RIVER NAVIGATION AND ASSOCIATED STRUCTURES

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1. Introduction

Navigation of rivers to transport people and goods precedes historical record. However, within the last few centuries, navigation structures have significantly augmented the ability of industry to transport goods to and from inland ports. In many cases, improvements in river navigation have provided an economical method of transporting large quantities of grain, petroleum, coal, metals and ores, fertilizers and chemicals, forest products, and other cargo, but the improvements have not come without a cost. Navigation structures have been necessary to increase river depths, eliminate meandering, and reduce water velocities in existing rivers. These structures are often expensive in monetary, societal and environmental costs.

In some cases, the necessary navigation structures include navigation dams or multipurpose dams. Navigation dams form a deep, low velocity reservoir in locations where passage was once impractical because the river was too shallow or currents were too swift. Multipurpose dams are often used to provide a steady supply of water in times when flows would normally be low. The steady supply allows navigation downstream of the dam that would otherwise be impossible during low flow periods. If a multipurpose dam can be circumnavigated by barge tows, the reservoir behind the dam aids navigation in the same way as the reservoir behind a navigation dam. Although both types of dams assist inland navigation, the dams may be associated with a variety of problems. Sediment laden rivers may deposit large quantities of sand in reservoirs, and severe erosion may occur downstream of the dam. Reservoirs formed behind the dam offer recreational opportunities, but other forms of river recreation may have been important prior to dam construction. Larger reservoirs sometimes inundate vast areas of agricultural land and populated areas. Finally, the dams may cause habitat loss, or restrict passage of migratory fish.

While dams often help reduce the risk of flooding, other structures may increase flood risks. In some locations, dikes are installed to increase river depths. During floods, the dikes continue to restrict flow in the river, causing higher river stages. Navigation structures also influence where sediment is eroded and deposited. Sedimentation always occurs in areas of low water velocities and low turbulence such as in reservoirs, backwater areas, and behind dikes. Erosion occurs where water velocities are high such as in channel cut-offs, or where natural sediment loads have been altered such as downstream of dams.

There is almost always an environmental cost when the natural flow of a river is changed; the cost may come in the form of erosion, sedimentation, introduction and propagation of exotic species, or loss of habitat. With careful planning and wise decisions, environmental costs can often be reduced. Dam releases can simulate natural flows in times when excess water is available, the size and location of dams can be chosen to limit habitat loss, and measures can be taken to prevent the introduction and spread of exotic species. Furthermore, placement of navigation structures and vessel operation procedures can be modified to reduce unwanted sedimentation and erosion.

2. River Morphology and Sediment Transport

In general, natural rivers are almost never straight. Straight channels develop secondary currents that meander between riverbanks. At the points where the secondary currents are strongest, erosion develops, and at the points where the currents are weak, deposition occurs. The secondary circulation patterns in the river cause bends to develop in the river. The newly formed bends accentuate the strength of the secondary currents. At the bends, higher velocity water is restricted to the outside of the bend. Consequently, most erosion occurs on the outside of a river bend and most deposition occurs on the inside of the bend. Given that the channel bed consists of erodible material, and that the channel does not have an excessively large sediment load, the originally straight channel becomes more sinuous, and a meandering river develops. Trees, bluffs, and variations in the properties of bank material influence how the meanders develop, but are not the underlying cause of meanders. The process of meander development in a straight alluvial channel is demonstrated in Figure 1.

As sediment is eroded from the outside banks of a bend, the size of the bend is expanded, and the length of the river is increased. Consequently, the streamwise slope of the river and the ability of the river to erode sediment decrease. During a flood, water is no longer restricted to the main channel. Instead, some of the flow is on the floodplain. If the flood is significant, and river meanders are large, the flood may cut a new channel between two bends of a meander (see Figure 1).

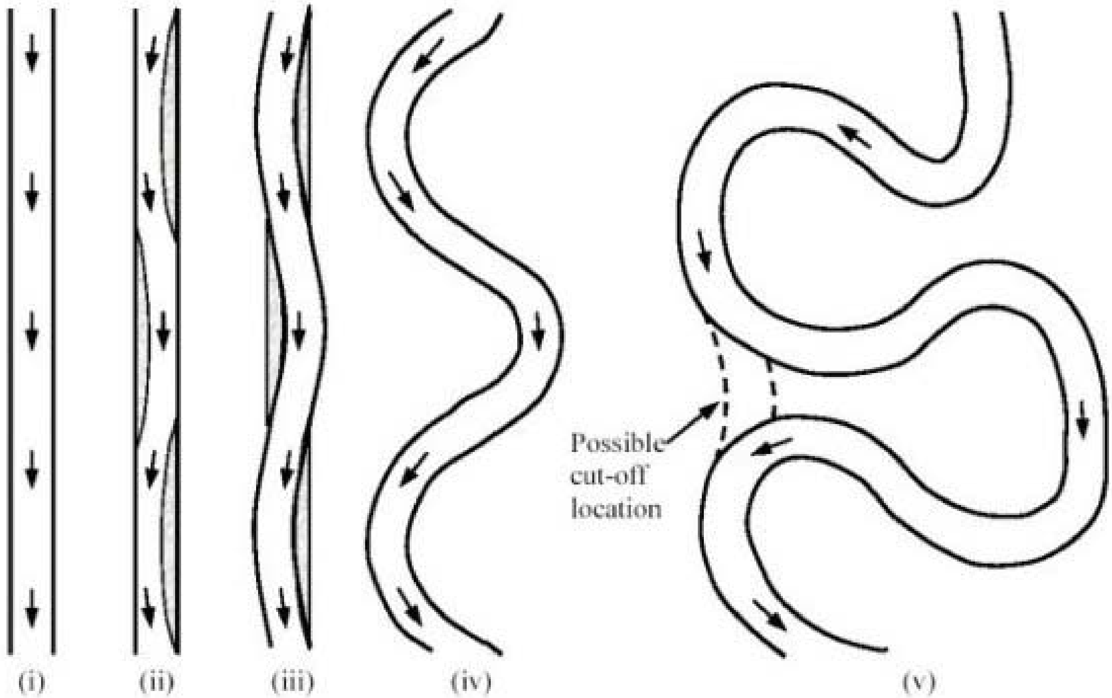

Figure 1. Meander formation: (i) original channel is straight with uniform cross section (ii) alternating pattern of erosion and deposition develops as a result of secondary currents
(iii) secondary currents intensify and banks erode (iv) curvature of stream increases, intensifying outer bank erosion and inner bank deposition (v) meanders are fully formed and do not increase in size, but they continue to migrate.

The new channel isolates the original meander, forming an oxbow lake. The cut-off that is formed reduces the effective length of the river. The slope of the channel is higher than before the cut-off was formed, and the erosion process intensifies. In areas of the river where velocities are low, sediment is deposited, forming sand bars. Depending on flow and sediment characteristics, the bars may be eroded away when a flood occurs, or they may compliment the natural meandering and migration of the stream.

In theory, the sediment load that is supplied to a river and the dominant discharge of the river determines what gradient the river tries to establish. If a river cannot transport the amount of sediment that is supplied to it, some of the sediment that is supplied is deposited, and the gradient of the river increases. When the gradient of the river increases, its ability to carry the sediment that is supplied to it improves. If a river is capable of carrying more sediment than is supplied to it, the river erodes material from the bed and banks of the river, causing either meandering or channel degradation. The additional erosion continues until the gradient of the river is reduced enough so that the carrying capacity of the river matches the sediment load supplied to the river.

Many of the rivers that are suitable for navigation are situated on wide alluvial floodplains, and meander between river bluffs that define the floodplain. In some cases river meanders are difficult or impossible to navigate, and because of the reduced slope of the river, meanders may promote excessive sedimentation in the navigation channel. Occasionally, in locations where sedimentation is severe or meanders are too sharp to navigate, cut-offs have been actively constructed across the natural meander of a river.

Deltas are depositional areas that form where rivers empty into the ocean or another large body of water. Upon entering a delta, a natural river forms rivulets that weave between the boundaries of the delta, depositing sediment carried from upstream. The sediment that is deposited is often rich in nutrients, and the fresh water that is supplied throughout the delta sustains a wide variety of plant and animal life. For navigation purposes, a single, deep channel is necessary, and the delta may be channelized from its inlet to its outer boundary. A single channel prevents most of the delta from being replenished with sediment and fresh water. Eventually, the lack of replenishment leads to subsidence of the delta, intrusion of salt water into the delta, or both. At the mouth of the Mississippi River in the United States, steps have been taken to divert some of the river water from the main channel into the delta to prevent saltwater intrusion. However, this will not prevent subsidence or erosion of the delta, and methods of diverting sediment into the delta are also being investigated.

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Biographical Sketches

David M. Admiraal was born in 1969 in Orange City, Iowa, USA. He became an Assistant Professor of Civil Engineering at the University of Nebraska in 1999. He has two degrees in Mechanical Engineering and has also served as an Intern for the Department of Energy at Pacific Northwest Laboratory during 1990 and at Sandia National Laboratory during 1991.
His research interests include sediment transport, hydraulic modeling, environmental hydraulics, and fluids instrumentation. He recently obtained his Ph.D. in Hydraulic Engineering at the University of Illinois at Urbana-Champaign, USA. His past work in Illinois includes shear stress measurements between barge tows, sediment transport by unsteady flows and measurements of sediment concentration using an acoustic concentration profiler.
Dr Admiraal is currently part of a team of Biologists and Engineers studying Dissolved Oxygen Transport in a tailwater reservoir. He is a member of the American Society of Civil Engineers (ASCE), the International Association of Hydraulic Research (IAHR), and the American Geophysical Union (AGU). He has published on his research in several journals and reports.

Marcelo H. García was born in 1959 in Argentina. Dr. García is currently Professor of Civil and Environmental Engineering, and Director of the Ven Te Chow Hydrosystems Laboratory, at the University of Illinois, USA.
His research interests lie in the area of Environmental Hydraulics and Sedimentation. In particular, he has developed one of the most popular predictors for sediment erosion and re-suspension in rivers, lakes and oceans. Recently he conducted a major study to assess the environmental impact of navigation-induced sediment re-suspension in the Upper Mississippi River Basin, including the Illinois River.
Professor García's research on sedimentation has been twice recognized, in 1996 and 1999, with the Karl Emil Hilgard Hydraulics Prize for best paper in the Journal of Hydraulic Engineering published by the American Society of Civil Engineers (ASCE), and received the Walter Huber Civil Engineering Research Prize in 1998 awarded for excellence in research.
Professor García chairs ASCE's Sedimentation Committee and is currently Editor-in-Chief and coauthor of Manual 54, Volume 2 on Sedimentation Engineering. He currently leads the Hydraulic and Sedimentation analyses components of an inter-disciplinary research project on the restoration and naturalization of rivers and streams in urbanized areas funded by the Environmental Protection Agency's Water and Watersheds Program.
Dr. García also serves on the editorial board of Water Resources Research of the American Geophysical Union and of Hydraulic Engineering in Mexico, published by the Mexican Institute of Water Technology. He has been an invited Professor and Lecturer at several Universities, the most recent assignments being at the California Institute of Technology, USA (1997), the Ecole Polytechnique Fédérale de Lausanne, Switzerland, (1999) and the Universidad de Castilla-La Mancha, Spain (2000).