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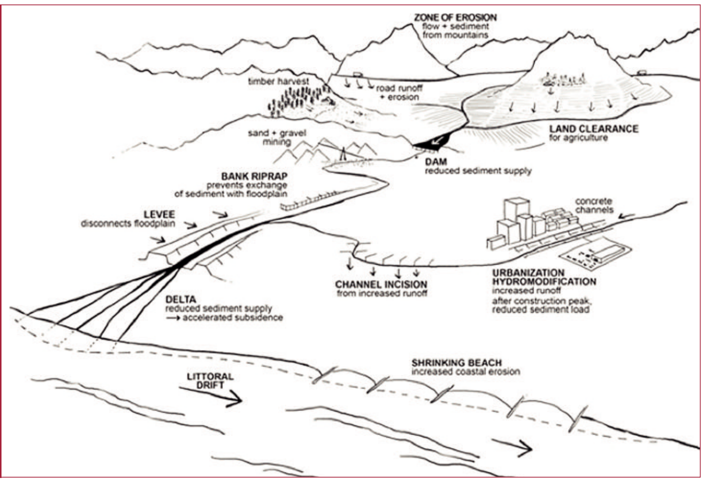
DAMS, SEDIMENT DISCONTINUITY, AND MANAGEMENT RESPONSES

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.

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



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.

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.

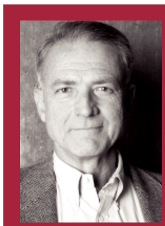
Restoring flow for geomorphic processes below dams

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.



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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.

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.

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.

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

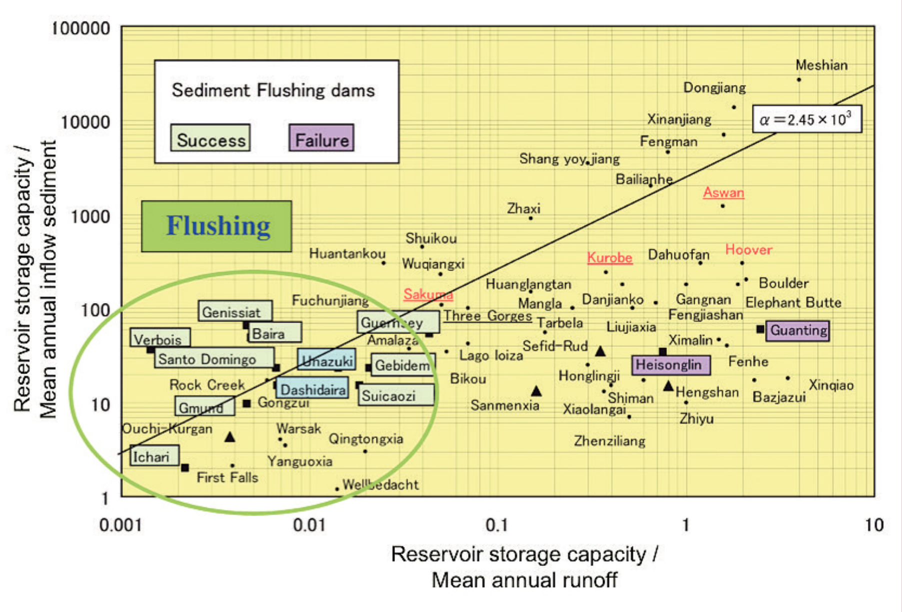

Figure 3. Plot of projects from diverse environments and with different sediment management strategies (flushing (squares), sluicing (triangles), excavation/dredging, check dams or no strategy (circles)). Reservoir life is indicated by the ratio between the reservoir storage capacity and the mean annual 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 $\alpha = 2.45\times10^3$). (Figure developed by Tetsuya Sumi, adapted from Kondolf *et al.*[17], used by permission of AGU/John Wiley & Sons)

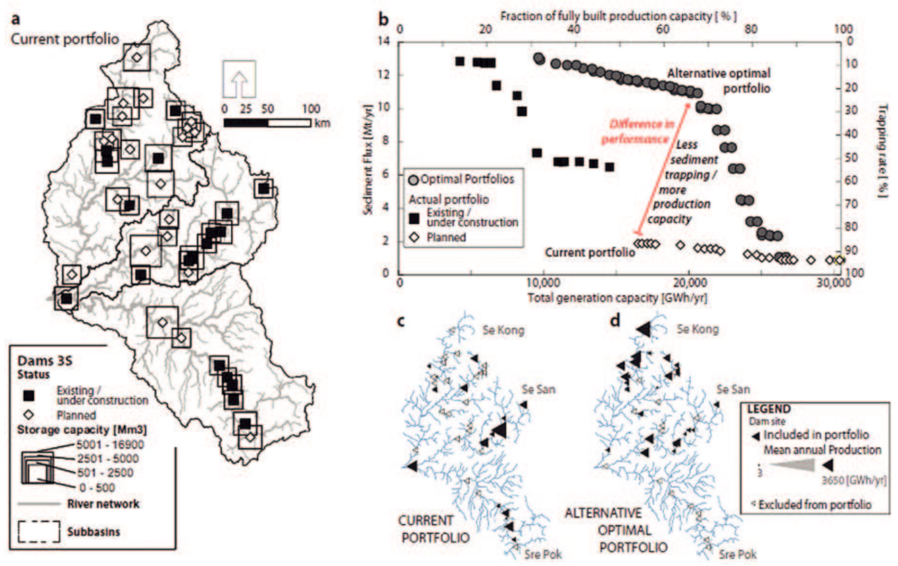

Figure 4. Power generation and sediment trapping from dam building in the Sre Pok, Se San, and Se Kong rivers (the '3S basin'), the largest downstream tributary to the Mekong River. (a) The current 3S dam portfolio includes twenty-one (21) dams built or under construction (black squares), and twenty-one (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

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