water

Editorial

Studies on River Training

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Abstract: This editorial regards a Special Issue of Water on river training. It introduces five papers in a framework of history, fundamentals, case studies and future. Four papers result from decades of experience with innovation, planning, design and implementation of river training works on rivers in Colombia, the Rhine branches in the Netherlands and the Brahmaputra-Jamuna River in Bangladesh. A fifth paper reviews the state-of-the-art in predicting and influencing the formation and behavior of river bars. The editorial argues that the future lies in more flexible river training, using a mix of innovative permanent structures and recurrent interventions such as dredging, sediment nourishment, vegetation management and low-cost temporary structures.

Keywords: river engineering; morphodynamics; riverbank erosion; riverbank protection; submerged vanes; Brahmaputra-Jamuna River; Rhine River

1. Introduction

This Special Issue of Water presents and reviews the latest insights, innovations and experiences in river training. The original invitation to authors focused on four specific areas. The first area regards the functioning of innovative river training structures, such as permeable groynes [1], submerged vanes [2] and geobag revetments [3]. The second area relates to the adverse effects of river training, often only becoming apparent and creating full awareness of their existence in the long term [4]. This awareness is now leading to more adaptive approaches to stabilizing river courses, protecting riverbanks, improving navigability, and providing safety against flooding. The third focus area concerns the advanced theory and modeling of hydrodynamics and morphodynamics to predict effectiveness and assess the impacts of river training [5]. The fourth area focuses on case studies to evaluate the long-term performance and sustainability of river training projects implemented in the past [1–4].

Most contributions to this Special Issue address several of the areas mentioned, so that they cannot be grouped strictly in distinct focus areas. This editorial, therefore, introduces them in a more general framework of history, fundamentals, case studies and an outlook on the future. The rationale for this collection of papers is that, generally, experiences from river training and associated innovations are either poorly documented or presented in poorly accessible reports and publications, notwithstanding the availability of valuable books [6–9]. The goal of this open-access Special Issue is, therefore, not only to produce a state-of-the-art for river scientists but also to provide guidance for practicing river engineers. Rodríguez-Amaya et al. [2] present the application of submerged-vane technology in Colombia. Havinga [4] discusses past and future training and management of the Dutch Rhine branches. Oberhagemann et al. [3] describe the development of riverbank protection technology for the Brahmaputra-Jamuna River in Bangladesh. Van der Wal [1] describes his experiences with bank protection structures along the same river, focusing on ways to reduce the risk of damage by flow slides. Crosato and Mosselman [5] review the state-of-the-art in predicting and influencing the formation and behavior of river bars.

2. History

The world's ancient civilizations developed in the valleys of major rivers: the Tigris and the Euphrates in Mesopotamia, the Nile in Egypt, the Indus in present-day Pakistan, and the Yellow River in China. That these valleys formed the cradle of cities and organized agriculture is a commonplace. Less commonly noted, however, is that they formed the cradle of river engineering too. Early river engineers founded the first ruling dynasties in Egypt and China. The first Egyptian pharaoh Menes (Narmer) diverted the course of the river Nile by a dam around 3100–3000 BC to create optimum conditions for his new capital Memphis. Around 2200–2100 BC, the first Chinese emperor Yu the Great devised a system to control floods by giving more space to the river instead of just building dikes and dams along its banks. His workers diverted flood water into a system of irrigation canals, dredged the river beds, and enlarged a narrow bottleneck in the Yellow River at Mount Longmen.

Herodotos [10] describes how rivers were modified in classical antiquity for military purposes, although the precise truth of his accounts is debated. He writes that the engineer-philosopher Thales of Miletus made the Halys River (Kızıl Irmak, east of Ankara) easily fordable for the army of Croesus by digging an additional channel. Cyrus even spent a full summer to let his army divide the Gyndes River (Diyálah, tributary to the Tigris) into 360 channels, so that his army could cross it without boats. In 539 BC, Cyrus diverted the Euphrates into marshes so that his army could march over a dry river bed into the walled city of Babylon by surprise.

The Roman Empire perfected river engineering, with bridges across the Rhine and the Danube as its most outstanding feats. In the Rhine delta, the Romans connected different river branches, implemented a river training mole at the bifurcation of Waal and Rhine near Herwen ("carvio ad molem" on tombstone in Het Valkhof museum, Nijmegen), and protected banks against erosion by groynes made of wood and basalt blocks (archeological information in Hoge Woerd museum, De Meern). Groynes continued to be constructed locally throughout the Middle Ages to protect land from fluvial erosion. Systematic training of long river reaches started in the 19th century, for instance in Tulla's "Rhine correction" in the Alsace and the "Rhine normalization" in the Netherlands. Hundreds of groynes were implemented along the Dutch Rhine branches between 1850 and 1880 to establish a uniform width, because locally wider sections with bars and islands gave rise to ice jams in winter, a major cause of dike breaches and flooding. The width was reduced further in the next 35 years by making the groynes longer, this time to improve navigability. Havinga [4] presents this history more extensively, along with more recent developments in river training and river management for the Rhine branches in the Netherlands.

Similar developments took place along other rivers. River training in the Mississippi River Basin started in 1824 by dredging and by removing large woody debris that formed snags for navigation. The navigability was improved further by implementing river training structures a century later. Bends were cut off and made less sharp. Banks were stabilized to limit the continuous feeding of the channel with trees from the banks [11].

British engineers faced challenges in the 19th century when training the unstable rivers of the Indo-Gangetic Plains [6,8]. Their main question was how to constrict meander or braid belts to limit the span of bridges across the rivers. By trial and error, they developed structures to lead deep channels properly under the bridge without migration of channels upstream to erode the abutments. These guide banks or Bell's bunds are longitudinal guiding structures that consist of an upstream curved head, a straight shank, and a downstream curved head [6,8,12,13]. Oberhagemann [3] describes in detail the subsequent developments in training the Ganges, Brahmaputra-Jamuna and Padma rivers over the last century. Van der Wal [1] complements this with additional historical information.

Parallel to these hard river training structures, more flexible temporary structures were developed too, such as bandals in South Asia [6–8,12], bottom and surface screens in the Soviet Union [14], and submerged vanes in the United States [15]. These structures are all based on the principle of generating a transverse circulation to move sediment near the bed sideways.

Rodríguez-Amaya et al. [2] present applications of submerged vanes in Colombia, permanent but adjustable to changes in the direction of flow attack.

3. Fundamentals

Indian river engineers [6,8] define five classes of river training problems: (i) flood protection by provision of sufficient cross-sectional area or construction of embankments ("training for discharge"); (ii) maintenance of a safe and good navigable channel ("training for depth"); (iii) sediment control, for instance to exclude sediment from the entrance of irrigation canals ("training for sediment"); (iv) prevention of bank erosion; and (v) directing of the flow along a pre-defined alignment, for instance towards irrigation canal offtakes or under bridges. In the common operational use of the term, river training refers to the last four classes only. Training for discharge usually is not called river training but flood risk management. Neither does river training apply to works for regulating river flows, such as weirs, dams and reservoirs.

River training works include transverse structures (e.g., groynes, spur dikes, spurs), longitudinal structures (e.g., bank revetments, guide bunds) and structures on the river bed (e.g., fixed layers, bendway weirs, checkdams). Experienced river engineers share some practical wisdom that is not immediately obvious to novices or laymen. For instance, groynes or spurs pointing downstream attract flows to the river bank rather than deflecting them away from the bank. Truly deflecting or repelling groynes have an upstream inclination. Another example is that the heaviest fluvial attack on training structures mostly occurs around bankfull conditions rather than flood conditions [16]. Extreme floods may represent the most important design conditions for embankments; they do not for river training works. A third example is that closing one of the channels around an island requires interventions over a larger area, because a single cross-dam ("channel plug") would be bypassed by erosion of the island [16].

Of pivotal importance is the morphological response of rivers to training works. This regards both intended morphological effects and adverse morphological impacts. Morphological responses occur at different spatial scales, the most relevant ones for river training being the reach scale, the cross-section scale and the depth scale [17].

The reach scale regards planform dynamics and the development of the longitudinal profile. River training often aims at reducing planform dynamics, for instance by stabilizing banks or constraining the development and migration of meanders. River training often also narrows a river reach [4]. This initially increases water levels (Figure 1) but starts an erosion process that reverses initial sedimentation and eventually results in lower water and bed levels in the narrowed reach as well as upstream (Figure 2). The longer the narrowed reach, the deeper the erosion, due to the reduction of the equilibrium slope in this reach. This flattening of the slope can be estimated as follows. Chézy's equation for steady uniform flow can be written as $u^2 = C^2 hi$, where u is flow velocity, C is the Chézy coefficient for hydraulic roughness, h is flow depth and i is the slope of the river. Assuming rectangular cross-sections with a width equal to B, flow velocity can be related to discharge, Q, through $u = Q/(Bh)$. Together, the two formulas yield $u^3 = C^2 Qi/B$. The sediment transport rate per unit width, q_s, can be related to flow velocity by a sediment transport capacity predictor $q_s = mu^b$ where m is a coefficient and b is an exponent for which only values above 3 are physically realistic [18]. Integration over the cross-section gives the total sediment load $Q_s = Bq_s$. Substitution of the relation for u^3 gives $Q_s = B^{1-b/3} m C^{2b/3} Q^{b/3} i^{b/3}$. As morphological equilibrium implies that the sediment load in the narrowed reach must be equal to the sediment load in the original unmodified reach, the ratio of new slope, i_1, to original slope, i_0, can then be related to the ratio of new width, B_1, to original width, B_0, by $i_1 / i_0 = (B_1 / B_0)^{1-3/b}$ [7] (Figure 5/2.28 in [7]). The narrowing of the main channel in the "Rhine normalization" in the Netherlands thus is a key factor in the bed degradation described by Havinga [4], along with other factors such as bend cutoffs, sediment mining and reduced sediment supply from upstream.

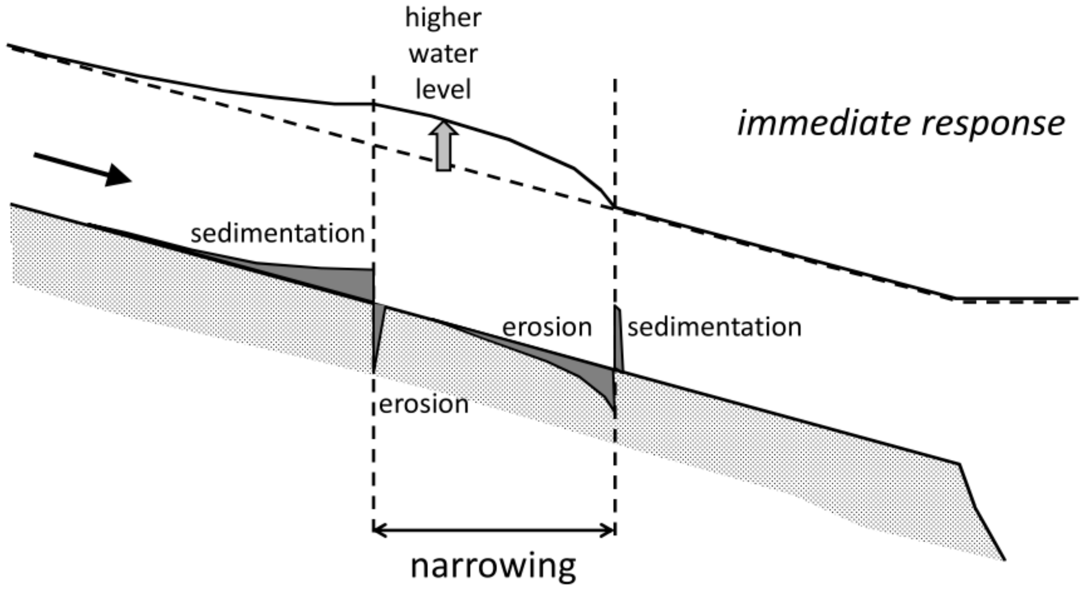

Figure 1. Immediate response of longitudinal water level and bed level profiles to narrowing. Vertical dimensions are exaggerated with respect to horizontal ones. The narrowing initially raises the water levels according to equations for gradually-varied steady flow (backwater equations). The resulting spatial variations in flow depth produce spatial variations in flow velocity. Spatially accelerating flows cause erosion; spatially decelerating flows cause sedimentation (Exner principle).

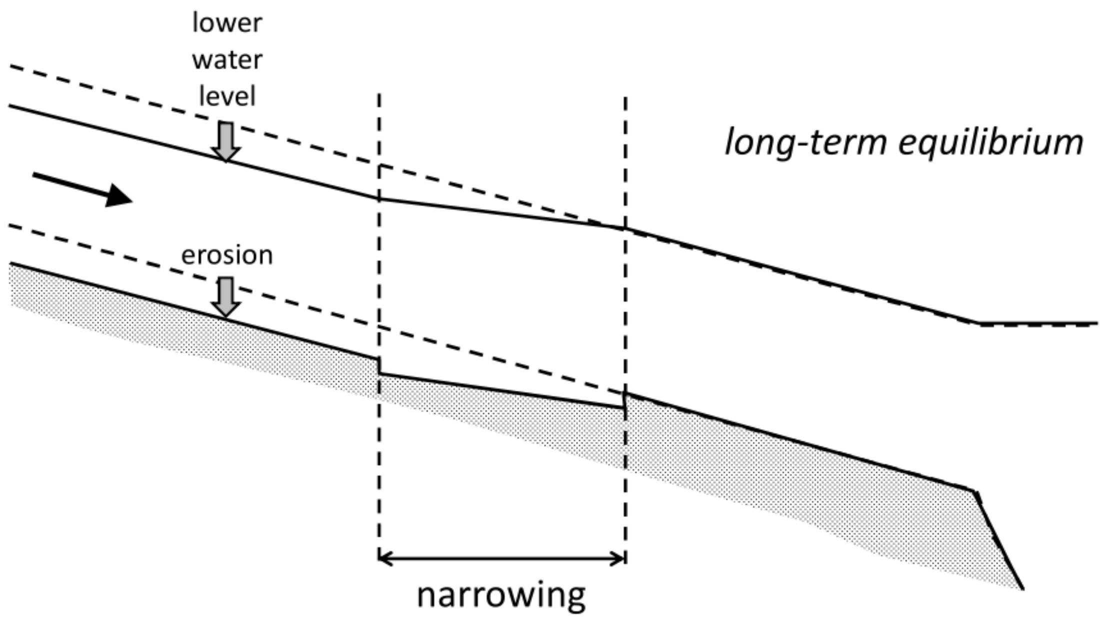

Figure 2. Long-term response of longitudinal water level and bed level profiles to narrowing. Vertical dimensions are exaggerated with respect to horizontal ones. The river attains a new equilibrium with a larger depth and a flatter slope in the narrowed reach. This lowers water levels and bed levels upstream of the narrowed reach too.

The cross-section scale regards the pattern of channels, bars and pools. In this Special Issue, Crosato and Mosselman [5] review today's knowledge on the formation and behavior of river bars, distinguishing free, forced and hybrid bars (Figure 3). Bar length and the number of bars in a cross-section can be influenced by modifying the width-to-depth ratio of the main river channel. The intensity of a local perturbation, producing a local forced bar, determines the growth rate and the locations of hybrid bars that arise further away as a dynamic response of the riverbed to the local forcing.

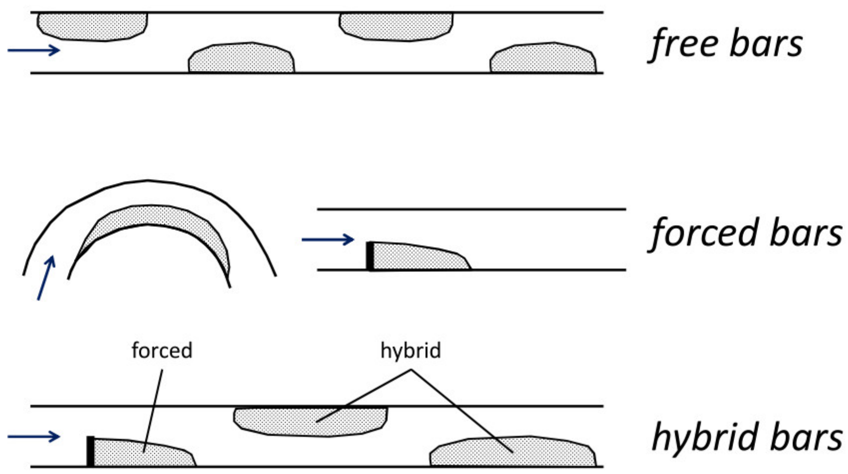

Figure 3. Distinction between free, forced and hybrid bars. Free bars are periodic bars that form spontaneously in the absence of geometrical features or discontinuities causing permanent flow perturbations. Forced bars are single bars that arise at the locations of geometrical features or discontinuities. Hybrid bars are periodic bars that form as a train behind a forced bar.

The most important morphological response on the depth scale is the formation of scour holes at structures for river training and bank protection. Prediction of scour still relies on empirical formulas [6,8,19]. Even for outer-bank scour along well-defined bends without significant planimetric changes, empirical predictors perform better than theoretical predictors for point-bar height and pool depth [5]. Crosato and Mosselman [5] list mechanisms by which the bed is scoured even deeper when bank protection and river training works are located along rivers with actively shifting channels. Oberhagemann et al. [3] testify of the challenges posed by scour depths of more than 50 m in the main rivers of Bangladesh; deep enough to contain 12-storey buildings.

4. Case Studies

This Special Issue contains papers by four river engineers who all have decades of experience with planning, design and implementation of river training, introducing innovations and improving their works by trial and error: Carlos Rodríguez-Amaya, Hendrik Havinga, Knut Oberhagemann and Maarten van der Wal.

Rodríguez-Amaya et al. [2] present five representative projects of applying submerged-vane technology in Colombia. They found riverbank protection with submerged vanes performed better than earlier protection with spurs. The structures did not fail and required less construction material, shorter execution times and less annual maintenance costs. They had less impacts on environmental conditions and trapped less floating debris.

Havinga [4] explains that rivers and their infrastructure fulfil important societal functions: safety against flooding, inland waterways, preservation of riverine nature, freshwater supply, and agriculture. Increasingly, programmes to improve individual functions of the Rhine branches in the Netherlands lead to conflicts with other functions and, therefore, call for an integrated approach based on a mix of recurrent sediment management measures and extensive structural measures that might change the layout of the river system. For instance, giving more space to the river to reduce flood water levels and to enhance natural values causes shoals in the fairway. The most prominent adverse effect of massive training of the Rhine branches in the past is the resulting large-scale bed erosion at rates up to 4 cm/year. This erosion lowers water levels, deteriorates nature by draining floodplains and wetlands, undermines hydraulic structures and compromises navigation as it increases the water level differences at ship locks that connect ports and canals with the fluvial waterway. A programme to stop or even revert the bed erosion could consist of longitudinal training walls, adaptation of groynes, non-erodible bed layers, and riverbed nourishment by supplying sediment, accompanied by monitoring and development of knowledge.

Oberhagemann et al. [3] describe how 25 years of developing riverbank protection technology suitable for the Brahmaputra-Jamuna River in Bangladesh have resulted in a low-cost system based on sand-filled geotextile bag (geobag) revetments. Their main experiences and lessons learned are: (i) knowledge-based development drives change; (ii) for bank protection longitudinal structures such as revetments are superior to transverse structures such as spurs (in accordance with the 19th-century optimization towards guide bunds [6,8,12] and Havinga's [4] recommendation of longitudinal training walls); (iii) learning by doing also holds for implementation of works, requiring a flexible design approach; (iv) the widely used launching and falling aprons provide only temporary protection and do not always work well; (v) geotechnical design is fundamental for stable riverbank protection (flat slopes, placement on consolidated strata); (vi) important elements of an adaptive approach to sustainable riverbank protection include prediction of river behaviour, multi-year allocation of funds, design based on geotechnical considerations, construction as per actual river requirement, preparation of as-built drawings, monitoring including evaluation, anticipation of adaptation works, and maintenance for long-term sustainability.

Van der Wal [1] presents his experiences with bank protection structures along the Brahmaputra-Jamuna River in Bangladesh, focusing on how the design of these structures can be improved to reduce the risk on damage by flow slides. Flow slides occur easily in loosely packed fine sand and are often triggered by deep or rapidly developing scour holes. The author offers five types of measures to reduce or prevent this type of damage. First, deep scour holes close to river training structures can be avoided by revetments with gentle bank slopes or groynes that are permeable. Second, rapid scouring during a monsoon flood can be prevented by phased construction. Third, extra protection material may be dumped as an emergency measure. Fourth, strata of loosely packed fine sand can be vibrated or replaced by coarser material to increase their bearing capacity. Fifth, innovative measures offer opportunities, for instance clay screens in the subsoil to reduce the destabilizing outflow of pore water. Van der Wal [1] agrees with Oberhagemann et al. [3] that falling aprons do not always work well. They may even have adverse effects.

5. Future

The future of river training will be governed by increased societal demands for protection, transport (navigation), energy (hydropower), water supply, nature conservation, recreation and tourism on the one hand, and increased awareness and understanding of the adverse effects on the other hand. Apart from compromising societal demands, these adverse effects also deteriorate the riverine ecosystem which has an intrinsic value, the loss of which might be irreversible. Many developed countries now seek to restore rivers ecologically by giving back space to nature and by removing or modifying river training works from the past. Havinga [4] advocates a fourth normalization of the Rhine in which groynes are removed and replaced by longitudinal training walls, providing a sailing width of approximately 100 m instead of the present 260 m and wide bank channels behind the walls with sheltered conditions for riverine biota. River engineer Henk Eerden pioneered this idea by realizing a 10 km long pilot implementation of longitudinal training walls on the Waal River. Numerical model results [20] suggest that the bed would have eroded less and that the navigability would have been better if the Waal River would have been trained straightaway with longitudinal training walls instead of groynes in the 19th century.

Developing countries are still in the stage of increasing river training to support economic development. Thanks to the present awareness and understanding of adverse effects that will incur costs later, however, they do not need to make the same mistakes as countries that developed earlier. The braided-anabranched Brahmaputra-Jamuna River exhibits natural cycles of widening and narrowing in response to interannual variations in hydrology and sediment yield of its catchment. The variations in sediment supply are related to earthquake-induced landslides, most notoriously landslides due to the 8.6-magnitude Assam earthquake in 1950 [1,3]. The episodic occupation of a larger width warrants caution with river training that would confine the river in a narrow strip. Numerical simulations by the Institute of Water Modelling [21] suggest that narrowing the river from 11 km to widths between 5 and 8 km could already lead to bed erosion and lowering of dry-season water levels by up to 5 m within 20 years.

The future in both developed and developing countries thus lies in less rigid river training, using a sophisticated mix of innovative permanent structures and recurrent interventions such as dredging, sediment nourishment, vegetation management and low-cost temporary structures. How to do this in practice remains a fascinating challenge for future generations of river engineers.

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