, Greg Morris, Peter Nelson, Tim Randle, John Shelley, Rene Vermeeren, Frank Weirich, and Michael Whelan.

Design and Operating Philosophy

The question that arises is why reservoir sedimentation management approaches are not more commonly considered in project selection, design, and operations; given that reservoir sedimentation management technology is available and has been successfully implemented on selected projects. The answer to this question is found in currently accepted practice as it relates to the economic evaluation of projects, engineering design philosophy and operations.

When considering sustainable development concepts, it is important to distinguish between the needs and objectives of national policy and operational demands. National policy should focus on the long-term welfare of the nation and emphasize the importance of sustainable development. Design and operational aspects of projects usually focus on short-term demands that more often do not consider the needs of sustainable development. Engineering design philosophy is largely influenced by operational needs and does not honor the criteria set by sustainable development policy and goals.

This results in engineering design philosophy adopting a "design life" approach, where a dam and reservoir are designed for a certain "life" of 50 or 100 years with no regard for conditions after this period (Figure 5). The design life is reached when sedimentation has filled to the level of critical dam or reservoir facilities such as the dam outlet, water intake, or boat marina. This sediment design life is reached long before the reservoir completely fills with sediment. The design life approach encourages viewing reservoirs as exhaustible resources that cannot be developed in a sustainable manner. The Team has great concern about this approach as it clearly leads to non-sustainable development of the nation's water resources, as shown in Figure 1.

Economics

For achieving sustainable development goals it is important to acknowledge that the future is all that remains of time, and the present is the vantage point from which we view it[7]. How we shape our view of the future determines whether we will reach sustainable development goals. Current economic analysis philosophy views the future as less importance than the present and uses discounting techniques to evaluate projects. This approach is obviously in conflict with sustainable development goals that aim at creating intergenerational equity. The reasoning often given for discounting the future is that

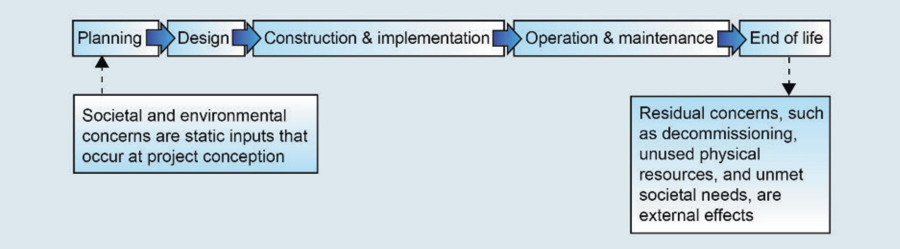
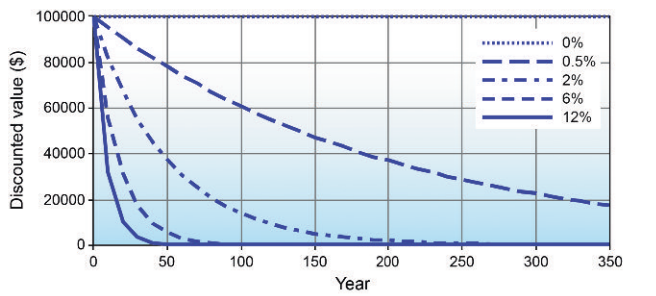


Figure 5. "Design life" approach to dam design[4]

Figure 6. Present value of $100,000 at different points in time using various constant discount rates.



Discount Rate	Approach without sediment management for 30 years	Approach without sedimentation management including decommissioning for 30 years	Approach with sediment management including decommissioning after 100 years of operation	Approach with sediment management including decommissioning after 200 years of operation
Constant Discount Rate 12%	$268 million	$239 million	$239 million	$239 million
Constant Discount Rate 6%	$478 million	$473 million	$482 million	$482 million
Declining Discount Rate	$492 million	$482 million	$509 million	$520 million

Table 1. The effect of alternative discount rates on the net present value of the PB Soedirman Project[6]

technological advances will resolve problems ignored in economic analysis. This approach may not be able to solve water storage, water supply, and irrigation problems.

Normally, a constant discount rate is used to conduct economic analysis and determine the net present value, *i.e.* the sum of benefits and costs expressed in terms of present value. Figure 6 shows the present value of $100,000 for constant discount rates of 12%, 6%, 2%, 0.5% and 0%. The graph shows that the present value of $100,000 is virtually zero after 50 years when using a discount rate of 12% (the previous default rate of the World Bank). When using the current discount rate of 6% used by the World Bank, its value becomes zero after about 80 years. This means that the costs and benefits to future generations are completely ignored after 50 to 80 years. For example, high decommissioning costs that occur 100 or 150 years from now would not be reflected in the present value. However, these decommissioning costs will be borne by a future generation who has not benefitted from such a project. The issue of intergenerational equity is not acknowledged in conventional economic analysis. If the same calculation is performed using smaller discount rates of 2% and 0.5%, greater credence is given to future costs and benefits. One may also ask why it would be expected of a future generation to place less value on $100,000 than a current generation. Using a 0% discount rate could resolve such an issue (Figure 6).

A different approach is required to incorporate the long-term costs and benefits of reservoir sedimentation management in economic analysis[7,8,9,10]. The literature recognizes two types of objectives, two types of discount rates, and the potential benefit of and justification for using a declining discount rate. The two types of objectives are those intended to augment social welfare and those aimed at achieving a net financial benefit for all. The discount rate associated with maximizing financial return is generally known as the investment-based (or finance-based) discount rate, while that associated with augmenting social welfare is known as the consumption-based discount rate. The consumption-based discount rate is the rate at which society is willing to trade consumption in the future for consumption today. Obviously, selection of a particular discount rate reflects society's commitment to intergenerational equity.

The impact on the Net Present Value (NPV) of a case study on the PB Soedirman Dam in Indonesia when using these different discounting techniques is shown in Table 1[6]. NPV is shown in columns two to five for discount rates of 12% and 6%, and a declining discount rate. Each column represents a different project scenario. Column two represents the NPV in the case where no sediment management is implemented, and the project life is limited to 30 years. Column three represents the same scenario, but adding the cost of decommissioning at the end of 30 years. Columns four and five represent NPV in cases where reservoir sedimentation management approaches are implemented for periods of 100 and 200 years, respectively, with decommissioning at the end of each of those periods. From the values in the table, it is evident that the declining discount rate approach more readily displays the intergenerational equity created by implementing reservoir sedimentation management strategies to extend the life of the reservoir. Neither of the constant discount rate calculations clearly illustrate the value of sediment management to future generations, while the declining discount rate approach does.

The long-lived character of dams and their reservoirs justifies use of a declining discount rate approach to economic analysis. Selecting this approach provides a means of quantifying the value to future generations of reservoir sedimentation management. Because the benefits or reservoir sedimentation management accrue over the long term, it is important to account for the benefits over the long term as well, thereby the need to use a declining discount rate.

Recommended Approach to Reservoir Management

An alternative approach to the economic evaluation, design and operation of dams and storage reservoirs is to follow a life cycle management approach. The life cycle management approach[3,4] relies on understanding that reservoirs can either be renewable or exhaustible depending on decisions made by the developer, design engineer and choices of the operator. When designing and operating a dam with an objective to maintain water storage through reservoir sedimentation management, the reservoir may be classified as a renewable resource.

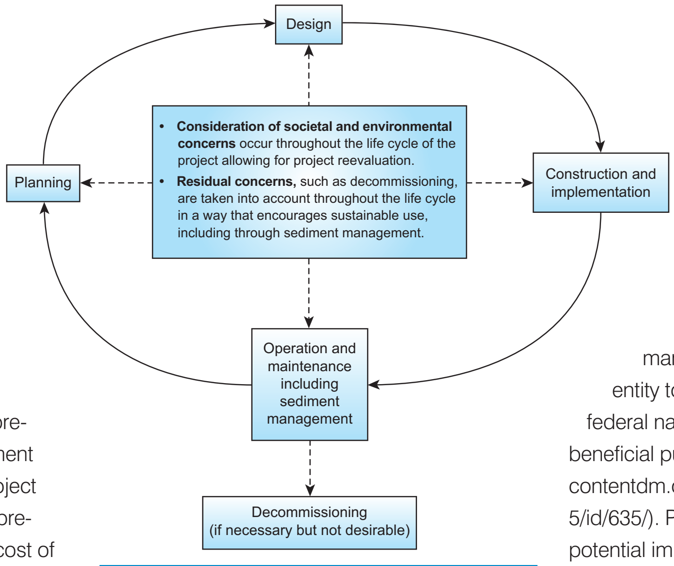


Figure 7. Lifecycle Management Approach[3,4]

Adopting a life cycle management approach (Figure 7) means designing and constructing a dam that is operated in a manner that regularly passes sediment through or around its reservoir; removes deposited sediment; and is refurbished on a regular basis with the intent of using the facility in perpetuity, and not assigning it a finite life. If a dam is designed and operated with the intent to maintain storage volume in perpetuity, both current and future generations benefit, thereby creating intergenerational equity and facilitating sustainable development. This approach will obviously require modification of conventional economic evaluation of reservoir projects, using low or declining discount rates or even considering the use of a zero discount rate[7] to reflect the value of developed resources to future generations.

Activities in the United States

Like other countries, the United States has not yet adopted a Lifecycle Management Approach (Figure 7) to the operation of its existing reservoirs. Doing so may require congressional action to modify existing policies governing Cost/Benefit analysis and how damages due to sedimentation and scour are addressed. However, both the U.S. Army Corps of Engineers (USACE) and the U.S. Bureau of Reclamation (Reclamation) are increasing their attention and activity in this area. USACE and Reclamation are compiling a national reservoir sedimentation database that allows federal employees to query and analyze sedimentation trends and conditions (www.usace.army.mil/Portals/2/docs/civilworks/climate/docs/ReservoirSedimentInformationplain06-11-2015.pdf?ver=2017-11-30-104449-697). They are also engaged to find ways to streamline the complex regulatory procedures that would simplify obtaining a permit to manage sediment at all U.S. dams. They have also sponsored two training seminars on sediment management at dams; one for managers and regulators and one for engineers.

The USACE is offering two pilot programs focused on sediment management. One allows a non-federal entity to profit by removing sediment from federal navigation projects and using it for beneficial purposes (https://usace.contentdm.oclc.org/digital/collection/p16021coll5/id/635/). Proposals are being reviewed for potential implementation. The other pilot program, not yet funded, offers the same opportunity to those dredging sediment from federal reservoirs (https://usace.contentdm.oclc.org/digital/collection/p16021coll5/id/635/. Additionally, there is a call for a feasibility study to manage the sediments on the Missouri River as a consequence of constructing six dams along its watercourse (http://cdm16021.contentdm.oclc.org/utils/getfile/collection/p16021coll5/id/1174).

The U.S. Bureau of Reclamation recently sponsored an international workshop on the topic with field trips to two reservoirs in Colorado where sediment is a special challenge. The SOS, along with its parent organization, the ACWI, passed a resolution in 2014 strongly encouraging federal agencies to prepare sediment management plans for each dam in their portfolio by the year 2030 (https://acwi.gov/sos/). To date, the NRSST has published Answers to Frequently Asked Questions (https://acwi.gov/sos/faqs_2017-05-30.pdf) and has recently aired six webinars on reservoir sedimentation including presentations on management, permitting, economics, and measurement techniques (https://cires.colorado.edu/news/announcing-reservoir-sedimentation-management-webinar-series). ■

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WHAT IS THE INTERNATIONAL COMMISSION ON LARGE DAMS (ICOLD) DOING ABOUT RESERVOIR SEDIMENTATION?

BY MARTIN J. TEAL

The International Commission on Large Dams (ICOLD, www.icold-cigb.net) is an organization dedicated to advancing the art and science of dam engineering and promoting the wise and sustainable development and management of world's water and hydropower resources. ICOLD also assists nations to prepare to meet the challenges of the 21st century in the development and management of the world's water and hydropower resources. Presently, ICOLD has 31 Technical Committees. Because reservoir sedimentation is a significant issue for nearly all nations regardless of their position along the development spectrum, ICOLD has made reservoir sedimentation a key issue in its publications and committee work for many years.

The Technical Committee on Sedimentation of Reservoirs is currently composed of 18 member countries, each with a representative from their national committee on large dams, and 4 coopted members with special technical expertise. Many of the committee members have contributed articles to this special edition of Hydrolink (*e.g.* CNR, EDF, DPRI, ETH). In addition, committee members contributed to the organization of and papers within "Question 100" at the recently completed (July 2018) ICOLD Congress held in Vienna, Austria (https://www.icoldaustria2018.com). Question 100 dealt exclusively with the topic of reservoir sedimentation and sustainable development and over 40 works were included. A general report on Question 100 was prepared by Professor Sumi[1].

The committee's current activities are focused on drafting two new ICOLD bulletins. The first of these bulletins is nearing completion and deals with National Regulations and Sediment Management Case Studies. In the first part a summary is given of national regulations, where they exist, that impact sediment management options. The second part consists of case studies from different countries that illustrate sediment management efforts regardless of their degree of success.

The second bulletin was only started last year and is tentatively titled Design of Sediment Bypass Systems. The bulletin will focus on design of sediment bypass tunnels and on continuous bypass systems. Topics are expected to include design, operation, monitoring, ecological impacts and economic analysis. Past bulletins developed by the committee can be found on the ICOLD website: www.icold-cigb.net. ■

Martin Teal is the current Chair of the ICOLD Committee on Sedimentation of Reservoirs, which consists of over 20 members representing different countries from all regions of the world. He joined the committee in 2011 as the United States representative and became Chair 2016. He is a Hydraulic Engineer with WEST Consultants in San Diego, California where he serves as Senior Vice President. His experience is in the areas of hydrology, hydraulics, sedimentation and fluvial geomorphology.

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Continued from page 71

book *Environmental flow assessment: methods and applications*, by J.G Williams, P.B Moyle, G.M. Kondolf, and A. Webb, published by John Wiley & Sons. The senior author gratefully acknowledges the Collegium de Lyon-Institut des Etudes Avancées de l'Université de Lyon, France, the EURIAS Fellowship Programme and the European Commission (Marie-Sklodowska-Curie Actions–COFUND Programme-FP7) for support of this research and manuscript preparation. ■

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RESCON 2: A TOOL FOR RAPID ASSESSMENT OF ALTERNATIVE OPTIONS FOR MANAGING SEDIMENATION IN RESERVOIRS

BY NIKOLAOS P. EFTHYMIOU, SEBASTIAN PALT, GEORGE W. ANNANDALE AND PRAVIN KARKI

There is a paucity of suitable locations for construction of new dams in watersheds where reservoirs have already been impounded in the past. Policy makers and engineers are focusing in-creasingly on the preservation of reservoir storage and prompting of sustainable dam projects. A plethora of sediment management strategies has been developed and successfully applied to counter reservoir sedimentation. REServoir CONservation (RESCON) 2 beta provides a tool for rapid assessment of expected reservoir sedimentation and screening of technically feasible and economically optimal sediment management techniques, based on easily accessible data.

From RESCON to RESCON 2 beta

The RESCON approach was originally published by the World Bank in 2003[1] to help selecting a sediment management strategy that is technically feasible, while maximizing net economic bene-fits. The RESCON approach is applicable to proposed or existing reservoirs and accounts for all major benefits and costs over the complete project life-cycle (*i.e.* intergenerational equity concept). The impact of climate change on infrastructure in the water sector and the importance of reservoir sustainability are now better understood and new methodological tools for economic analysis of renewable resources have been developed[2,3]. The RESCON tool was tested against data from numerous dams around the world (*e.g.* Morocco, Sri Lanka, Kenya) and was shown to yield results in agreement with observations and field data and proven detailed mathematical models[1]. These reasons have prompted the World Bank to update the computer model of the RESCON approach. Fichtner Consulting Engineers has developed recently the beta version of the upgraded RESCON 2[4], which is a freeware tool to download at www.hydropower.org/sediment-management/resources/tool-reservoir-conser-vation-model-rescon-2-beta.

The RESCON 2 software provides a rapid evaluation of the state-of-the-art for sediment management alternatives, addressed to both engineering industry and decision-making communities. The purpose is to identify, based on readily available data, the optimum sediment management alternative able to convert a reservoir with a finite service life time to a sustainable one. The analysis is based on empirical approaches, and therefore it is not intended to replace detailed planning sup-ported by numerical and/or physical modelling.

Selection of optimum sediment management alternative

The RESCON 2 methodology comprises the following steps (Figure 1):

- Assessment of the technical feasibility of sediment management strategies,
- Prognosis of the change in time of the usable reservoir storage capacity and the corresponding firm water yield,

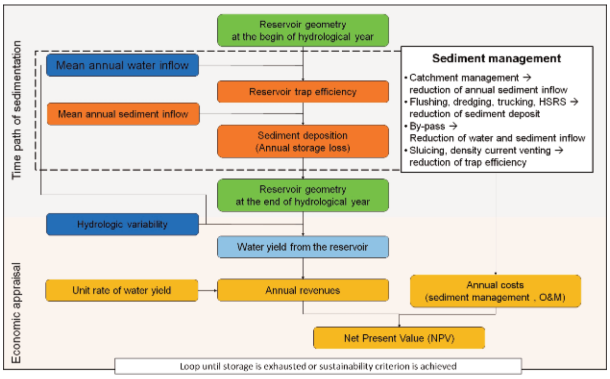

Figure 1: Flow chart of RESCON 2 analysis for the assessment of reservoir performance. O&M: Operation & Maintenance

- Estimation of the annual reservoir benefits, which are determined according to the revenue obtained by the firm water supply and cost for reservoir operation and maintenance, and sedi-ment management. The annual benefits are discounted to calculate the corresponding Net Present Value (NPV),
- Selection of the sediment management technique that maximizes the economic performance of the reservoir. The latter is quantified as the Aggregate NPV of benefits over the life of the res-ervoir.

The following sediment management techniques can be assessed with RESCON2:

- Reduction of sediment inflow into the reservoir through watershed management,
- Sediment routing (*i.e.* sluicing, by-pass, density current venting),
- Removal of sediment from the reservoir (*i.e.* flushing, dredging, trucking, Hydro-Suction Remov-al Systems (HSRS)),
- User-defined strategy combining a sequence of up to five different techniques,
- No Action Scenario (*i.e.* no sediment management intervention), which can be the baseline approach to which other sediment management alternatives are compared.

The calculation of reservoir storage loss is based on empirical trap efficiency predictors and partitioning the sediment inflow into bedload and suspended load. The spatial pattern of reservoir sed-imentation is assessed by schematizing the reservoir geometry into compartments and calculating the corresponding deposits and invert elevation. This allows the allocation of sediment deposits in active and inactive storage pools, respectively. Several calibration possibilities are available to tailor the analysis onto the site-specific conditions. RESCON 2 can determine through economic optimization the parameters affecting the sediment management technique efficiency, and conse-quently the change of the reservoir storage over time. In addition, it is possible to specify explicitly these parameters, such as the implementation time schedule, in case of project specific con-straints.

The model has been validated using a large number of existing and green-field projects, showing an overall good agreement between the predicted and measured (or numerically simulated) evolu-tion of the reservoir storage capacity over time (Figure 2).

Water storage can be either an exhaustible resource, if the reservoir is non-sustainable, or renew-able, if the reservoir is sustainable by effective sediment management. The virtues of sustainable development and intergenerational equity are accounted for in the economic appraisal performed by RESCON 2 in two manners:

- Optional calculation of sinking fund in case of

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Pravin Karki is leading the World Bank's work on sediment management and climate change resili-ence in the hydropower and dam sector. He has over 25 years of professional experience relating to hydropower, mainly in engineering, international policy and academic research. He managed the RESCON2 project on behalf of the World Bank.

Figure 2: Comparison between predicted and measured or simulated devel-opment of storage over time for the Fierza Reservoir, Albania (left) and Moragolla Reservoir, Sri Lanka (right) Intergenerational equity

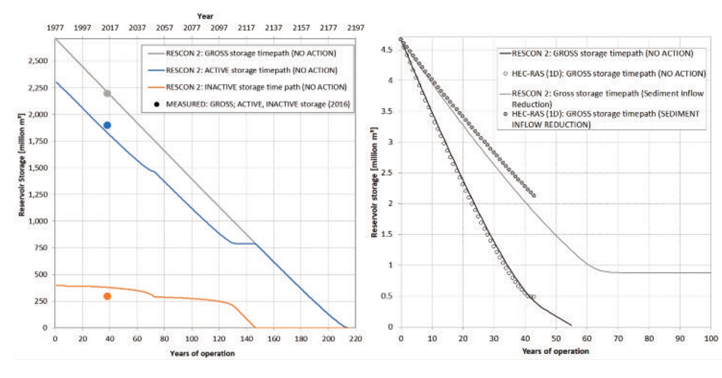
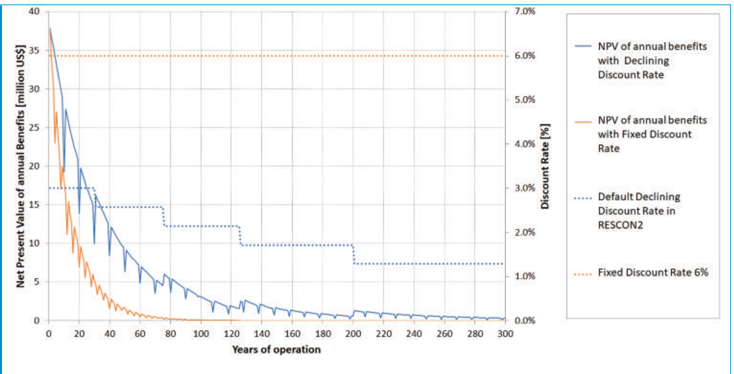


Figure 3: Calculated NPV of annual benefits with fixed discount rate (6%) and with time-declining discount rate for a large storage reservoir where the sediment flushing alter-native is applied Climate change



non-sustainable storage development that allows placing the burden of dam decommis-sioning on the current generation benefiting from the in-frastructure,

- Option to discount the future benefit streams using a time variant Declining Discount Rate. This allows attributing higher NPV for benefits associated with the utilization of infrastructure by the future generations. Figure 3 illustrates how applied discount rates impact the valuation of future reservoir benefits.

The continuous loss of reservoir storage due to sedimentation will reduce the resilience of the existing water sector infrastructure against the unavoidable increase of hydrologic variability driven by climate change[3]. Sediment management can provide therefore an effective adaptation strate-gy through preservation of the available storage capacity, protecting thus the reliability of water supply. RESCON 2 can perform an assessment of the effects of climate change on reservoir sus-tainability. Using data retrieved from the Climate Change Knowledge Portal of the World Bank[6], *i.e.* predicted changes in mean annual runoff and temper-ature[7], it is possible to assess the im-pact of climate change on the reliability of water and power supply from reservoirs with diminished volume. The climate change data represents the results of 22 GCMs and three climate change scenarios, provided on river basin level. It is also possible to empirically estimate changes in sedi-ment yield using the changes in average annual flow with application of the BQART equation[8]. Finally, the user is asked to specify the expected increase of hydrological variability. The latter can be assessed by statistical analysis of precipi-tation time series derived from open climate change data sources. This analysis performed by RESCON2 has the following objectives:

- Climate "stress test": assessment of how vulnerable different project configurations (*i.e.* different sediment management alternatives) might be across a sensible range of potential climate change effects.
- Robust Decision Making: identification of the robust sediment management configuration that minimizes the expected maximum regrets due to climate change on the economic performance of the reservoir.

Environmental safeguards

In addition to technical feasibility and economic viability, environmental and social impacts of sed-iment management play a decisive role in selecting the optimum alternative. RESCON 2 includes the safeguard rating method, which allows the differentiation between environmen-tally and socially constrained and unconstrained sediment management alternatives during the evaluation proce-dure.

Graphical User Interface

RESCON 2 has a Graphical User Interface (GUI), which facilitates a structured setting-up of the model and reading of results. The GUI allows for a real-time validation of the inserted data and easy access to text providing further explana-tions on the input parameters. The model output includes summary tables and graphical plots of the time evolution of the most important parame-ters (*e.g.* reservoir storage, trap efficiency, deposit removal, water yield, NPV of reservoir benefits). The results are saved in a MS Excel spreadsheet that can be easily processed by the User. ■

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CHARM – CHALLENGES OF RESERVOIR MANAGEMENT – MEETING ENVIRONMENTAL AND SOCIAL REQUIREMENTS

BY FELIX BECKERS, STEFAN HAUN, SABINE U. GERBERSDORF, MARKUS NOACK, DANIEL R. DIETRICH, DOMINIK MARTIN-CREUZBURG, FRANK PEETERS, HILMAR HOFMANN, RÜDIGER GLASER AND SILKE WIEPRECHT

The project CHARM aims at contributing to a better understanding between reservoir management and its impact on the surrounding environment and the reservoir itself. CHARM is a multidisciplinary research project addressing five fundamental issues of reservoir management: sedimentation, biostabilization, harmful cyanobacterial blooms, greenhouse gas emissions, and societal implications. These issues are tackled through analytical approaches, field monitoring, laboratory experiments and numerical models, thus gaining insights into the involved processes at different scales. The project outcomes will support the development of reservoir management strategies to meet challenges related to increasing anthropogenic impacts on water bodies and to climate and demographic changes resulting in altered energy and water demands.

Reservoirs serve a multitude of purposes: hydropower production, drinking and irrigation water supply, flood retention, and recreation. The significance of reservoirs is highly increasing due to anthropogenic influences exacerbated by climate and demographic changes[1]. The ongoing debate about sedimentation in dam reservoirs often ignores accompanying side effects, which have been insufficiently investigated. Apart from a loss in reservoir storage space due to sedimentation, further processes are involved such as the production of greenhouse gases and, in many cases, the development of harmful cyanobacterial blooms[2]. One of the reasons is that reservoirs affect the development of benthic and pelagic bacterial communities that may in turn change the biochemical processes. Furthermore, the effect of biofilm growth in reservoirs is hardly studied although it has considerable implications for sediment transport processes[3]. All these effects can alter reservoir use and perception, leading to possible conflicts between stakeholders, revealing that not only the construction but also reservoir operation and management have societal implications.

The need for sustainable, economically, socially and environmentally acceptable reservoir management strategies is now recognized. Selecting optimal strategies is a challenging task due to the complexity and interconnection of the processes involved (*e.g.* hydraulics, sediment transport, biochemistry), requiring collaborative research work from complementary disciplines.

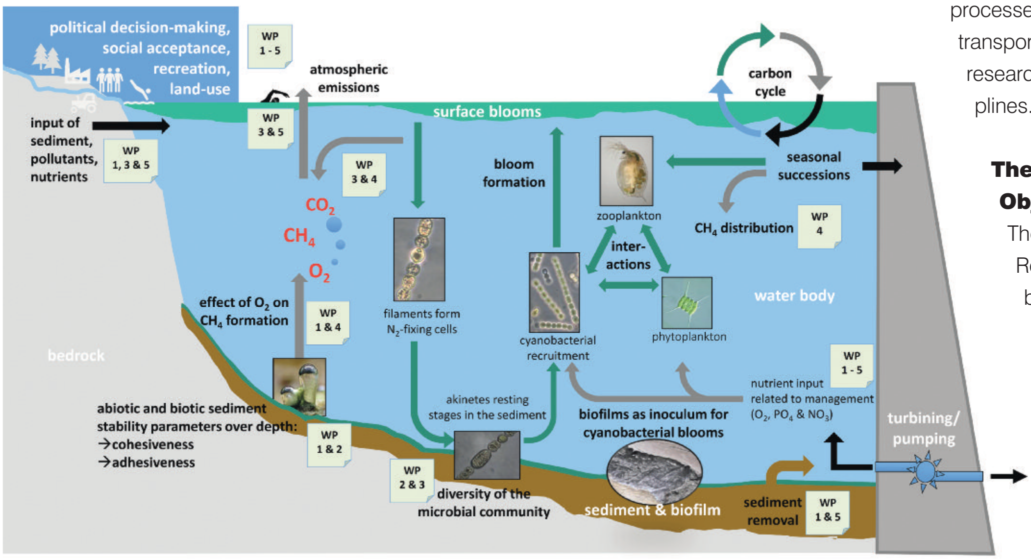

Figure 1. Interconnections between major physicochemical and biological processes in reservoirs. These processes and their relations are addressed within CHARM in a holistic approach by five cross-linked work-packages: Sedimentation (WP1), Biostabilization (WP2), Harmful cyanobacterial blooms (WP3), Greenhouse gas emissions (WP4), and Societal implications (WP5).

The project "CHARM"

Objectives and work packages

The project CHARM (CHAllenges of Reservoir Management, www.charm-bw.de) brings together scientists, with expertise in engineering, natural and social sciences, from three German universities (Stuttgart, Konstanz and Freiburg) to address, in cross-linked work packages, five of the main issues related to reservoir management: sedimentation, biostabilization, harmful cyanobacterial blooms, greenhouse gas emissions, and societal implications. The CHARM project seeks to address complex interconnections (Figure 1). For instance, the sediment deposit stability depends on several abiotic and biotic parameters that include both cohesiveness and adhesiveness. Gas produced in sediments impacts the atmospheric emissions and depends on the oxygen concentration in the deep water that is affected by reservoir operation[4]. The nutrient inputs impact the close interactions between zooplankton, phytoplankton, and cyanobacterial recruitment and initiate or boost the development of algae blooms. Algae blooms are important for socio-economic weighting, evaluation, and development of a balanced and sustainable reservoir management. Thus, the project requires considerable inter- and transdisciplinary research to reveal these interconnections, which is accomplished by close collaboration between scientists working across different fields.

Figure 2. Schwarzenbach Reservoir at maximum operation level (left) and during water level lowering (right)

Figure 3. Kleine Kinzig Reservoir used for drinking water supply (left) and reservoir Großer Brombachsee initially constructed for low water regulation but also used for local recreation (right).

Study areas and reservoirs

Research is conducted in three reservoirs (Figures 2-3): Schwarzenbach Reservoir (hydropower and recreation), Kleine Kinzig Reservoir (drinking water supply) and reservoir Großer Brombachsee (low water regulation and recreation). Joint field measurements provide data which are used (i) to correlate sediment stability with sediment parameters and greenhouse gas emissions, (ii) as background information for biofilm cultivation, (iii) for the assessment of temporal development of the phyto- and zooplankton community considering toxin production and release, and finally (iv) as a basis for hydrodynamic, sediment transport, and water quality modelling. Some aspects are investigated under controlled conditions in the laboratory, such as the vertical sediment stability over depth using novel erosion detection methods[5], the stabilizing capacity of biofilms by conducting manipulative experiments and adhesion measurements with a magnetic device[6], and the formation and toxicology of cyanobacterial blooms using mesocosm experiments[7]. To evaluate the social environment of the reservoir systems and the associated conflict potential, methodical approaches (*e.g.* constellation analyses, surveys, interviews, composite programming[8]) are used. In addition, a Collaborative Research Environment (CRE) will be prepared.

The Schwarzenbach Reservoir case

In 2016 and 2017, the focus of the project was on the Schwarzenbach Reservoir (SBT), used for hydropower production since 1926 (pumped-storage operation). The reservoir is also an attractive recreation destination ("Nationalpark Schwarzwald"), with a surface area of approximately 60 ha, a maximum depth of 65 m (average depth of 21.8 m), and a volume of about 14.4 Mm³ at maximum operation level. An intensive data acquisition, involving stationary, continuous, and spatiotemporal resolved measurements, was conducted to record a comprehensive abiotic and biotic dataset. A mooring station equipped with an Acoustic Current Doppler Profiler (ADCP), thermistors (T), optodes (O_2, CO_2) and pH sensors was installed to obtain long-term, vertically resolved datasets. Autonomously measuring funnels were installed along the thalweg and at the river mouth of the reservoir to measure the ebullition of CH_4. During regularly conducted field campaigns, the spatial distribution of CH_4 and CO_2 flux above the air-water interface was measured by floating chambers in combination with automatic CO_2 sensors, or with a portable gas sensor. In addition, local profiles of temperature, conductivity, O_2, pH, CO_2, turbidity, and Chl-a pigments were measured with different probes. The field campaigns were complemented by measurements of nutrient concentration (P, N), alkalinity, phyto- and zooplankton composition, collection of water for experiments, sediment sampling (grab and core sampling) at selected locations, and the collection of resting stages of cyanobacteria and *Daphnia* in the pelagial, profundal, and benthic sediments of the reservoir.

Sediments in the SBT consist of mainly silty material with a decreasing grain size along the thalweg towards the dam (Figure 4). The extracted sediment cores are characterized by a low bulk density (0.9 to 1.3 g/cm³) that can be due to large water and gas contents as well as a high organic content (7 to 14%). The laboratory experiments of sediment deposit stability suggest that erosion should be initiated at low shear stresses. Moreover, they emphasize that the erosion behavior can only be described by taking into account both cohesive and adhesive forces.

In 2016, water samples from the SBT (oligotrophic, slightly acidic) were collected to cultivate biofilm in the laboratory. The reservoir water was circulated in six independent, identical flumes. While the biofilm growth was studied in relation to varying flow conditions, the effects on species composition, metabolic activity, and functionality, here the ***biostabilization*** potential, were studied over a period of several weeks. The results illustrated the high potential of biofilm to stabilize fine sediments (up to 15 times as compared to the control) and revealed a strong link of this biofilm function to the nutrient and flow condition. Altogether, these first investigations indicate the impact of microorganisms on sediment deposit stability and dynamics in reservoirs.

The investigation of ***cyanobacterial blooms*** revealed that the blooms in the SBT primarily consist of *Anabaena* species and that the composition of the zooplankton community changes during the formation of a cyanobacterial bloom, *i.e.* the abundance of large

zooplankton species decreases (*Daphnia longispina*) while smaller species increase (*Ceriodaphnia* sp. and *Bosmina* sp.). Reasons for this shift in the zooplankton species community, caused by the formation of cyanobacteria, are currently investigated in laboratory and mesocosm experiments.
Based on the obtained dataset from the field campaigns, ***greenhouse gas emission*** and storage can be linked to hydrodynamic conditions, sediments, and phytoplankton development. In the SBT, the diffusive CH_4-fluxes from sediments are comparatively low (Figure 4). However, a significant correlation between ebullition and daily water level fluctuations can be seen[9]. In general, the release of methane bubbles through pumped storage operations contributes considerably to the total emission of CH_4. The O_2 concentration in the deep water decreases less with pumping compared to no pumping operation. As a result of the high O_2 concentration, the CH_4 accumulation in the deep water is reduced. Hence, the pumped storage operation indirectly contributes to the fact that CH_4 emissions of stored methane are comparatively low in the SBT during the autumn overturn.

The combination of the gained insights on biological, chemical and geological processes and the management procedures help to understand the reservoir as a system embedded in its immediate social surrounding. This knowledge can be used to mitigate ***societal implications***. For example, the formation of cyanobacterial blooms has notably increased since 2002 and is likely connected to a change in the reservoir operation. The combined relationships between major effects and the potential impairment of reservoir functionality are considered by all involved experts, to jointly derive sustainable management strategies that are designed to attenuate or avoid conflicting interests.

First lessons

The first results gained within the CHARM project reveal that there are complex interdependencies between the processes of sedimentation, biostabilization, harmful cyanobacterial blooms, greenhouse gas emissions, and their societal implications. These interdependencies can only be addressed by transdisciplinary research among the involved disciplines. It is recommended to take into consideration biochemical parameters (*e.g.* biostabilization) in investigating sediment stability in reservoirs. The reservoir management also impacts greenhouse gas emissions, showing a clear correlation between ebullition and water level fluctuations. This knowledge is of significant importance for drawdown periods or pumping operations, which further affect the nutrient influx and the distribution of dissolved substances and algae in the reservoir that may support the formation of cyanobacterial blooms. The latter may lead to conflicts between stakeholders, especially when the reservoir is used for other purposes (*e.g.* recreation).

After the completion and evaluation of the integrated data collection, it is intended to implement the obtained information in a numerical model that takes into account physical and biological processes, thereby contributing to a better understanding of sediment dynamics, distribution and release of greenhouse gases, and water quality in reservoirs. The model can be used to simulate and predict the effects of reservoir management scenarios to derive sustainable strategies, meet multiple interests, and increase societal acceptance of reservoirs. Conclusively, reservoirs with different purposes and management (Kleine Kinzig, Großer Brombachsee) will be considered within the next two years in order to ensure the transferability of the results. ■

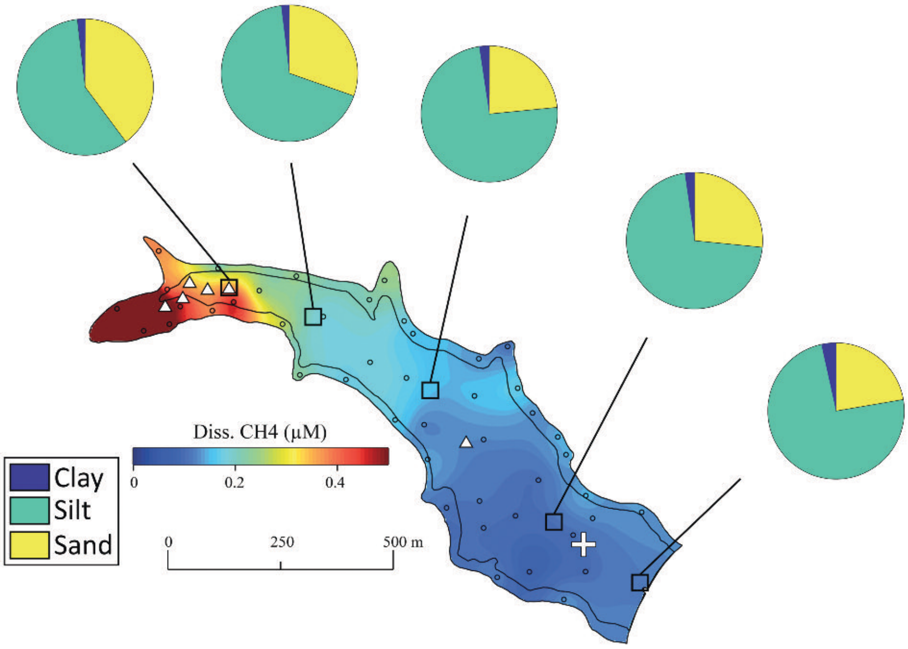

Figure 4. Spatial distribution of the dissolved CH4 concentration in the Schwarzenbach Reservoir and surface sediment composition along the thalweg (data recorded in 2016). Black circles: CH4 sampling stations; White triangles: ebullition funnels; Black squares: sediment sampling locations; White cross: mooring station. The map shows the reservoir at maximum operation water level, whereas the black contour line indicates the minimum operation level.

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The CHARM-Team i
The project *CHARM "CHAllenges of Reservoir Management - Meeting Environmental and Social Requirements"* is part of the Water Research Network Baden-Württemberg. It is funded by the Ministry of Science, Research and Arts of the federal state of Baden-Württemberg, Germany.

Under the lead of Prof. Dr.-Ing. Silke Wieprecht, 17 researchers and various students contribute to achieve the project goals.

For further information about CHARM:
www.charm-bw.de

ON SEDIMENT-INDUCED PROBLEMS UNDER THE DAM REHABILITATION AND IMPROVEMENT PROJECT IN INDIA

BY SANJAY GIRI AND PRAMOD NARAYAN

Reservoir sedimentation in India

Dams and reservoirs are important assets in India with strong seasonal flow pattern variations and highly increasing water and energy demands due to rapid growth of economy and population. The negative impacts of dams and reservoirs can be attributed to poor planning, mismanagement, inefficient operations and insufficient consideration (or negligence) of mitigation strategies. The importance of dams and reservoirs and both their positive and negative impacts should be objectively measured vis-a-vis multi-sectorial benefits, specific priorities and demands.

India has 5,262 completed large dams, of which 2,329 were commissioned before 1980 and 437 dams are currently under construction. The loss of storage capacity in these reservoirs has become one of the major concerns for water security and structural safety. For comparison's sake, reservoir sedimentation studies of 243 dams in India[1] have revealed that about 26 billion m^3 of gross storage volume has already been lost, which is more than the total storage capacity (about 23 billion m^3) of all large dams in Japan. Figure 1 shows the gross storage losses in selected reservoirs in eight Indian states. To review the actual sedimentation in some relevant reservoirs, a plan scheme has been initiated by the Ministry of Water Resources, River Development and Ganga Rejuvenation to conduct surveys on a regular basis.

Dam safety and rehabilitation efforts in India

Construction of new dams and reservoirs has become more difficult due to increasing social, environmental, resettlement and rehabilitation constraints and compliances. In most cases, the water stress situation in several states of India can be attributed to improper management of available resources and infrastructure like dams and canals. Consequently, dam rehabilitation and improvement efforts have become indispensable. The Central Dam Safety Organization (CDSO) of the Central Water Commission (CWC) encourages and facilitates dam safety and rehabilitation practices in India. A Dam Rehabilitation and Improvement Project (DRIP) (www.damsafety.in) was initiated by the Government of India in 2012 with the assistance of the World Bank as a continuation of the previous Dam Safety Assurance and Rehabilitation Project (DSARP). The primary objective of DRIP is to improve the safety and operational performance of about 250 dams in seven states of India along with strengthening institutional capacity and promoting sustainable dam management, not only at the central level,

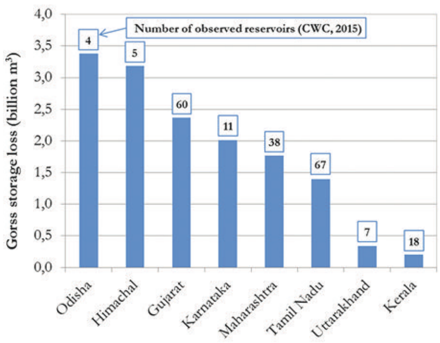

Figure 1. Reservoir gross storage loss in some states of India (based on data of CWC[1])

Figure 2. Sediment-induced damages of spillway glacis, guide bank and stilling basin at Maneri Bhali Stage-1

but also in participating states and agencies. Initially, sediment-induced problems were not identified as a priority within DRIP. However, growing concerns lead different dam authorities in the states to explore sediment management strategies for some reservoirs. These reservoirs are not only losing storage capacity, but also suffering from abrasion, clogging and malfunctioning of civil structures, such as weirs, spillways, desilting basins, stilling basins, roller buckets, under-sluices, guide banks (Figure 2), mechanical and electrical equipment and apparatus (*e.g.* turbines, gates, trash racks). Priority has been given to rapid assessment and handling of sediment-induced problems in few selected reservoirs. A handbook is being prepared synthesizing past and on-going experiences, technologies, existing research, case studies and practices related to a broad spectrum of sediment-induced problems in reservoirs. The handbook shall provide guidance on how to assess and manage/combat reservoir sedimentation.

Rapid assessment and handling considering beneficial reuse

Based on requests from the state dam authorities, five reservoirs have been selected for rapid assessment of sediment-induced problems, namely the Kundah Palam, Pillur and Papanasam reservoirs in Tamil Nadu State (located in sedimentation zone of south part of India, characterized by Deccan Plateau[1], and the Maneri Bhali Stage-1 and Dakpathar barrage in Uttarakhand State (located in the sedimentation zone of the north part of India, characterized by Himalayan Region and Indo-Gangetic Plains[1]. In addition, a pilot study is being carried out for the Dakpathar barrage, supported by the Dutch Partners for Water (PvW) Programme.

Rapid assessment and analyses were made based on field reconnaissance, some old data and information that were readily available. Results for some of these reservoirs are summarised in Table 1, including sources of the problems and sediment handling options based

Table 1. Sediment-induced problems, their sources, preliminary selection of sediment handling and beneficial reuse options in selected reservoirs under DRIP

Dam (Type)	Gross storage	Sediment Zone[1]	Purpose	Problems	Sources/Reasons	Sediment Handling/Reuse Options
Kundah Palam (Forebay)	1.76 million m^3	Deccan Plateau	Hydropower	• Storage loss (≈60%) • Partially clogged scour vent and trash rack at tunnel intake, leading to risk of failures and disruption in power generation (Figure 4)	Surface erosion, erosion of bare lands (due to cultivation on slopes without terrace), mud, fine sediment (not harmful for turbines)	• Phase-wise sediment removal plan in three reaches (divided based on morphological feature) to minimize hindrance to power generation[2] • Dry excavation in upstream reaches, trucking and dumping[2] • Hydraulic dredging (syphoning/pumping) near dam area and partly downstream release[2] • Sediment measurement and monitoring (Reservoir Morphology Information System) • Regular sluicing during monsoon **Sediment reuse options** • Land improvement by filing a valley-like area, owned by dam authority, and develop it as a playground or recreational park[2] • Top soil enhancement for agricultural land • Sediment trap upstream (by simply keeping intact a part of consolidated deposition in form of a spur) • Downstream morphological and ecological enhancement by controlled release of deposited material
Pillur (Storage)	34.97 million m^3	Deccan Plateau	Hydropower Water supply	• Storage loss (≈42%; ≈ 20 million m^3 of deposition) • Increasing sedimentation near water supply intake • Clogged under-sluices • Sediment consolidation	Surface erosion, erosion of bare lands (cultivation on slopes without terrace), mud, fine sediment (not harmful for turbines)	• Regular maintenance using hydraulic dredging (syphoning or pumping)[3] • Downstream release and replenishment[3] • Regular sediment removal (recurrent measure) from key locations (*e.g.* near water supply intake, hydropower intake, under-sluices) • Proper study and measurement to avoid downstream impacts • Investigation of sediment bypass system • Sediment measurement and monitoring (Reservoir Morphology Information System) • Regular sluicing/venting during monsoon **Sediment reuse options** • Land improvement and agricultural enhancement • Construction material • Enhancement of downstream river environment
Maneri Bhali Stage-1 (Run-of-the-River)	0.6 million m^3	Himalayan Region	Hydropower	• Abrasion and damage of spillway, gates, stilling basin, guide banks/walls (Figure 2) • Large deposition (up to spillway crest, Figure 4) • Migrating sediment delta	River erosion, landslides, debris flow, road construction, graded materials, fine silt (like quartz, harmful for turbines)	• Sediment removal by dry dredging and trucking (removing sediment in front of the spillway provides favorable condition to minimize damages of spillway and gates due to the trapping of gravels and boulders[4] • Regular maintenance using hydraulic dredging (pumping or syphoning) • Soft and temporary sediment trap upstream of the reservoir (also to assess the transport[4] • Improved gate operation during high flows and sluicing[4] • Monitoring and forecasting systems **Sediment reuse options** • Construction materials for river and other infrastructure • Soft structural and recurrent measures (geotubes, gabions) to trap sediment
Dakpathar (Barrage, forebay)	0.71 million m^3	Indo- Gangetic Plain	Hydropower Irrigation Recreation	• Storage loss • Unfavorable sediment deposition in power intake area	River erosion, landslides, debris flow, large materials, fine silt (like quartz, harmful for turbines)	• Intelligent dredging (pumping) and dumping within reservoir considering morphological features, location of power channel intake and gates • Regular maintenance using hydraulic dredging (pumping or syphoning) • Regular and intelligent sluicing • Improved gate operation • Monitoring and forecasting systems **Sediment reuse options** • Filling geotubes to be used as baffle and traps for improving morphological condition in the reservoir • Construction materials for using within (for bank protection) and outside the reservoir • Improving environmental conditions for migrating birds and habitats

on a quick assessment of technical, economic and environmental feasibility and impacts[2,3,4]. Emphasis is given to beneficial reuse of the deposited material as a potential resource and not as a waste, supporting therefore the circular economy concept (Figure 3).

Variability in type, magnitude and sources of sediment-induced problems reveals their complexity and distinctiveness, indicating the need for a tailor-made approach to each individual dam. It should be mentioned that reservoir sedimentation problems in the southern reservoirs (Tamil Nadu State) are not always due to high erosion rate in upper catchments, but rather to unprofessional dam operations and lack of regular sediment handling measures. There are provisions of addressing sediment problems, but they are usually ignored by hydropower entities and water resources authorities, particularly in water stressed areas. Therefore, a judicious trade-off is essential to

Figure 3. Sediment reuse concept for circular benefit

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Pramod Narayan is working with Central Water Commission for more than 22 years. Currently, he is the director of Dam Safety Rehabilitation Directorate and a project director for World Bank assisting ongoing Dam Rehabilitation and Improvement Project (DRIP) in India. He is also the nodal officer coordinating the DRIP activities with various international partners. He has worked as member secretary for various expert review panels and he has been one of the contributors publishing guidelines and manuals for dam safety management.

address these problems holistically. It is recommended that proper measurements and detailed analyses be carried out to fine-tune the proposed options of sediment handling.

Constraints

Complexity and constraints, associated with reservoir sediment management in India, are related not only to techno-economic feasibility, but also to social, environmental and legal aspects. Major constraints include social and environmental impacts of sediment removal, transport and disposal options, the presence of preserved areas and sanctuaries in the vicinity of reservoirs, and the consolidation and contamination of the deposited materials. There are several legal and institutional constraints, such as ambiguous regulations for sediment removal and disposal from reservoirs, inefficient rules and decision-making processes for hydropower and multipurpose reservoir operations, and inter-state disputes on the operation and management of transboundary reservoirs. Reservoirs located in reserved forest areas are governed by different rules and regulations, ultimately leading to unwarranted delays that impact adversely the overall implementation of rehabilitation projects. For such reservoirs, new set of rules and guidelines need to be established in order to have a balance between societal needs and environmental safeguard. Also, lack of relevant data and information create certain constraints to undertake sediment management.

Application of knowledge, tools and technology

For rapid assessment of impacts associated with sediment management options and alternatives (cf. Table 1) within DRIP and PvW programme, several methods, tools and technology have been applied[2,3,4] such as (i) professional knowledge and local experience, (ii) morphological numerical modelling with Delft3D, coupled with Feedback Control Tool to simulate gate operation, (iii) sediment and bathymetry measurements (for Dakpathar pilot case), (iv) smart sediment dredging using environmental friendly equipment, (v) application of innovative techniques for dewatering, treatment and reuse of dredged materials (sludge, mud, fine sand, gravels).

It has been proposed to establish flow and sediment monitoring as well as inflow forecasting systems for all these reservoirs. For example, a Reservoir Morphology Information System (RMIS) has been described in the DRIP handbook. This handbook contains also materials about worldwide experiences and state-of-the-art approaches and technologies for the assessment and management of sediment-induced problems in reservoirs. These materials can serve as a knowledge base

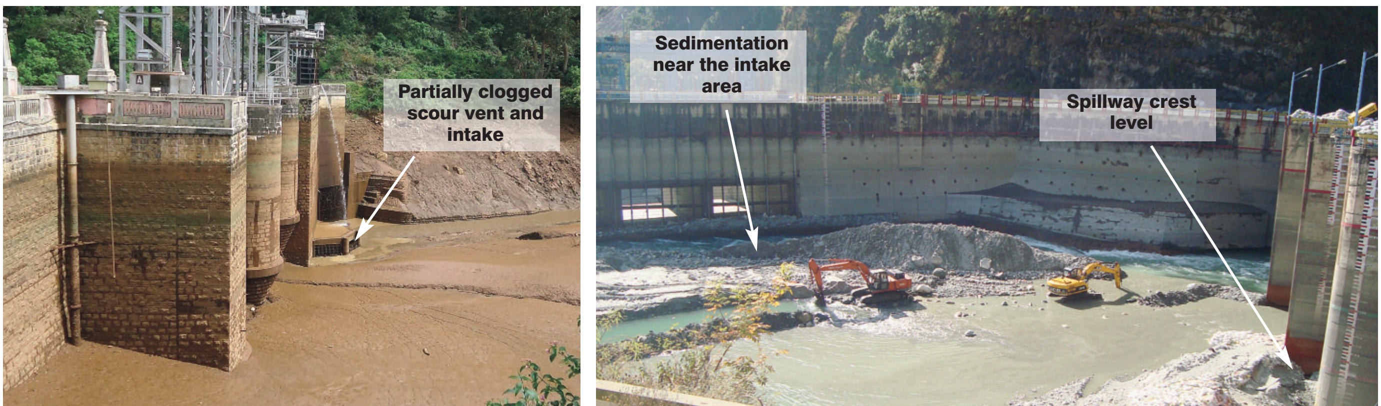

Figure 4. Sediment deposition at Kundah Palam in Tamil Nadu (left) and Maneri Bhali Stage-1 in Uttarakhand (right), revealing differences in source, feature and sedimentation rate

to prepare tailored guidelines and procedures to assist dam owners to address reservoir sedimentation challenges systematically and holistically. Additionally, a tool for supporting decision-making processes, currently being developed, will be useful for selecting and prioritizing sediment management options[5].

Failure examples and lessons learnt

Hereafter, two failure examples are given, serving as lessons to be considered while preparing and executing sediment management operations.

Sediment disaster at Pillur reservoir: An attempt was made to empty the Pillur reservoir in 1991 (after about 30 years of dam operation) through drawdown flushing, but ended in disaster. The deposited amount of sediment was huge for uncontrolled flushing through the under-sluices (scour vents)[2, 3]. The slurry was an hyper-concentrated fluidized sediment mass that did not behave like normal sediment-water mixture, bursting toward the powerhouse (located downstream at the left side of the dam body). The powerhouse was covered with large amount of sediments and the generation had to be stopped for few months. Since then the under-sluices have never been used for sluicing or flushing, and apparently they have become clogged again.

Environmental havoc at Kallarkutty reservoir: There was a serious environmental disaster caused by an uncontrolled reservoir flushing[6] in this reservoir, located in the Pariyar River (Kerala State) in the downstream-most area of Mudirapuzha basin. Apparently, the area near the Pariyar River and its banks was polluted by industrial effluents6, contaminating reservoir sediment deposits. Sediment removal operations had not been carried out for more than 18 years regardless of the fact that there were provisions for regular sluicing6. Moreover, no proper investigation was carried out to assess quantity and quality of deposited materials. This led to spreading of contaminated flushed sediment and water into several rural water supply pumping systems, located in downstream areas. The water supply system in the entire Kochi region as well as aquatic and habitat life in the downstream reach were severely affected[6]. ■

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Professor Geoffrey Petts (1953-2018)

Geoffrey Petts was an outstanding scientist who made distinguished contributions to river science and, notwithstanding his move into university senior management in 2001 and becoming Vice-Chancellor and Rector of the University of Westminster, he continued to conduct research, supervise doctoral students and edit a major international journal. While his research profile is stunning, his personal qualities made him a particularly exceptional individual, explaining why so many people across the globe will miss him deeply.

Geoff was a larger-than-life character, who always maintained a positive attitude even during difficult times, facing life's challenges with endless good humour. He treated everyone equally, hearing and acknowledging people's views even if he did not agree with them. He was also prepared to make what he believed to be the right decisions, even when they might be unpopular. He was an exceptional leader, a great team player, an inspirational teacher and speaker, and a sincere, reliable friend.

Geoff's doctoral research focussed on the geomorphological response of river channels to flow regulation by dams. Unusually for the time, but typical of Geoff's interests throughout his academic career, this research tackled an important applied problem as well as delivering an excellent piece of fundamental science. Although starting as a geomorphologist, he soon recognised that river science needed to address the intimate linkages between geomorphology, hydrology and ecology. He was one of the first to recognise that multidisciplinary understanding was the key to developing sustainable solutions to river management problems.

Geoff published on numerous aspects of river science from physical to chemical and biological, from patch to catchment scales, and always with the aim of developing practical applications of the results. In adopting this holistic approach, he was adhering to the truly geographical (integrative, multi-scale) tradition to which he subscribed. Pursuing this tradition, his early research on dams and geomorphology resulted in the publication in 1984 of his best known and scientifically revolutionary book 'Impounded Rivers', which, according to Google Scholar, has achieved over 1500 citations. Geoff authored and edited a further 21 books and the Web of Science lists 129 papers. He founded the journal River Research and Applications (previously Regulated Rivers), reflecting his multidisciplinary and applied interests in river research and management, and served as Editor in Chief from 1985 to 2016. These numerous and varied academic outputs are all the more remarkable considering that such a large part of his career was devoted to university management.

As well as publishing prolifically, Geoff supervised 22 research students. He also held many influential appointments related to river science including: Director of the International Water Resources Association; President of the International Society for River Science (2011-13); and President of the British Hydrological Society (2015-17). Among many awards, he received the Busk Medal from the Royal Geographical Society (2007) and a Lifetime Achievement Award from the International Society for River Science (2009).

Geoff made so many good friends across the globe. He spread good will internationally and was a magnificent ambassador for river science and its related disciplines of geography, geomorphology, hydrology and river ecology. He was also a family man, who stressed the important contribution of his parents in encouraging him to work hard and aim high. He is survived by his wife of over 40 years, Judith, who gave him enormous support throughout those decades. Geoff Petts - Vice Chancellor, Professor, scientist, teacher, mentor and friend - will be sorely missed by all of us.

Angela Gurnell
(based on an obituary written for the British Society for Geomorphology and the Royal Geographical Society)

PREDICTING RESERVOIR CAPACITY LOSS FROM SEDIMENTATION AT LARGE INDIAN DAMS

BY DAVID C. FROEHLICH

Eroded sediment transported by natural streams tends to settle out when it enters the comparatively calm water of an artificial lake (a reservoir) created by a dam. The rate of water storage loss depends on the annual sediment load carried by the streams and the extent to which that material is kept in the reservoir. The amount of sedimentation is controlled by a number of factors including the area and geologic origin of the catchment, the land uses (cultivation practices, grazing, logging, construction activities, and conservation practices), the amount of rainfall, the reservoir storage capacity, the duration of storage in relation to the sediment load of the stream, the particle size distribution of sediment, the planform configuration of the reservoir, the location and size of sluices and other outlet works at the dam, and the method and purpose of water releases through those outlets.

As time passes, a reservoir continues to fill with sediment, which reduces the available storage volume and may interfere with the operation of dam outlet works and hydropower intake structures (Figure 1). The question that needs to be answered is: How long will it take before the functions of the dam and its reservoir are so severely affected by sedimentation that continued operation becomes untenable? The rate of sedimentation in a proposed or existing reservoir may be estimated in the following ways[1]:

1. From sediment discharge rating curves combined with flow-duration relations on significant streams entering the reservoir. The sediment discharge rating curves may be prepared using measured or calculated values of sediment loads.
2. From calculations of the total amount of land surface erosion, the ability of the sediment to be transported to the impoundment, and the reservoir trapping efficiency.
3. From predictions based on sedimentation in existing reservoirs in which the accumulated deposits have been surveyed over a lengthy period.

It is the third approach that is followed here. The data are obtained from a compendium of storage loss from siltation at 243 reservoirs in India[2]. Mathematical models are developed that relate reservoir capacity loss to catchment area, reservoir surface area, the original storage volume, and the time since the first filling of the impoundment. Models prepared for sedimentation of reservoirs found on the eastward and the westward-flowing regions differ significantly. The formulations give good fits to the assembled data and allow an uncomplicated calculation of the half-life of reservoirs (that is, the time needed for the storage capacity to be reduced by 50%), which offers a measure of when sedimentation will have a significant adverse impact on functioning.

Analysis of Reservoir Capacity Loss and Half-Life

Estimating the amount of sedimentation in a reservoir could require extensive calculations of the sediment yield from the catchment, the amount of eroded soil that is transported to a reservoir, the additional sediment inflow contributed by stream channel bank and bed erosion, and the quantity of water that flows into the impoundment. However, a more simple and faster approach to estimating reservoir sedimentation is developed here by analyzing

Figure 1. Sediment accumulation reduces storage volume and may interfere with the operation of dam outlet works. Removal of sediment by dredging or excavation (as shown in the photograph of the Maneri Bhali Stage 1 dam during maintenance of the spillway.) may be needed to enable the dam to function.

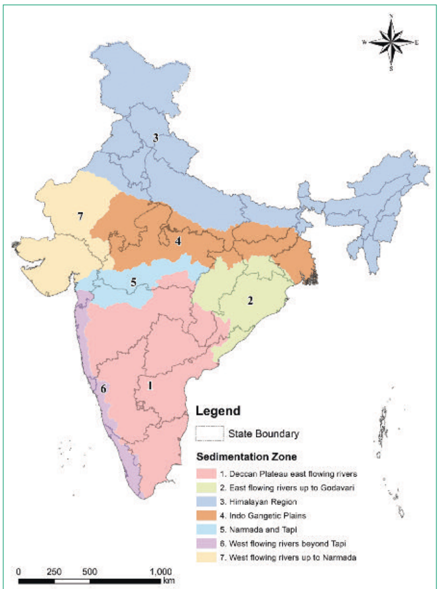


Figure 2. Sedimentation Zones of India[2]

data from the compendium of siltation in reservoirs at large Indian dams[2] where the accumulated deposits have been surveyed over a suitable period. The compilation divides India into seven sedimentation zones as shown in Figure 2. Zones 1, 2, 3 and 4 cover geographic regions in which rivers flow eastward to the Bay of Bengal, while Zones 5, 6 and 7 encompass areas where rivers flow westward into the Arabian Sea. After filtering the data, 130 reservoirs on eastrward-flowing rivers and 90 reservoirs on westward-flowing rivers were analyzed.

Reservoir Capacity-Loss Calculation

For both eastward and westward-flowing rivers, a general mathematical model of the form:

$$\ln\hat{Y} = \theta_1 + \theta_2 \ln A_c + \theta_3 \ln A_r + \theta_4 \ln C_o + \theta_5 \ln T \qquad (1)$$

provides a linear relation for $\ln\hat{Y}$ with constant variance and good fits to the assembled data, where $\hat{Y}$ expected value of reservoir capacity loss in Mm^3, A_c = catchment area in km^2, A_r = surface area of the reservoir when filled to the controlled retention level (FRL) in km^2, C_o = initial storage capacity of the impoundment in Mm^3, and T = time in years since the initial filling of the reservoir. Values of the parameters θ_1 to θ_5 were found using multivariate optimization and were slightly rounded to obtained the following relations (after transformation from logarithms) for $\hat{Y}$:

$$\hat{Y} = \begin{cases} 0.0064 A_c^{0.10} A_r^{0.05} C_o^{0.8} T^{0.90}; & \text{eastward flowing rivers} \\ 0.030 A_c^{0.15} A_r^{0.30} C_o^{0.5} T^{0.65}; & \text{westward flowing rivers} \end{cases} \qquad (2)$$

The coefficient of determination of Eq. (1) fit to the 130 reservoirs on eastward-flowing rivers is 0.929, and the residual standard error is 0.600. Predicted Y_{east} values are plotted against measured values in Figure 3. Similarly, for the 90 reservoirs on westward-flowing rivers, the coefficient of determination is 0.880, and the residual standard error is 0.496. Predicted values of Y_{west} are plotted against measured values in Figure 4.

The expression for the loss of reservoir storage volume on westward-flowing rivers Y_{west} varies significantly from the equation for Y_{east}. While the relative influence of A_c is the same, the remaining independent variables have different effects on reservoir capacity loss. The most significant difference is related to time. All other factors being the same, capacity loss of reservoirs on westward-flowing rivers is considerably slower than on eastward-flowing streams resulting in a comparatively longer half-life. Regional reservoir sedimentation differences are the result of combined meteorological and geological influences on land surface runoff and sediment yield.

Reservoir Half-Life Calculation

Reservoir half-life is determined from Eq. (2) by setting Y/C_o = 0.5 and solving for T to obtain

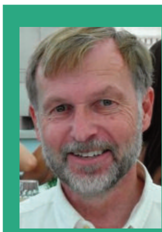
$$T_{50\%}(\text{years}) = \begin{cases} [74.2 A_c^{-0.15} A_r^{-0.1} C_o^{0.3}]^{1.11}; & \text{eastward flowing rivers} \\ [16.6 A_c^{-0.15} A_r^{-0.3} C_o^{0.5}]^{1.54}; & \text{westward flowing rivers} \end{cases} \qquad (3)$$

The regional difference in the calculated half-life is shown by considering the value found for a proposed reservoir where C_o = 80 Mm^3, A_c = 200 km^2, and A_r = 5 km^2. Inserting variables in Eq. (3) gives $T_{50\%}$ = 178 years for the reservoir built on an eastward-flowing river and 309 years on a westward-flowing river.

Summary and Conclusions

Mathematical models are presented, relating reservoir capacity loss at large Indian dams to catchment area, reservoir surface area, initial storage volume, and time since the initial filling of the impoundment. Two models are developed, one for reservoirs on eastward-flowing rivers and one for westward-flowing regions. The expressions for the loss of reservoir storage volume in the two regions differ significantly because of the joint meteorological and geological influences on land surface runoff and sediment yield.

The models give good fits to the assembled data and allow an uncomplicated calculation of the half-life of reservoirs (that is, the time needed for initial storage capacity to be reduced by 50%), which provides a measure of when sedimentation will have a significant adverse impact on functioning. The relations provide a straightforward and rapid means of estimating the loss of reservoir storage capacity caused by sediment deposition. ■



Specializing in complex and computationally-intensive designs and plans for water resource engineering projects, **Dr. Froehlich** has accumulated more than four decades of domestic and international knowledge in design, research, teaching, project management, and institutional counseling.

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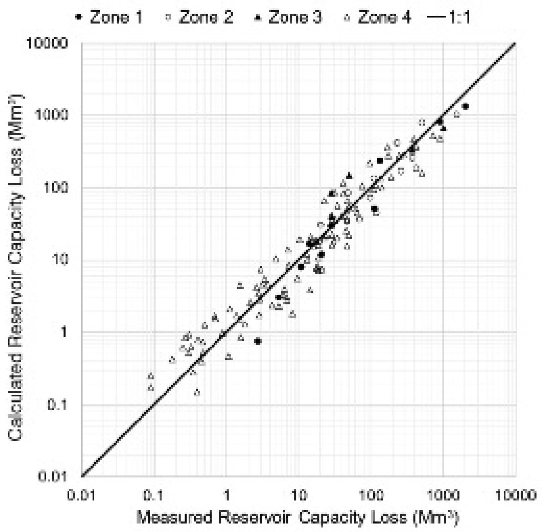

Figure 3. Comparison of measured and calculated reservoir capacity losses in 130 reservoirs on eastward-flowing rivers in sedimentation zones 1, 2, 3 and 4

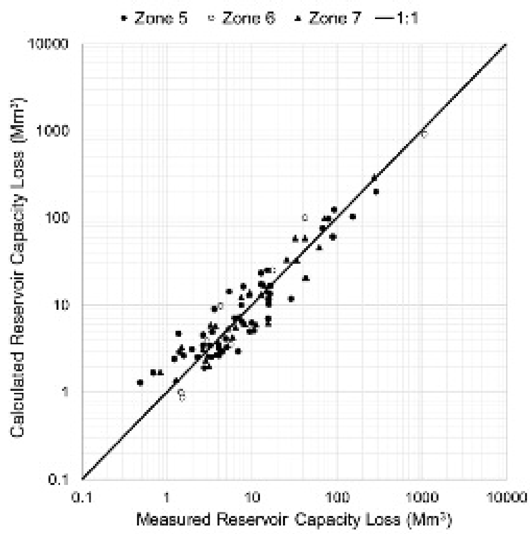

Figure 4. Comparison of measured and calculated reservoir capacity losses in 90 reservoirs on westward-flowing rivers in sedimentation zones 5, 6 and 7

IMPACTS OF LAND USE CHANGE ON THE SEDIMENTATION OF THE MANGLA RESERVOIR, PAKISTAN

BY I. HUSSAIN, A. CATTAPAN AND M. J. FRANCA

Land use changes alter soil erosion patterns, which in-turn change the sediment yield of a catchment. Experimental investigation and worldwide catchment studies revealed the sensitive relation between land use, erosion rate and relevant human activities[1]. Different land use types tend to reduce or increase the sediment inflow.

The problem might seem quite simple to analyse at a local scale; however, the sediment yield of a river basin is affected by other factors, such as surface run-off, temperature, slope stability, making the sedimentary processes more complicated to model and requiring basin scale approaches. The multipurpose Mangla Reservoir, in Pakistan, is losing its storage capacity at a yearly rate of about 0.5 % (1,970 million of m3 lost between 1967 and 2010, before up-raising the dam in 2011). The impacts of land use changes in the Mangla Dam basin were assessed, showing that the current trend will not be affected greatly if the land use remains unchanged from the present conditions. However, if large levels of deforestation occur in the future, the increase in the sedimentation rate would have a dramatic effect on the sustainability of the Mangla Reservoir.

Background

Pakistan is confronting a major issue of sedimentation, which is continuously reducing the useful storage space of reservoirs. The global storage capacity loss due to sedimentation is of 0.5 to 1% annually[2]. The sustainability of reservoirs, vital parts of the infrastructure developed to meet the country's needs for drinking water, agriculture and power generation, is under threat. Urgent measures are required for attaining sustainable use of reservoirs, thereby changing them from exhaustible into sustainable renewable resources[3,4].

The Mangla Dam, was constructed across the Jhelum River between 1961 and 1965 and was commissioned in 1967. Its primary purpose is irrigation, with secondary functions of hydropower production, fisheries and flood control. Its height at construction was 138.38 m, with a design gross storage of around 7,250 million of m^3 (Mm^3). In order to counteract the loss of storage due to sedimentation, the dam was raised up to around 147 m, which brought the gross storage to around 9,110 Mm^3 in 2011. The reservoir collects the water from the Jhelum River (Figure 1) and plays an important role in managing the water resources of Pakistan. Particularly, the reservoir supplies water, through a network of interlinked rivers and canals, to the eastern rivers (Ravi, Sutlej, and Bias rivers) which suffer from water scarcity.

Most of Mangla Reservoir's catchment is hilly, with steep slopes and relatively thin vegetation. This results in high sediment inputs into the reservoir, particularly during the rainy monsoon season from July to September. Periodic bathymetric surveys carried out by the Water and Power Development Authority (WAPDA) have shown that more than 20% of gross storage capacity of the reservoir was lost over the period of 1967 and 2010, which means that the gross storage capacity of the reservoir is declining at an average rate of about 0.5% per year. Evidence of this large sedimentation process is the formation of a delta on the left bank of the reservoir (Figures 2), gradually advancing toward the dam structures[5].

Statistics have indicated that there exists a deforestation trend in the basin of the Mangla Dam due to rapid population growth. Usually, inhabitants of the Himalayan region cover the majority of their energy needs from the forests. Fuelwood is identified as the most significant cause of deforestation in developing countries[6]. It accounts for more than 54% of global harvest per annum, and the Mangla Dam catchment is not an exception. Other significant reasons for deforestation include timber logging for shelter, livestock fodder, wood export, clearance for cultivation and urbanization[7]. In addition, agriculture is growing in the region. Poor practices increase the surface of loose soil which is more prone to erosion.

Herein this article presents an investigation to verify if both, deforestation and increased agricultural practices, are a major catchment-scale factors determining the sedimentation of the Mangla Reservoir. A modelling approach, supported by field observations and data, was developed at the basin scale. Several scenarios

Figure 1. Mangla Reservoir with indication of the Jhelum river (source Google Earth)

Figure 2. Formation of a delta in the left side of Mangla Reservoir (source Google Earth)


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Mário Franca is Professor of Hydraulic Engineering and River Basin Development at IHE Delft and TU Delft, and Head of the chair group for River Basin Development at IHE Delft, the Netherlands. His sphere of research activities includes fluvial flows, sediment transport and non-conventional hydropower production. He belongs to the leading team of the IAHR section on Experimental Methods and Instrumentation. He is associate editor of Water Resources Research (AGU).

of land use development were tested comprising (a) the continuation of a similar situation in terms of land use as the present one (where business is the usual scenario), and (b) two different conditions of deforestation activity within the catchment defined by worst case scenarios.

Modelling approach

The Jhelum River is the major contributor of sediment arriving to Mangla Reservoir. The catchment corresponding to the Jhelum River is about 80% of the total Mangla Dam watershed. The total sediment yield of the upper Jhelum river was estimated and the impacts of possible future land use changes were evaluated using the Soil and Water Assessment Tool (SWAT)[8]. SWAT is a semi-distributed, physical based model which was mainly developed to evaluate land management impacts in complex river basins. The whole catchment is divided into small sub-catchments which are then reclassified in HRUs (Hydrologic Response Units) as the basic simulation units. An HRU is a homogeneous entity in terms of soil type, land cover and slope. The model then integrates the contributions at the sub-catchment level using a weighted-area average method. SWAT requires different catchment data at different spatial scales: catchment, sub-catchment and HRU. Climatic data are defined at the sub-catchment level and SWAT applies the same data to each HRU in that particular sub-catchment. Flow routing and snow melt data are provided at the global catchment level whereas land management and soil data are processed at the HRU level.
For modelling purposes, the catchment of the Mangla Dam was taken as the geographic unit for the aggregation of data, planning and computations. The existing trends in land use change were projected into the future to predict upcoming configurations. Possible future *worst-case scenarios* were formulated under two hypotheses that, in order to satisfy the food production needs of a growing population, 15% or 21% of the forested land will be converted into irrigated agriculture, respectively. SWAT simulated the hydrological processes in the watershed. The future land-use changes were incorporated into the model to predict the future variations in water and sediment balance in the Mangla Reservoir.

Data

Remote sensing and observed data were used for the modelling setup, calibration and validation. Remote sensing data included:

- Digital Elevation Model (DEM) of the catchment, extracted from Shuttle Radar Topography Mission (SRTM) with 90 m resolution (released by the U.S. Geological Survey in 2013).
- Soil Maps obtained from the Food and Agriculture Organization (FAO) classification project (400 x 400 m resolution).
- Land Use Land Cover (LULC) maps from USGS Global Land Cover Characterization (GLCC) database, which is a series of land cover dataset classifications primarily based on unsupervised classification of 1-km Advanced Very High Resolution Radiometer (AVHRR) 10-day Normalized Difference Vegetation Index (NDVI) composites.
- Meteorology data obtained from The National Centre for Environmental Prediction (NCEP) for Climate Forecast System Reanalysis (CFSR).

Observed data, used for model calibration and validation, included:

- Hydrological daily data from the Surface Water Hydrology Project (SWHP) conducted by WAPDA Pakistan. Observed data at the "Azad Pattan" gauging station, the last station upstream of the Mangla Reservoir, was used. The flow discharge of the Jhelum River at "Azad Pattan" station represents almost 80% of the discharge entering the Mangla Reservoir.
- Sedimentation data collected by WAPDA Pakistan. Unlike flow data, which was observed on daily basis, sediment data was observed fortnightly and when required/necessary. Observed sediment concentrations at the "Azad Pattan" gauging station could be obtained from WAPDA on different dates. Rating curves were then developed to compute the total sediment yield.

Model setup

The SWAT model setup involved the following steps:

- **Watershed delineation**: the whole catchment was delineated into 29 sub-catchments using a threshold area of 500 km^2. The process was accomplished through manual delineation which provided flexibility to edit closure locations and sub-catchment shape.
- **HRU analysis**: developed soil and land use maps were used as model data input along with slopes of the area. In order to develop utmost land use detail, the threshold value for land use was set to zero. However, 10% threshold value was assigned to slopes and soil classes. The overall catchment was subdivided into three slope classes according to FAO guidelines: undulating areas with 0 to 8% slopes; steep lands with 8% to 30% slopes; mountainous areas with slopes exceeding 30%. Following this procedure, a total number of 840 HRUs was generated.
- **Meteorological data**: SWAT performed simulations using different meteorological variables, such as solar radiation, wind speed, relative humidity, temperature and rainfall. For the purpose of this research, only temperature and precipitation data were available. Therefore, in the proceeding steps the Hargreaves method was used for estimating evapotranspiration.

Depending upon the data input, suitable methods for reproducing different processes were defined: the SCS curve number method for surface runoff simulation, the Hargreaves method for evapotranspiration, variable storage method for surface routing, and the simplified Bagnold's method for sediment routing.
The simulations were made for the period wherein observed data was available, *i.e.* from January 1st 1979 to December 31st 1995. The first two years (1979 to 1981) were regarded as a 'warmup period'. The simulations were made on a daily time step, as it was more appropriate for accurate sediment yield estimations, although the output is presented monthly for the sake of legibility.

This work is part of a more general thematic research held at the River Basin Development chair group of IHE Delft, which includes the three-years research program on Sustainable Hydropower and Multipurpose Storage to meet Water, Food, and Energy Development Goals: A Program for Collaborative Research and Innovation (S-MultiStor), https://www.un-ihe.org/projects/sustainable-hydropower-and-multipurpose-storage-meet-water-food-and-energy-sdgs.
The program is supported by the Programmatic Cooperation between the Directorate-General for International Cooperation (DGIS) of the Dutch Ministry of Foreign Affairs and IHE Delft in the period 2016 - 2020. This program investigates and demonstrates improved approaches to sustainable multipurpose storage, including sedimentary issues. S-MultiStor creates a common research and innovation platform, where researchers from IHE Delft and southern partner institutions engage with leading international initiatives in a structured program of collaboration. Activities are focused on Irrawaddy Basin (Myanmar), Zambezi Basin (Southern Africa) and Magdalena Basin (Colombia). Targeted development outcomes include improved catchment management for water, food and energy security that is socially and environmentally sustainable.

SWAT-CUP was used for sensitivity analysis, calibration and validation of the model. This is an independent software for automated calibration and uncertainty analysis. It includes five different algorithms for calibration. In this research the "Sequential Uncertainty Fitting, version 2 (SUFI–2)" algorithm was employed which uses the transposed modelling method for calibration. Uncertainty of input parameters was considered as uniformly distributed, whereas the uncertainty of output parameters was represented by the 95 PPU (95% prediction uncertainty) band. The method works under the hypothesis that with the increase in input uncertainty, output uncertainty also increases and *vice versa*. Briefly, the goal of calibration was to narrow down the uncertainty in output parameters to fall within the 95 PPU band. This objective was achieved by successive iterations, which resulted in sequential change in the weight of the 95 PPU band. Every iteration consisted of 500 simulations.

The hydrological component was calibrated by varying the parameters for soil and vegetation, such as the SCS Curve Number for moisture condition II, the soil evaporation compensation factor, the plant available water capacity, the surface runoff coefficient and the plant uptake compensation factor. The model calibration was assessed using a number of performance estimators (Percentage BIAS, coefficient of determination (R^2) and Nash-Sutcliffe Efficiency (NSE)). The choice of the best set of parameters was made according to the maximum NSE. Observed discharge data at the outlet, *i.e.* at "Azad Pattan" gauging station, was compared with the simulated discharges. Calibration was implemented for eight years (1981 to 1988) and a remaining period of seven years (1989 to 1995) was used for validation. Calibration and validation was accomplished on a mean monthly basis.
For the calibration of the sediment transport component, the parameters that have been used are the channel and basin erodibility factors. The calibration and validation procedure is the same as the one adopted for the hydrological component. However, the objective function selected for the optimization was the Percentage BIAS instead of NSE, because the limited number of observed data did not allow a full consideration of the temporal variations of sediment transport.

Main results and conclusions

The simulation period from 1981 to 1995 was considered as the *base case simulation*. The simulation was performed after model calibration for flow and sediment transport. Figure 4 shows the time evolution of the flow discharge and sediment transport rate. The future *business as usual* LULC scenarios were developed for the years 2035 (12.97% deforestation) and 2060 (18.84% deforestation) by projecting the current land use trend. The deforested areas were converted to other land use types, such as irrigated agriculture, built up areas, barren land, horticulture, plantation and exposed rock according to prevailing trends. In addition, two *worst case scenarios* were developed under the hypothesis that, in order to meet the food production needs of a growing population, 15% and 21% of the total catchment area would be fully converted to agricultural irrigated land. The future LULC scenarios were built and updated in SWAT. While updating the LULC scenarios in SWAT, all other inputs (weather and soil type) remained unchanged. The results of the simulations were compared on long term monthly, yearly and seasonal basis.

The comparison of sedimentation rates between the *base case scenario* and *business-as-usual scenario* shows that no significant change is to be expected. The current modest trend on the land use change does not have substantial effect on sedimentation in the Mangla Reservoir: an increase of 0.42% in sedimentation on a mean monthly basis by 2035, and an increase of 0.70% by 2060, are to be expected. However, in the *worst-case scenarios*, where a large scale deforestation is to occur, with a complete transformation of forest areas to cultivable ones, substantial increases in the sedimentation rate are expected: 1.3% for the scenario of 15% deforestation and 2.05% for the scenario of 21% deforestation by 2035 and 2060, respectively. Moreover, results show clearly that the conversion of forested areas into agricultural lands should be discouraged to attain sustainability of the Mangla Reservoir. Instead, to meet the ever-increasing needs of food, modern agricultural practices should be adopted in order to increase the productivity of present-day agricultural areas and/or to decrease the soil loss (*e.g.* through conservation tillage). ■

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Figure 3. Example of a sedimentation area in the Mangla Reservoir

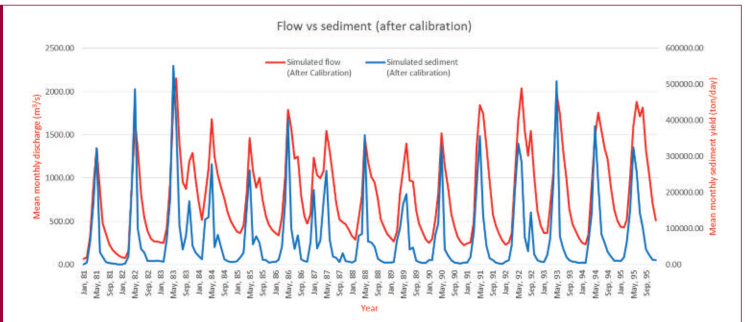

Figure 4. Simulation outputs for the base case scenario. Red: flow discharge, Blue: sediment transport rate.

RESERVOIRS SILTING IN MOROCCO

BY D. LOUDYI, M. CHAGDALI, S. BELMATRIK AND K. EL KADI ABDERREZZAK

The Kingdom of Morocco is an arid country that relies heavily on water supplied by reservoirs (Figure 1). Long periods of drought, spreading over several years, are common. In the 1960's Morocco launched a vast dam building program to help solve the issues of water scarcity and rainfall variability which affected thousands of farmers and the agricultural based economy. Morocco now counts 140 large dams (meeting the ICOLD definition) with an overall capacity of about 17,600 million cubic meters (Mm^3), 13 hydraulic water transfer structures and more than 100 small dams and hill reservoirs. The main objective of reservoirs is to secure primarily domestic water supply for large urban centers, to store water for irrigation, to mitigate flood risk and finally to generate hydropower. Demand for domestic and industrial water supply is increasing at a rate of 8% per year. Reservoirs supply 66% (as of 2016) of the water demand (80% in 2020)[1]. About 1,500,000 ha are irrigated. The annual production of hydropower is 2,527 GWh (10% of the total production), out of a total potential capacity estimated at 5,100 GWh.

Figure 1. Map of Morocco and general information[1]

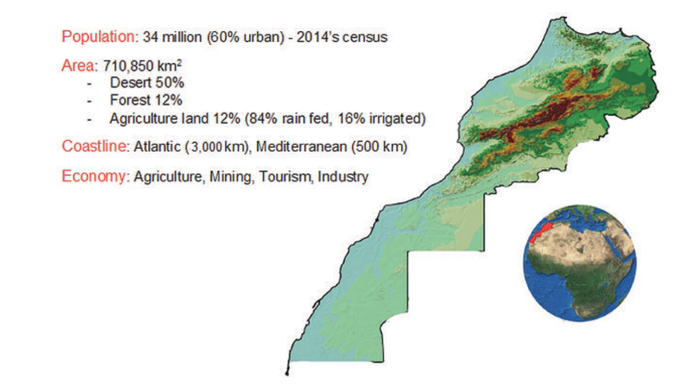

Table 1 Silting rates in a selection of Moroccan reservoirs[3]

Dam	Basin	Service year	Initial capacity (Mm^3)	Total sedimentation volume (Mm^3)	Silting rate (Mm^3/year)	Lost storage capacity (%)
Oued El Malleh	Bouregrag-Chaouia	1931	18	14.9	0.2	83%
Sidi Driss	Oum Er Rbia	1984	7	5.5	0.35	78%
Al Khattabi	Loukkos	1981	43.3	31.7	1.1	73%
Mohamed V	Moulouya	1967	725.8	486.2	11.5	67%
Dkhila	Souss Massa Draa	1986	0.7	0.46	0.03	67%
Allal Al Fassi	Sebou	1990	81.5	48.5	2.4	59%
Nakhla	Loukkos	1961	9	4.8	0.1	53%
Lalla Takerkoust	Tensift	1979	78.7	26.1	0.8	33%
Ibn Battouta	Loukkos	1977	43.6	14.5	0.4	33%
El Kansera	Sebou	1966	294.4	77.9	1.8	26%
Aoulouz	Souss Massa Draa	1991	110	21.0	1.1	19%
Hassan Eddakhil	Ziz	1971	380	69.7	1.7	18%
Bin El Ouidane	Oum Er Rbia	1953	1,484	292.0	5.0	18%
Sidi Mohamed Ben Abdellah (after elevation)	Bouregrag-Chaouia	1974 (2007)	508.6 (974.8)	76.9 (55.3)	2.2 (9.5)	15% (6%)
Youssef Ben Tachfine	Souss Massa Draa	1972	320	21.1	0.6	7%
Al Wahda	Sebou	1996	3,730	208.2	14.3	6%
Al Massira	Oum Er Rbia	1979	2,785	87.1	2.3	3%

Silting of Moroccan dams: facts

The latest monthly monitoring surveys for Moroccan reservoirs showed that, at the end of June 2018, the storage rate of the 55 largest reservoirs was 66% against 50% at the same period in 2017 and 45% in 2016. These fluctuations are due to the variability of rainfall and temperature, but also to the accumulated sediment in the reservoirs. The silting phenomenon has caused a loss of nearly 10% of the total storage capacity of reservoirs, which represents a volume of 1,740 Mm^3. Reservoir sedimentation translates into a storage capacity loss of nearly 75 Mm^3 per year according to the Moroccan State Department in charge of water, which is equivalent to losing the average storage space of one reservoir every year. The total storage capacity loss may reach 150 Mm^3/year in the near future if any mitigating measures are not undertaken, depriving about 15,000 ha of agricultural land of irrigation[2].

The rate of siltation varies between 0.03 Mm^3/year in Dkhila reservoir to 14.3 Mm^3/year in Al Wahda reservoir (Table 1). It was noted that for most of Moroccan dams (older than 30 years) the dead storage has been already filled or will be in very near future[3]. The accelerated pace of water development requires a thorough knowledge of erosion, sediment transport and siltation of dam and hill reservoirs. These natural phenomena, which depend on climatic conditions, landform and vegetation cover, are accelerated and intensified by human activities such as land use, cultural practices, grazing and deforestation.

Most Moroccan basins are characterized by a strong erosion rate (» 2,000 t/km^2/year, a peak value of 5,900 t/km^2/year in the Nekor basin)[4,5]. Among the nine river basins of Morocco (Figures 2 to 5), the annual specific degradation indices evaluated at the level of different watersheds show that the country has seven geomorphological regions whose erodibility decreases from north to south. Dams built in the Moulouya basin (North of Morocco) are in a critical situation because of the siltation losing on average 39% of reservoirs' storage capacity. They are followed by reservoirs in Tensift basin, Souss-Massa Draa basin and Loukkos basin.

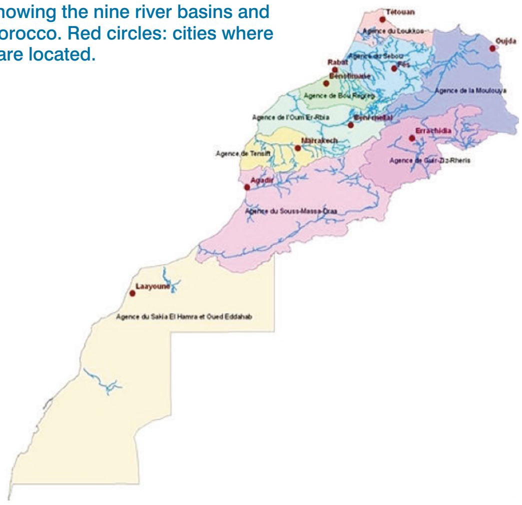

Figure 2. Map showing the nine river basins and main rivers in Morocco. Red circles: cities where basin agencies are located.

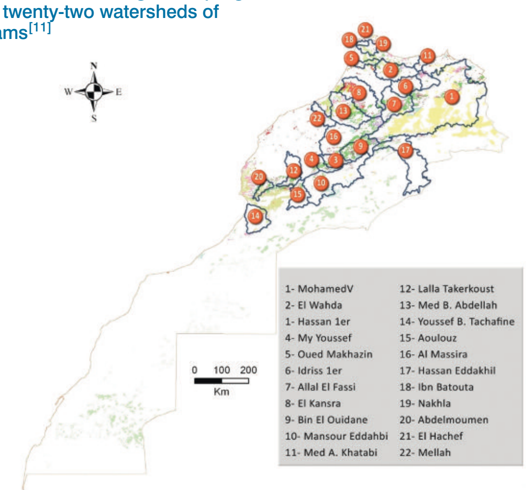

Figure 7. National management program for the afforestation of primary twenty-two watersheds of large dams[11]

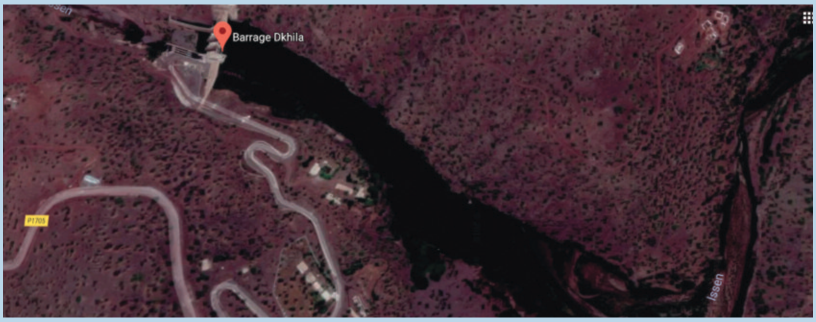

Figure 3. Dkhila dam (service year: 1986, height: 37 m, initial reservoir capacity: 0.7 Mm^3, sedimentation rate: 0.03 Mm3/per year), Issen River, Souss Massa Draa basin (Google Earth)

Figure 4. Al Massira dam (service year: 1979, height: 82 m, initial reservoir capacity: 2,785 Mm3, sedimentation rate: 2.3 Mm^3/year), Oum Rbia River, Oum Rbia basin

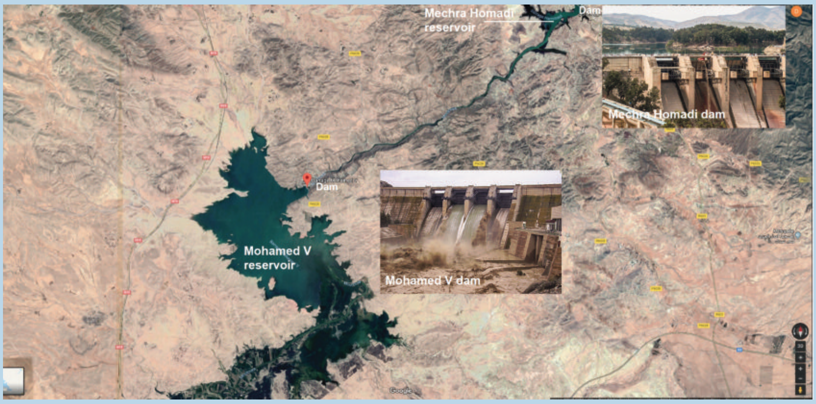

Figure 6. Mohamed V dam (service year: 1967, height: 64 m, initial reservoir capacity: 728.5 Mm^3, sedimentation rate: 11.5 M^3/year) and, downstream, the Mechra Homadi dam (service year: 1955, height: 57 m, initial reservoir capacity: 42 Mm^3, sedimentation rate: 1 Mm^3/year), Moulouya River, Moulouya basin (adapted from Google earth)

Figure 5. Bin El Ouidane dam (service year: 1953, height: 133 m, initial reservoir capacity: 1,484 Mm^3, sedimentation rate: 5 Mm^3/year), Oum Er Rbia River, Oum Er Rbia basin

The situation of reservoirs in the North and Rif's mountains is very serious due to the high level of erosion and the hilly slopes. One such case is the Oued El Malleh dam, constructed in 1931 and now almost completely silted up. In the Oum Er Rbia basin, Sidi Said Maâchou dam, the oldest modern dam in Morocco (completed in 1929) is in a similar situation. This dam has lost its storage function to become exclusively a compensation dam for the turbines of Daourat plant which supplies drinking water to the western part of Casablanca, the industrial hub and economical capital of Morocco. Dkhila (Souss Massa basin) and Sidi Driss (Oum Er Rbia basin) dams are also in the same situation. In the absence of immediate interventions, Al Khattabi (Loukkos basin), Allal Al Fassi (Sebou basin) and Mohamed V (Moulouya basin) reservoirs would be completely silted up by 2024, 2027 and 2032, respectively.

Solutions and mitigating measures

Eighty-eight (88) large dams (64% of the total number of dams) are now more than 20 years old[6]. Given that the economic life cycle of a dam in Morocco is 50 years, fourteen major hydraulic structures have exceeded their lifetime. The situation is critical, which explains the launch of new dam projects to replace "end of life" ones. The Moroccan State Department in charge of water aims to build 59 dams by 2030. Since 2015, the construction of 35 dams of different sizes, with an overall storage capacity of 3,064 Mm^3, has been launched. These new dams will help ensure continued water supply for domestic and industrial uses in remote areas which suffer from water shortage, increase the irrigated area (the Green Morocco Plan has a goal of reaching 70% of irrigated arable lands by 2030), mitigate the flood risk, and produce hydropower energy.

With the support of World Bank, a RESCON team (see the paper by Efthymiou *et al*. in this issue describing the RESCON tool) worked in 2001 with Moroccan engineers and managers to determine the needs for mitigation measures at several reservoirs. The RESCON approach was applied to ten existing reservoirs with the objective of identifying optimal sediment management strategies that are both technically and economically feasible[7]. The selected dams ranged from relatively small, with a reservoir capacity of 5.6 Mm^3, to large, with a reservoir capacity of 1,500 Mm^3. An interesting outcome of this work was the sensitivity of the RESCON tool results to the assumed unit cost of dredging (cost provided by Moroccan engineers *vs* cost calculated by the RESCON program). For instance, when the default dredging costs calculated by the RESCON program (which were higher than US$ 4/m^3), the optimal sustainable management strategy shifted from dredging to flushing for three of the reservoirs. More details are given by Palmieri *et al*.[7].
At present, solutions are being put in place, aiming to reduce the negative impact of sedimentation on reservoir storage capacity. Apart from the construction of new dams, the Department of Water, in charge of the supervision of dams, uses either technical or natural methods to mitigate against the silting process. The elevation of hydraulic structures is carried out when technically feasible. This solution was put in place for four dams: Lalla Takerkoust, El Kansera, Oued El Malleh and Sidi Mohamed Ben Abdellah. In addition to the sizing of dead storage, flushing operations are carried out during flood periods to remove part of the sediment through the bottom outlets. However, flushing operations remain limited because of the water scarcity and growing needs for water supply and irrigation. Density current venting under low flow discharges is applied to only few dams which are equipped with bottom outlets (*e.g*. Ibn Battouta, Youssef Ben Tachfine, Aoulouz, Hassan Eddakhil)[8]. Building of upstream check structures (weirs and small dams) has been initiated since 1980 to help to trap sediments upstream of large dam reservoirs. Sediment dredging is another effective solution for silting control. However, its cost remains very high and water and agroforestry operators do not reuse the extracted sediments. The removal of 1m^3 of sediment now costs 50 Moroccan Dirham (MAD), approximately US$ 5. This solution was implemented at the Sid Driss dam and the Mechra Homadi dam (Figure 6). The latter was constructed in 1955 with an initial storage capacity of 42 Mm^3 that has been drastically reduced over time (silting rate of 1 Mm^3/year). The dam reservoir was in a critical situation by the end of 1990 (storage capacity of about 10 Mm^3), so that dredging operations were conducted in 1994 (removing 3 Mm^3) and between 2003 and 2009 (removing 5.4 Mm^3), costing in total 120 million MAD (US$ 12 million)[7]. The dam was also equipped with bottom outlets.

The Department of Water is in favor of afforestation, which remains an ecological method that both protects soils against erosion and preserves the efficiency of hydraulic infrastructures. A National Watershed Management Plan (PNABV)[9] was adopted in 1996 as a strategic framework setting priorities for interventions and proposing approaches as well as financial and institutional mechanisms for implementing erosion control for twenty-two high-priority watersheds. Morocco aims to reforest catchments covering 1,500,000 ha at a rate of 75,000 ha/year. Since 1996, 650,000 ha have been reforested in eighteen watersheds (Figure 7). Morocco has also increased the rate of bathymetric survey of reservoirs by a Differential Global Positioning System (DGPS) system. Twenty reservoirs are surveyed per year compared with only eight reservoirs per year in the period from 1991 to 1998. Other methods to measure sedimentation include sediment monitoring at gaging stations (bed load and suspended load), aerial surveys, radioisotope methods and the use of degradation prediction relationships for upstream basins[10]. These measures are undertaken by different departments according to their legal jurisdiction and location. The main stakeholders involved in silting control of reservoirs are: the State Secretary in charge of Water, the High Commissioner for Waters, Forests and Combating Desertification, the Hydraulic Basin Agencies and the National Office for Electricity and Drinking Water ONEE - Water branch. ■

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