Water Engineering

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Water engineering has been a fundamental dimension of anthropogenic impacts on the environment since humans first started to live upon river banks. The subject spans a range of topics and is especially divided into coastal and freshwater environments, with the latter primarily focused towards hydraulic engineering. This entry considers the subfields of water engineering from the perspective of surface water, and especially alluvial rivers. Hydraulic engineering involves a multitude of discreet actions and structures designed to alter the functioning of flowing rivers for the benefit of humans. Alluvial rivers are physical systems which adjust to changes in sediment and energy, both of which are impacted by water engineering structures.

The earliest comprehensive and large-scale water engineering occurred in the Middle East and North Africa for crop irrigation within the Tigris–Euphrates and Nile Deltas. New sophisticated approaches to water engineering continue to rely upon some of the same principles laid out centuries or even millennia ago. Surface water engineering requires knowledge of basic fluid mechanics to computationally analyze the force of water and its interaction with sediment and the channel boundary layer. Additionally, hydraulic engineering requires knowledge of statistics to forecast time series of stream discharge and suspended sediment data. Common analytical tools apply mathematics and statistics in computer-based hydraulic models (e.g., Hydrologic Engineering Center – River Analysis System (HEC-RAS)), which combine hydrologic, topographic, and channel geometric data within the framework of a geographic information system (GIS). Additionally, much water engineering requires fieldwork, including topographic surveying and leveling, in addition to more job-specific tasks such as stream gauging and sediment sampling. These tools may be applied to, for example, estimating stream power, reservoir storage capacity, sediment transport, or irrigation potential, or to forecasting the impact of dam removal on downstream channel geometry and aquatic habitat.

Inventory of major water engineering structures and impacts

Surface water engineering includes a comprehensive range of activities and structures (Table 1), such as dams and reservoirs, groynes (wing dikes), meander cutoffs and channel straightening, dikes (levees), dredging (cut and fill), bridges and culverts, bifurcations, flow diversions and sluice gates, and revetments. As such, actual engineering structures may range in size from the smallest of culverts (<1 m) placed within small first-order channels in headwaters, to dams and reservoirs, among Earth's largest human-constructed features.

Groynes

Groynes are elongated rigid structures extending outwards from the river channel bank, emergent at low stage but inundated at moderate to high water levels. The goal of engineering groyne

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fields is to create a deeper self-cleaning channel, such that it maintains a navigable channel with minimal need for dredging. Morphologically, groynes are oriented nearly perpendicular to stream flow and most often located in shallow channel reaches on the inside of elongated bends and riffles, whereby they trap coarse sediments. Groynes are often placed in a series of relatively closely spaced sets. Groynes are usually semipermeable, constructed from concrete, granite, or basalt. Along large rivers intensively utilized for economic activities, such as the Ohio River, groynes are an ever-present component of the riverine environment.

In addition to reducing fish habitat, because of their resistance to flow, groynes also increase flood stage levels. Indeed, an important measure of the new integrated flood management program along the Dutch Rhine entitled "room for the river" requires that groyne fields are lowered from 0.5 m to 1.0 m to reduce flow resistance at high flow events, which is expected to lower flood stages by between 6 cm and 10 cm.

Dikes (levees)

Floodplain embankment by dike construction for flood control is among the oldest and most common forms of water engineering. Earthen dikes have been constructed for millennia along large rivers, providing flood control and access to agricultural lands, water resources, transportation, and aquatic environments. Development and increased population density follows floodplain embankment, such that dikes are also associated with increased flood risk. Dike construction should be informed by a thorough understanding of flood frequency, floodplain hydraulics and sedimentology, and subsidence, in addition to the ecological values of the local floodplain environment.

Underseepage is a major geotechnical concern along dikes underlain by highly permeable sands and gravels, especially with long duration floods, and can result in sand boils and local flooding along the backside of dikes. Environmentally, dikes are associated with a multitude of negative impacts, such as restricted hydrologic connectivity, degradation of aquatic habitat, and subsidence of local floodplain reaches on the backsides of dikes. A major component of many modern integrated floodplain management plans is to create more "room for the river" by moving dikes further away from the channel, thereby increasing storage capacity for floodwaters while also restoring exchanges of nutrients and fish between rivers and floodplain aquatic habitat.

Revetments

Channel revetments are constructed to prevent bank erosion and are placed along the eroding channel bank, especially cutbanks. Revetments should extend from above the average high water line to between the toe of the river bank or channel thalweg to prevent scour and undermining. Revetments are often constructed of natural materials, such as willow saplings, for small rivers, or of articulated concrete pads for large rivers. Concrete revetments increase local channel velocities and shear stress, and are mainly detrimental to fish diversity. Their effectiveness in maintaining channel stability has resulted in revetments being a major component of the environment along intensively utilized alluvial rivers.

Dams and reservoirs

The most substantial water engineering projects are dams and reservoirs. The purpose of riverine dam construction varies, and includes hydroelectric generation, flood control, agriculture, recreation, and consumption by humans and industry (Graf 2006). Dams are constructed from concrete or earthen materials, with the latter being particularly important along lowland

Table 1 Major features of water engineering and potential impact.

Engineering action	Primary justification	Intended effect	Potential adverse impact	Hydraulic/ morphologic location	Hydrologic events (low, moderate, high)	Timescale for impact	Spatial impact (upstream, local, downstream)
Flow diversion	Flood risk	Reduce downstream flood risk	Channel bed aggradation, overbank burial of wetlands	High in water column	High	1–10 years	Local
Groynes (wing dikes)	Navigable and stable channel	Narrow channel, increase depth	Disruption of sediment budget, trapping of coarse bed material, channel bed incision	Channel bed, banks	Low, moderate, high	10 years to permanent	Local, downstream
Cutoffs and straightening	Flood risk	Reduce frequency and duration of flooding	Knickpoints and channel incision, channel widening, disconnection of floodplain habitat	Meander bend	High	5 to approx. 50 years	Upstream, local, downstream

(*Continued opposite*)

Table 1 *Continued*

Dikes (levees)	Flood risk	Reduce flood extent	Reduction of connectivity, floodplain accretion, increased flood risk due to increased settlement and economic activities	Floodplain	High	10 years plus	Local
Revetments	Channel stability	Prevent bank erosion	Thalweg scour, disruption of sediment budget	Channel banks (cutbanks)	Moderate, high	10 years	Local, downstream
Dredging	Navigation	Increase channel depth	Disruption of sediment budget	Bars, riffles	Low	Instantaneous	Local, downstream
Dams (main-stem)	Flood risk, irrigation, human/commercial consumption	Prevent flooding, support agriculture and economic activities	Disruption of sediment budget, upstream storage of sediment, disruption of flow regime, downstream channel incision, habitat degradation	Channel bed, banks	Low, moderate, high	10–50 years	Upstream, local, downstream

rivers. Dams may also be created by natural processes, such as earthquake-triggered mass wasting events which result in large volumes of material blocking river valleys. Several general categories of dams include check-dams, low flow dams, and large main-stem dams. While large main-stem dams constructed upon large rivers receive much publicity, small dams located on low-order rivers are nearly ubiquitous across many parts of Earth's riverine landscapes.

Dams alter the downstream hydrologic regime by reducing high flows and increasing low flows. Dams also trap sediment behind reservoirs, with sediment trap efficiencies commonly exceeding 95%. The altered hydrologic regime and reduction in sediment load result in downstream channel incision, degrading aquatic habitat. Simulated flow events and sediment flushing can be an effective management regime, but are dependent upon the physical setting and dam operation.

Globally there are currently two main contrasting trends concerning dams: construction of large dams in Asia, Africa, and South America, and removal of small dams in North America and Europe. The science of understanding the downstream impact of dam removal on rivers is in its infancy, with important questions pointed towards understanding the effects of released sediment on channel and floodplain habitat, including the magnitude of change and the timescale for recovery.

Meander bend cutoffs

Meander cutoff for channel straightening is among the most commonly utilized engineering procedures for flood control, but is also used to increase the navigability of rivers heavily utilized for commerce (Gregory 2006). Many meandering rivers in the Northern Hemisphere have been straightened by the process of artificial cutoff. Cutoffs are created by dredging and cutting a ditch across a point bar, especially at an elongated meander neck, during the low flow season. Because the sandy point bar material is noncohesive, the ditch rapidly enlarges as stage levels increase, further accelerating inflow and subsequent incision and widening of the new channel cut. Within several years the cutoff is usually complete, depending upon the sedimentology and subsequent streamflow events. Well-known examples of rivers straightened by artificial meander cutoffs include the Yangtze, the Rhine, the lower Mississippi, and the Kissimmee River in Florida. Meander bend cutoffs were an especially common engineering practice in the United States during the early half of the 1900s, and were seen as part of a broader management program for river "improvement" to reduce flood risk and increase the depth of navigable waterways. Along many meandering rivers, cutoffs have achieved their desired goal of reducing flooding. Unfortunately, the practice has had profound unintended geomorphic and environmental consequences, requiring further management and engineering.

Meander bend cutoffs reduce channel length (and sinuosity) and locally increase channel gradient, thereby causing a channel knickpoint. Hydraulically this is important because the increased channel gradient increases shear stress. The combination of the greater shear stress and higher velocity results in channel bed incision, dependent upon the channel substrate and bed material. Along many rivers which have undergone multiple cutoffs within a relatively short period of time, knickpoints migrate upstream and result in extensive channel degradation. Following channel bed incision, channel banks then become over-steepened and subsequently erode and input large volumes of sediment into the channel. Thus, upstream migration of knickpoints frequently results in downstream channel bed widening and aggradation. This presents a new problem to river management authorities, which may now need to increase both the frequency of dredging and the construction of revetments to prevent bank erosion and groynes to "train" the channel.

Because meander cutoffs for flood control result in reduction in overbank hydrologic events, the natural hydrologic connectivity is substantially diminished, resulting in significant adverse consequences to floodplains and associated aquatic environments. Management strategies to reconnect rivers to their floodplains are oriented towards increasing freshwater pulse events into aquatic environments. This may involve a gamut of engineering options, including sluice gates, diversion structures, side channel creation, and floodplain lowering, as well as breaching of floodplain dikes.

Sequence of water engineering

The timescale for engineering to occur ranges greatly according to the sophistication and scale of the feature, as do the benefits to humans and the adverse impacts to the river environment. Planning should take into account several distinct phases, including (i) initial planning, (ii) construction, (iii) implementation, and (iv) abandonment and/or removal of structures.

The *planning* phase should include a multidisciplinary team of scientists and stakeholders, and establish hydrologic and environmental baseline conditions of the setting. This often includes a review of hydrologic and sediment databases from government agencies, as well as of the geomorphic and environmental setting. The *construction* phase is completed by engineers with heavy machinery, and should be organized with a view to minimizing the construction footprint. Many water engineering activities are closely synchronized to the hydrologic regime, implying a seasonality of construction activities. The *implementation* phase awaits actual hydrologic events to test the effectiveness of the structure, which may then require further calibration. Constructing sluice gates, for example, to manage or restore freshwater inputs into floodplain water bodies often requires additional calibration to optimize sediment inputs. *Abandonment* of structures is common and unfortunately many rivers are littered with relict engineering structures (local dikes and bank protection works), which may continue to influence active hydrologic processes and effectively become part of the modern environment. In some instances prominent features are being *removed*, such as dikes and some dams, but this depends on the budget and management priorities of government agencies which oversee such activities.

SEE ALSO: Fluvial depositional processes and landforms; Fluvial erosional processes and landforms; Geomorphic hazards; Geomorphic systems; Geomorphic thresholds; Rivers and streams; Water resources and hydrological management

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