Smart Infrastructure for the Mekong Program

Cambodian Navigation Channel Management

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1 Background and Need

Cambodia contains three major navigation waterways: the Mekong, Bassac, and Tonle Sap Rivers. All three of these waterways require navigation dredging to maintain unimpeded water transport in both the wet and dry seasons. The Mekong River is the primary waterway for commercial transport of international goods into and out of Cambodia. Thus, the Mekong River navigation channel is maintained from the Vietnam border upstream to Kampong Cham and the Tonle Sap River is maintained from Phnom Penh to Siem Reap. A navigation channel is not currently being maintained on the Bassac River, although commercial vessels do use this route during the wet season and there is local use during both the wet and dry seasons. Improvement of navigation from Kampong Cham to Kratie is currently under investigation through a separate study. According to the Phnom Penh Autonomous Port (PPAP, personal communication, January, 2016), international vessel traffic on the Mekong River from the Vietnam border to Phnom Penh is approximately 15 cargo ships per week, and 5 to 10 passenger vessels per week, depending upon the season. All international vessels require a PPAP pilot.

Currently, navigation dredging is conducted on an as-needed basis, but in many areas dredging occurs at least annually. The need for dredging is determined by reports from the PPAP pilots and annual surveys conducted by the PPAP and the Ministry of Public Works and Transport. The Ministry authorizes the exact location and extent of navigation dredging, but private contractors complete the work.

Various types of suction dredges are employed for sand dredging, although clamshell dredging is employed in nearshore areas when fine sediments are being removed. The Cambodian government contracts with multiple operators with various types of equipment to conduct navigation dredging. Most dredged material is removed from the river systems, and is typically sold for aggregate or fill, depending on the sediment composition.

2 Purpose

The Cambodian government is interested in immediately improving their navigation program to address both navigation constraints and increased bank erosion due to dredging activities and ship traffic. The Mekong River Commission (MRC) recently completed a two volume comprehensive treatise titled "Design of a Master Plan for Regional Waterborne Transport in the Mekong River Basin" (2015). These documents provide very specific information about short and long-term projects in support of navigation for all of the Mekong River countries. The Korean International Cooperation Agency (KOICA) has funded a feasibility study on waterway improvement for port logistics in Cambodia that is still underway, but is expected to be completed in February, 2017. The study area includes 215 km of the Mekong River from Phnom Penh to Kratie. The purpose of the KOICA project is to produce a master plan for waterway improvement, which includes guidelines for waterway management. Specifically, the scope of work comprises channel management guidelines, plan of aids to navigation, embankment reinforcement plan, and a waterway maintenance control plan. Additionally, at the global level, there are extensive documents and design guidelines available for navigation dredging, but much of that guidance emphasizes sediment management rather than determining navigation channel locations, sizing, and long-term management. The intent of this document is not to repeat any past or on-going efforts, but rather to create a navigation program framework within which these actions can be effectively integrated and implemented.

Before specific, ongoing navigation management issues can be adequately addressed, such as accelerated bank erosion, flow control, and sediment management, four primary elements of a navigation program need to be implemented. Primary elements include:

(1) permanent, **designated navigation channels**;
(2) **aids to navigation**, including maps, GPS coordinates, and field indicators, such as buoys and navigation markers;
(3) designated and enforced **speed limits** within the navigation channels for various sized vessels and weights to minimize bank instability from wave-induced erosion and for increased safety;
(4) **consistent channel dimensions,** including specific depths and widths that are maintained both over time and throughout the length of the various navigation channels.

Once these four primary elements are addressed, the projects proposed in the MRC and KOICA reports will be more effective and sustainable. The purpose of this document is to discuss specific options for the four primary elements of a successful and sustainable navigation program, supported by Best Management Practices.

This document has been prepared for the Mekong River and tributaries located within the Kingdom of Cambodia, thus the focus is on navigation in rivers or inland waterways, not coastal or estuary settings where salinity and tidal fluctuations must be considered.

3 Primary Elements

3.1 Element 1: Designated Navigation Channels

Although Cambodia does have some navigation channels designated on maps and charts, navigation channels shift from year to year and many of the maps are now out-of-date. Because extensive dredging is cost prohibitive, the current navigation channel is opportunistic in nature and generally follows the natural thalweg (deepest part of the channel), even when it is directly adjacent to high eroding river banks. Based on numerous interviews, it is evident that navigation dredging is used to artificially connect naturally deep river reaches. Thus, the location of the navigation channel is generally dictated by river processes.

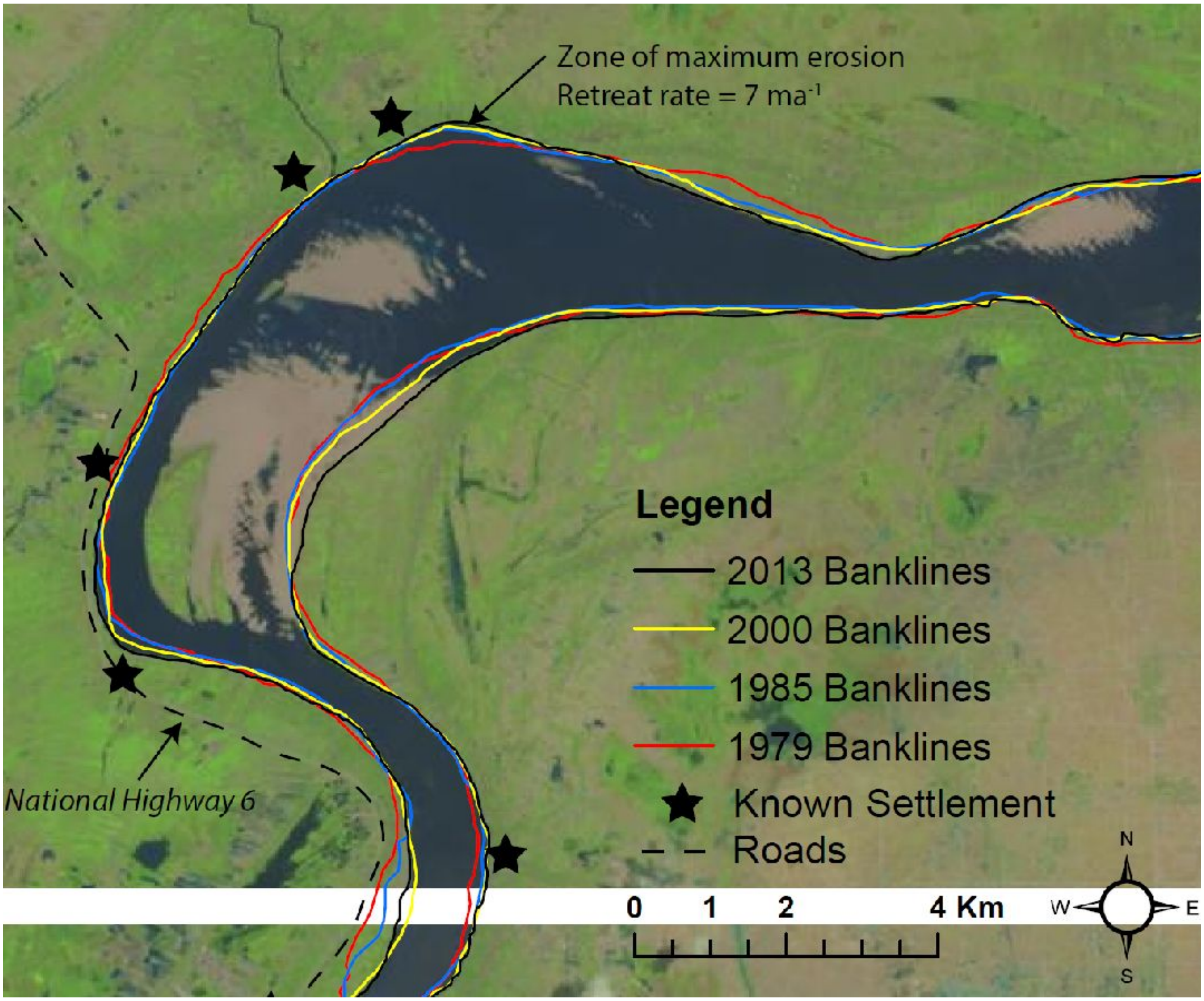
In general, thalwegs follow a more sinuous pattern than the overall river, and the deepest pools are often located in tight bends immediately adjacent to river banks on outside bends. Using the natural thalweg position for the navigation channel may result in additional erosion to banks that are already destabilized due to natural river processes (Figure 1). In the absence of extensive flow redirection and deflection structures, such as groins or jetties, navigation channels that follow the centerline of the channel reduce river bank impacts, such as bank suction, while also reducing wave-induced erosion. Ships that travel too close to river banks create bank suction forces that increase in magnitude with increasing ship speed (USACOE, 2006).

Navigation channel location can be designated based upon up-to-date bathymetric surveys. While the use of existing deep channels is often the preferred choice, deep channels may increase bank instability when the channel is adjacent to actively eroding river banks or when the close proximity of a vessel to the shoreline results in bank suction.

Designating a navigation channel along the entire length of the Mekong River in Cambodia, not just along sections of channel where navigation is affected by shallow depths, would allow for additional management actions to be employed, specifically navigation aids and speed enforcement. It will also locally improve sediment transport in the navigation channel due to increased velocities between the bottom of the vessel and the river bed, which helps to keep the bed mobile within the navigation channel. This is described later as the “ship squat” effect.

Element 1: Designate commercial vessel navigation channels for all navigable waterways.

Figure 1. Example of lateral channel adjustment on the Mekong River at a site located just upstream from Phnom Penh. Figure provided by Steve Darby (2016).



3.2 Element 2: Navigation Aids

Currently, aids to navigation (primarily buoys) on the Mekong River between the Vietnamese border and Phnom Penh are placed in limited areas where navigation is affected by shallow water or tight curvature bends (Figure 2). Navigation aids are not currently used to keep commercial vessels along a single path through river reaches that are navigationally unrestricted. The lack of a consistent and complete navigation aid system not only causes navigation challenges through restricted river reaches, it also forgoes the benefits of passive navigation channel maintenance that can occur with frequent ship traffic and increased safety for smaller vessels.

While buoys are an important part of a navigation program, there are challenges to their installation and maintenance on the Mekong River because of the 10 to 20 meter fluctuation in river stage between wet and dry seasons. To accommodate high flows, tethers must be long enough so that the buoy is not submerged. At low flow, the tethers are too long and thus do not effectively mark the edge of the navigation channel. Other aids to navigation, such as range markers placed along the river bank, should be considered in areas where buoys are difficult to maintain or are at risk of being washed away during flood events.

Chapter 5 of the MRC's Navigation Master Plan (MRC 2015) titled "Short Range Aids to Navigation" provides an excellent overview of the various types of navigation aids, including their common applications and limitations, and explains the U.S. Aids to Navigation System. These short range aids to navigation are often referred to as NAVAIDs, and comprise a warning system to alert vessel pilots to potential navigational dangers and to keep larger vessels within designated channels. In addition, the KOICA funded waterways project will provide aids to navigation recommendations for the Mekong River between Phnom Penh and Kratie.

Element 2: Establish a consistent and complete navigation aid system in commercially navigable waterways that is functional during both high and low flow seasons.

Figure 2. Existing navigation aids in Cambodian waterways, from MRC (2015)

3.3 Element 3: Speed Limits

Setting speed limits within navigation channels and harbors addresses numerous river management concerns, including excessive bank erosion and public safety. While bank erosion along the Mekong River is a natural process, it is exacerbated by vessel wakes. Speed limits are one strategy for reducing the impact of ship wakes on bank erosion. Speed limits typically are not constant, but vary depending upon the size and shape of the vessel, the distance from the bank line, the velocity of the river, and the direction of travel (Trung, et al., 2015).

Speed limits for various ships operating within designated channels and harbors can be selected carefully to reduce ship squat and vessel-wake effects on river banks. Although there may be economic incentive for ships to travel at high speeds to efficiently transport goods, these benefits must be weighed against negative effects, such as increased erosion and consequent need for bank stabilization.

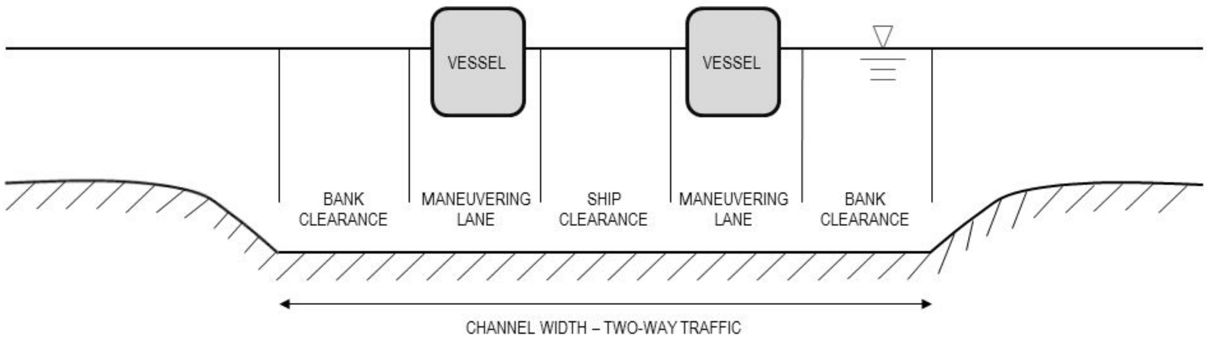
Ship speeds vary depending upon the direction of travel and the relative river velocities. Most ships must maintain at least 4 knots relative speed to maintain rudder control and maneuverability, although some ships begin to lose rudder control below 6 knots (USACOE, 2006). This typically results in much higher speed limits for ships travelling in a downstream direction with the flow, compared to vessels travelling upstream against the flow. According to the US Army Corps of Engineers (2006), transit speeds from 5 to 10 knots are the most common ship speed in typical harbor channels as observed on a number of projects.

Element 3: Determine appropriate speed limits for common vessels under a variety of conditions. Prominently post and enforce these limits.

3.4 Element 4: Consistent Channel Dimension

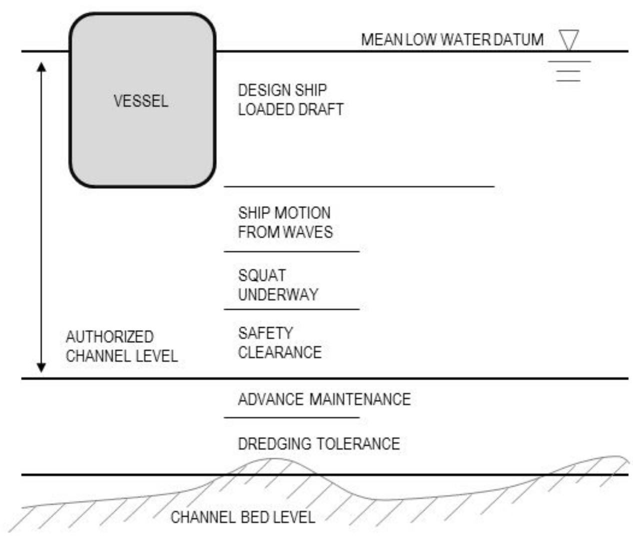
Vessel safety and transit times can be optimized if navigation channel width and depth are consistently maintained. The design width of the navigation channel can be calculated to include the width of the maneuvering lane(s), bank clearance, turning radius, and, for two-way traffic, adequate distance for ship clearance (see Figure 3). Narrower channels may be appropriate for passenger and domestic commercial vessels. Navigation channel width in bends requires special consideration to account for the increased width required by turning ships (ASCE, 2005).

Figure 3: Channel width design for two-way traffic in trench-type channel, modified from ASCE (2005).



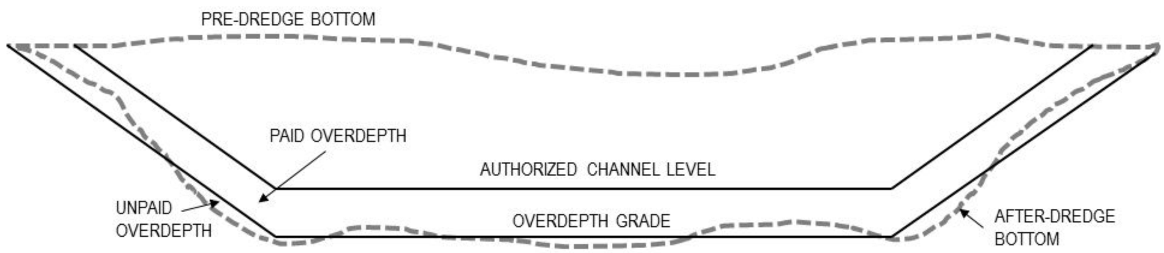
The minimum navigation channel depth is based upon the largest vessel with the deepest draft that is expected to navigate through the system during low flow (Figure 4). This idealized vessel is referred to as the “design ship”. The selected depth is usually determined through an economic analysis that compares the annual value of goods being transported, compared to the annual cost of maintaining the navigation channel. Initial costs of establishing the navigation channel depth are generally much higher than the subsequent annual costs for maintenance of the established depth (ASCE, 2005).

Figure 4: Design depth factors, modified from ASCE (2005).



Because the side slopes of the navigation channel need to be relatively flat to maintain stability, the actual size of the excavated channel will exceed the minimum navigation channel width. The dredged depth will also exceed the minimum navigable depth to accommodate side slope sloughing, bedform development, such as sand dunes, variable river discharge, and inherent inaccuracies in the dredging process (Tavolaro et al., 2007). The navigable channel size is termed the “authorized dimension” or "authorized channel level", while the expanded dredged prism is termed "overdepth dredging" (also known as dredging tolerance), as shown in Figure 5 below.

Figure 5. Overdepth dredging, modified Tavolaro et al. (2007).



Ideally, the navigation channel is designed such that it is passable by the design vessel at most times of year and under most river conditions when piloted by an experienced captain. However, seasonal elements to river discharge and flow patterns may temporarily limit navigability. Such considerations are especially relevant to the Mekong and tributaries, because of pronounced seasonal fluctuations in discharge and associated water levels. Hydrologic analyses informing channel design should explicitly consider frequencies, durations, and amplitudes of water-level fluctuations.

Element 4: Develop and maintain a standardized navigation channel prism.

4 Navigation Channel Best Management Practices

Once the location and size of the navigation channel is determined, a comprehensive navigation program can be established. Sedimentation is a primary cause of navigation channel maintenance. Because navigation dredging is expensive, time intensive, and can have extensive negative environmental impacts, it is critical to first employ methods to prevent or reduce sedimentation within the navigation channel. If sedimentation cannot be avoided through preventative measures, and flow redirection structures are either prohibitively expensive or not feasible, a comprehensive dredging program that includes avoidance and minimization measures for adverse impacts may be employed.

The U.S. Army Corps of Engineers (USACE) developed an approach for managing sediment for navigation channels that aims to minimize dredging because of the expense and related environmental impacts. This approach to sediment management focuses first on prevention, second on treatment, and then finally on accommodation (ASCE, 2012; Table 1).

Table 1: Navigation Sediment Management Taxonomy

Category	Strategy	Techniques
Prevention	Keep Sediment in Place	Erosion control on land; maintain a stable bed and reduce bank erosion
	Keep Sediment Out	Connect floodplains and create islands; sediment traps, gates, and dikes
	Keep Sediment Moving	Flow deflection and redirection (training structures; agitation and flushing flows
Treatment	Keep Sediment Navigable	Mobilize sediment with ship traffic
	Dredge Sediment	Initiate dredging program
Accommodation	Adapt to Sediment Regime	Lighten loads, use smaller vessels, navigate with the tides, seasonal navigation

Adapted from ASCE (2012).

4.1 Prevention

Prevention includes reducing sediment inputs from external sources, the river bed, and from bank erosion, while concurrently providing depositional areas within the channel for sediment storage. Prevention may also include keeping sediment moving through the navigation channel with flow deflection or redirection structures. The preferred option is to keep the sediment in place before it affects navigation. For example, management practices may be employed within the watershed to reduce erosion. Once sediment is delivered, to and mobilized within, the river system, provision of depositional areas can help to reduce sedimentation within the navigation channel. When these preventative techniques are not sufficient to address navigation problems caused by sedimentation, then treatment strategies become necessary.

4.1.1 Keep Sediment in Place

Rivers are natural conduits of sediment across the landscape. However, human activities may accelerate the delivery of sediment to rivers or exacerbate rates of bank erosion. The aim of *Keeping Sediment in Place* is to minimize delivery of sediment to the navigation channel, whether the sediment is derived from upland areas in the watershed, from banks along the river, or from the river bed.

River channel beds have various levels of mobility depending upon their composition, especially the percent of fine sediment, their exposure to hydraulic forces, and disruption due to human influence, such as dredging. To keep sediment in place, river beds near the navigation channel should be protected from excess shear stress, if possible, and from direct manipulation by equipment. The only bed-disrupting activity that should take place in the vicinity of a navigation channel is dredging within the designated navigation prism.

Over-widened river reaches often pose navigation hazards due to shallow depths. It may seem reasonable to allow additional dredging and/or commercial mining in an over-widened reach to increase the flow depth, but in actuality, it can reduce depths and exacerbate navigation problems. This is due to increasing the overall channel cross-sectional area, which then results in decreased flow velocity and increased deposition. Beyond increasing the cross-sectional area, in-channel mining also causes river bed instability and remobilizes sediment, which may be deposited within the navigation channel downstream. To increase bed stability near navigation channels, mining areas can be relocated to areas where over-widening and shoaling are of less concern. However, there are significant negative environmental impacts associated with sediment removal from river systems (Bravard et al., 2013).

River banks may be subject to accelerated rates of erosion due to a variety of human activities, including but not limited to removal of vegetation and effects of boat traffic. Vegetation removal and grazing on river banks may lead to erosion, and hence exacerbate channel widening. Bank erosion can be mitigated through vegetation and grazing management. Bank vegetation increases roughness and thus encourages sediment deposition in the near-bank area. Vegetation also increases soil strength and resistance to flowing water through the increased tensile strength provided by plant roots (Simon and Collison, 2002). A recent study in the Mekong Delta found that well-vegetated river banks are a viable countermeasure to minimize the effects of boat wake erosion (Trung et al., 2015).

Boats may destabilize a river bank in two primary ways: bank suction and wake action. Bank suction occurs when a ship travels close to one river bank or when the banks are not symmetrical, leading to asymmetric pressure forces on the hull (along the longitudinal axis). As a ship's hull moves through the water, a pressure gradient is formed with higher water pressure at the front, or bow, of the boat and lower pressure at the rear, or stern, of the boat. Bank suction typically rotates the stern closer to the bank and the bow further from the bank, thus making navigation more difficult.

The impacts of wakes are determined by a variety of factors, including vessel size, speed, frequency of trips, and proximity to the bank. A decision tree for use in management of vessel wakes is provided in Appendix C.

4.1.2 Keep Sediment Out

River beds and bars provide temporary storage for coarse sediment, while floodplains provide depositional areas for finer sediment. This differentiation in sediment storage is revealed in the finer soils typically found in the floodplain, compared to the coarser nature of in-channel bars. Sediment shoaling in shallow-water areas of over-widened river reaches often reflects deposition of both the coarse and fine sediment fractions. Shoaling can become increasingly persistent in areas where cohesive sediments lock coarser sediment in place. To reduce shoaling, connect floodplains to provide off-channel storage for fine sediments.

To encourage the formation and expansion of floodplains and vegetated islands, anchor the head of emergent mid-channel bars with vegetation, wood piles, or other structures. Stabilization of the head of a bar allows bar expansion through increased deposition, which then provides an increased planting surface. If dredge material is available, placement on these new bar surfaces can help stabilize the river reach. Once the new bars and floodplain surfaces become vegetated, the flow is confined to a relatively smaller cross-sectional area, thus resulting in deeper channels (Figure 6).

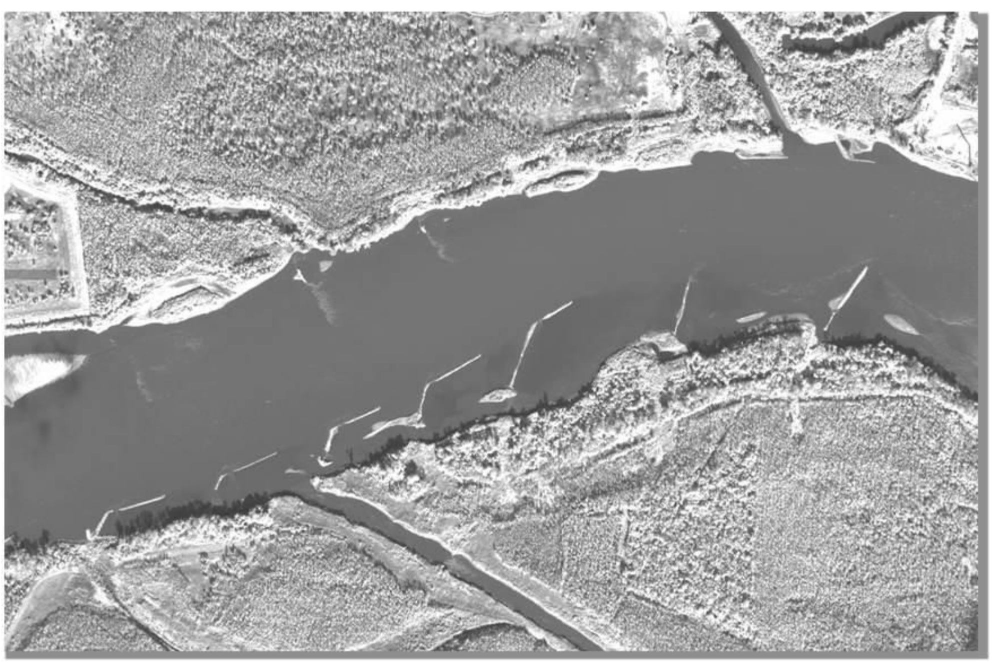
Figure 6. Examples from the Kootenai River, Idaho, USA, of wood pilings installed to create new floodplain areas to increase channel depth.

4.1.3 Keep Sediment Moving

Flow deflection and redirection structures are used in many navigable rivers to address sediment management issues and, specifically, to reduce the need for maintenance dredging. Typical structures fall into two primary categories: resistive and redirective (ASCE, 2012). Resistive structures, such as revetments, are used to reduce bank erosion and channel migration. Resistive structures create a physical barrier, between the bank and the erosive force of flowing water. Rock revetments are most commonly used; however, other materials include large wood, sheet pile, timber piles or articulated concrete mats (ASCE, 2012). While traditional revetments can negatively impact aquatic habitat, the inclusion of vegetation in the structure design can reduce these impacts, while increasing bank stability.

Redirective structures, such as groins and jetties, stabilize the channel cross-section by redirecting or constricting the flow area, thus altering the velocity distribution and creating a more coherent high-velocity core (ASCE, 2012). This in turn affects erosion and deposition patterns and alters channel dimensions. In some settings, extensive use of redirective structures produces a self-maintaining navigation channel, and hence the need for dredging becomes negligible. However, redirective structures are relatively expensive, impact aquatic habitat (especially shallow water habitat), and transported sediment is deposited in downstream reaches, which may cause additional navigation challenges.

Figure 7. Example of redirective structures on the Lower Missouri River, USA.



Many types of groins and jetties are used in riverine settings; selection of the appropriate type depends on channel geometry and alignment (ASCE, 2012). Rock is typically the preferred material for construction, although timber or a combination of rock and timber may be used in some settings. Established engineering guidelines dictate design geometry for factors such as height, crest width, crest profile, side slope angle, structure angle, and spacing. The design must be specific to local channel alignment and navigation objectives. Newer styles of redirective structures employed in the U.S. include bendway weirs, chevrons, and hardpoints. Each address specific challenges in maintenance of navigation channels and detailed design materials are available elsewhere (ASCE, 2012). Redirective structures and revetments, however, may have unintended consequences, such as negative impacts to the river ecosystem and native fishes (Jacobson and Galat, 2006). The effects of such structures can be evaluated to ensure that the social, economic, and environmental impacts of river modifications are fully understood and considered by all stakeholders.

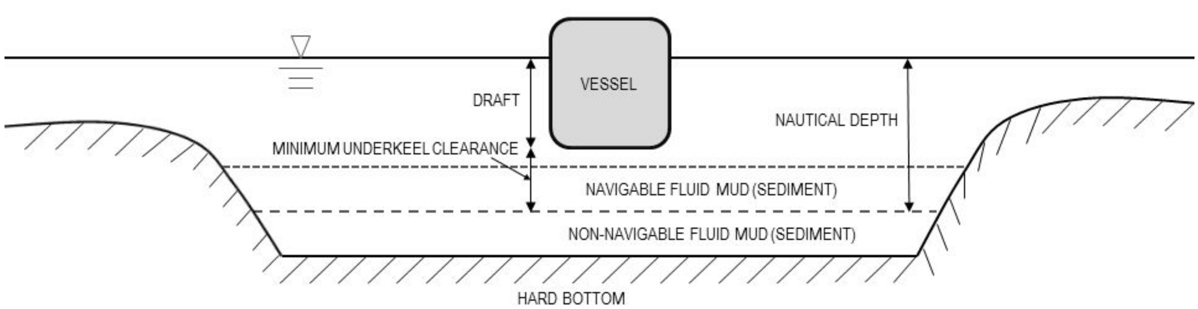
4.2 Treatment

Preventative techniques alone may be insufficient to maintain a navigation channel. Once sediment has entered a navigation channel, then treatment strategies may be necessary. Treatment of sediment in the bed of navigation channels can be addressed by two broad measures – keeping sediment navigable and implementing a dredging program.

4.2.1 Keep Sediment Navigable

Maintenance of navigation channels need not solely depend upon an active dredging program. Confining deeper draft vessels to a single navigation lane can help maintain bed-sediment mobility. This occurs because of “ship squat”, which is a lowering of the ship in the water column due to higher flow velocities between the bottom of the vessel and the river bed, thus causing a relative pressure decrease (Briggs, 2006). The higher velocity increases the shear stress on the bed, keeping it more mobile than the adjacent river bed (Figure 8). This effect is maximized when all large vessels travel within the navigation channel, which both increases bed mobility inside of the navigation channel and helps maintain bed stability in areas outside of the navigation channel.

Figure 8. Nautical depth (adapted from William H. McAnally, Mississippi State University).



Channel depth in reaches with a fluidized sediment layer and no easily definable bottom is referred to as “nautical depth” (Figure 8). It is possible for larger ships to travel through several meters of this semi-liquid sediment layer (PIANC, 1997; ASCE, 2005). The minimum underkeel clearance (Figure 8) must be selected such that there is no contact between the moving vessel and non-navigable portion of the channel bed. Traditional survey techniques, such as echosounders, are not suitable for determining the boundary between the navigable and non-navigable layers of fluid sediment. Thus, non-traditional survey methods may be required to accurately identify the depth of navigable sediment and to ensure vessel safety. Additionally, this approach requires specific knowledge about the navigation response of ships in areas with fluidized sediment.

While keeping sediment mobile within the navigation channel can help reduce sedimentation, it rarely eliminates the need for sediment removal, although it may reduce the frequency and extent of dredging.

4.2.2 Dredge Sediment

The two main categories of dredges used to maintain navigation channels are mechanical and hydraulic (ASCE, 2005). Mechanical dredges scoop and lift sediment from the river bed using a bucket and crane system. Common types of mechanical dredges include a dipper or bucket dredge; bucket styles include clamshell, orange peel, or dragline. Hydraulic dredges use pumps and pipes to suction sediment from the channel bottom to the dredge vessel. The most common hydraulic dredge used in river settings is the cutterhead dredge, which is also known as a hydraulic pipeline dredge.

Dredging operations produce large quantities of sediment and sediment slurries, which then must be properly disposed. Three general options for dredge sediment disposal include upland, open-water, and flow-lane disposal (ASCE, 2005). While it is understood that much of the sediment dredged from Cambodian rivers is disposed of in upland areas or sold for aggregate, both of which are considered upland disposal options, there may be circumstances where other disposal methods are required or preferred.

Open-water disposal is used when sediment is free of contaminants and can be used within the aquatic system to create desirable habitats and/or to modify channel hydraulics. An example is island creation, which may provide habitat benefits, create an area for sediment storage, and help concentrate flow to increase channel depth. Flow-lane disposal is generally less desirable than upland or open-water disposal because it simply transfers the dredged sediment from one reach of the navigation channel to a downstream reach where bed sedimentation is of less concern. However, this approach keeps the sediment within the navigation channel and may cause subsequent increased sedimentation at downstream locations.

Dredging is an essential tool in the construction and maintenance of navigation channels; however, the practice may cause undesired environmental impacts, such as increased turbidity, decreased dissolved oxygen, entrainment of fish and other aquatic species, and resuspension of contaminated sediments (ASCE, 2005). Dredging Best Management Practices (BMPs), such as those provided by the New Jersey Department of Environmental Protection’s Dredging Manual (1997), should be considered to reduce inadvertent impacts from dredging activities (see Appendix A). Links to additional resources are provided in Appendix B: Web Resources.

4.3 Accommodation

Sediment accommodation techniques are employed when (1) preventative actions are insufficient to avoid sedimentation problems in navigable waterways, and (2) sediment treatment options to address these problems are limited by resource availability. Because of the limited number of maintained navigation channels within Cambodian rivers, accommodation of sediment is currently being practiced in most navigable waterways.

4.3.1 Lighten loads

If river reaches are depth-limited, decreasing the total load carried aboard ships reduces the draft and allows for navigation through restricted reaches. Additionally, loads may be lightened by transferring cargo from larger to smaller ships, thus decreasing vessel draft for the cargo in transport (ASCE, 2005).

4.3.2 Seasonal navigation

Seasonal limitations can be accommodated through the use of smaller vessels with shallower drafts during the dry season. Because smaller ships are already used in upstream reaches and through the Tonle Sap, this accommodation technique could simply be employed by using existing vessels in downstream reaches during the dry season.

4.3.3 Navigate with the tides

When navigation depths are limiting, timing transport during high tide periods can allow for passage through depth-limited river reaches. The effects of tidal influences on navigation are not addressed in this report.

5 Additional Engineering Guidance for Navigation Projects

For additional guidance, the U.S. Army Corps of Engineers "Hydraulic Design of Deep-Draft Navigation Projects" provides detailed information regarding the planning, development, and design of navigation projects (USACOE, 2006). They provide the following checklist for preliminary project planning:

a. Review appropriate engineering guidance and literature.
b. Consult with local port authority, pilot associations, and harbor terminal users.
c. Collect and analyze pertinent physical and environmental data.
d. Review appropriate local pilot or captain ship maneuvering strategies and evaluate existing project navigation conditions.
e. Determine volume and type of ship traffic and largest ships to be accommodated.
f. Determine volume and type of commodity to be moved.
g. Determine amount, type, and frequency of hazardous cargo (liquified natural gas (LNG), ammunition, oil, radioactive, etc.) movement and evaluate special requirements.
h. Select and list the required project design operational conditions.
i. Select channel layout and alternative dimensions to be considered and determine advantages and disadvantages with annual costs.
j. Assess any adverse environmental and other impacts.
k. Define environmental mitigation needs and enhancement opportunities, especially beneficial uses for dredged material.
l. Review accident records for existing ship channels that are to be enlarged.

6 Summary

Navigational dredging is just one component of the suite of activities that can be used for design and operation of navigation channels. In order to effectively address sedimentation issues within waterways used for navigation and transport of goods, the location and dimensions of the navigation channel must first be established. Primary elements of a navigation program include:

(1) permanent, **designated navigation channels;**
(2) **aids to navigation**, including maps, GPS coordinates, and field indicators, such as buoys and navigation markers;
(3) designated and enforced **speed limits** within the navigation channels for various sized vessels and weights to minimize bank instability from wave-induced erosion and for increased safety;
(4) **consistent channel dimensions,** including specific depths and widths that are maintained both over time and throughout the length of the various navigation channels.

Sedimentation is a primary cause of problems in the maintenance of navigation channels. Because sediment management via dredging is expensive and time intensive, it is useful to initially explore methods to prevent and/or reduce sedimentation within the navigation channel. Thus, maintenance of navigation channel dimensions may first focus on prevention of sedimentation problems, second on sediment treatment, and then finally on sediment accommodation. In addition to the guidance presented here, existing international standards and Best Management Practices (BMPs) can be used to minimize environmental impacts. Even if BMPs are used, activities associated with the creation and maintenance of a navigation channel may fundamentally alter riverine habitat in ways that negatively impact aquatic species such as fish. Full consideration should be given to the wide-ranging effects of physically modifying river ecosystems.

7 References

ASCE (American Society for Civil Engineers). 2005. Ship Channel Design and Operations. ASCE Manuals and Reports on Engineering Practices No. 107. ASCE: Reston, VA.

ASCE (American Society for Civil Engineers). 2012. Inland Navigation: Channel Training Works. ASCE Manuals and Reports on Engineering Practices No. 124. ASCE: Reston, VA.

Bravard, J.P, Goichot, M. and Gaillot, S. 2013. Geography of sand and gravel mining in the Lower Mekong River, EchoGéo, 26 | 2013, URL : http://echogeo.revues.org/13659;DOI:10.4000/echogeo.13659

Briggs, M. (2006). Ship squat predictions for ship/tow simulator. Coastal and Hydraulics Engineering Technical Note CHETN-I-72, U.S. Army Engineer Research and Development Center, Vicksburg, MS. http://chl.erdc.usace.army.mil/chetn/

Darby, S. 2016. Unpublished data from University of Southampton, UK.

Jacobson, R.B., and Galat, D.L. 2006. Flow and form rehabilitation of large-river ecosystems: An example from the Lower Missouri River. Geomorphology 77, pp. 249-269.

MRC (Mekong River Commission), 2015. Design of a master plan for regional waterborne transport in the Mekong River Basin. Final Report, Volume I, December 2015.

NJDEP (New Jersey Department of Environmental Protection). 1997. Dredging Technical Manual, The Management and Regulation of Dredging Activities and Dredged Material Disposal in New Jersey’s Tidal Waters. Dredging Task Force, October, 1997, (http://www.state.nj.us/dep/cmp/analysis_dredging.pdf)

PIANC. 1997. Approach channels – a guide for design. Supplement to Bulletin no. 95, First Rep. of the Joint Working Group PIANC and IAPH, in cooperation with IMPA and IALA, PIANC.

Simon, A., and Colison, A.J.C., 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms 27, pp. 527-546.

Tavolaro, J. F., J. R. Wilson, T. L. Welp, J. E. Clausner, and A. Y. Premo. 2007. Overdepth dredging and characterization depth recommendations. ERDC/TNEEDP-04-37, Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Trung, L.V., N. Tanaka, and J. Yagisawa, 2015. Application of vegetation on mitigating riverbank erosion caused by boat-generated wave attacks. Research Report of Department of Civil and Environmental Engineering, Sitama University, Vol. 41.

USACOE (United States Army Corps of Engineer). 2006. Hydraulic Design of Deep-Draft Navigation Projects, Engineering and Design, Engineering Manual EM 1110-2-1613, 31 May 2006

APPENDIX A: Dredging Best Management Practices (BMPs) from the New Jersey Department of Environmental Protection's Dredging Manual (1997)

1. Hydraulic Dredging - preferable when an acceptable upland disposal site or storage facility is available within pumping distance of the dredging area, which reduces the generation of suspended sediments. However, this method results in the production of large volumes of dredged material slurry. Thus, the proposed upland site must be designed and operated to accept such material.
2. Closed Clamshell - the use of a closed, watertight clamshell reduces the production of suspended sediments at the dredging site. A closed clamshell should be required when the sediments are contaminated. A number of procedures can be employed by the dredging contractor to minimize the creation and dispersal of suspended sediments when using a clamshell dredge. These include: (1) maximizing the size of the "bite" taken by the clamshell; (2) slowly withdrawing the clamshell through the water column; and (3) not rinsing sediments off the sides and gunwales of the barge.
3. No-Barge-Overflow - reduces the creation and dispersal of suspended sediments when finer-grained sediments are dredged and is essential when the dredged material is contaminated. The purpose of this BMP is to limit the dispersal of contaminated sediments from the dredging site.
4. Shunting - the active pumping of free water in a barge to the bottom of the water column at the dredging site. It may act to reduce turbidity in the upper water column. The discharge end of the shunting system must include a diffuser in order to minimize the potential for additional disruption of benthic sediments. Additionally, the pumping rate and location of the discharge must not result in the disruption of in-place sediments. This approach could be used as an alternative to barge-overflow in reducing the volume of water in the barge.
5. Seasonal/Migratory Periods - depending on the location of the dredging area, operations may be limited or prohibited during certain times of the year to minimize potential adverse impacts to fish and other aquatic species.
6. Silt curtains - may be practical for use in areas where the water current is less than one (1) knot. The use of silt curtains may minimize the upper water column dispersal of sediments from the dredging area. This BMP can also be used to protect sensitive areas adjacent to the dredging area.
7. Split-hull barges - should only be used in dredging projects which use open-water disposal methods or subaqueous disposal pits.
8. Dredged Material Pumping Systems - the use of a number of pumping systems can provide for more precise dredging operations and minimize the resuspension of sediments at the dredging site. In addition, these systems can reduce the volume of the dewatering discharge from an upland disposal or storage site, thus reducing the potential for impacts to surface water quality. The greatest percent solids transfer is obtained using positive displacement pumps which move material at in situ moisture levels. Typically used for concrete, these devices can achieve pumping capacities in excess of 140 cubic yards per hour. Reduced water content of dredged material can also be achieved through the use of vortex type pumps, which in combination with a directional control system serve the same function as a closed clamshell or a hydraulic cutterhead. However, the material removed has an increased solids content compared to typical hydraulic dredges, and is similar (if not greater than) a closed clamshell, but with far less sediment disturbance and turbidity generation.

APPENDIX B: Web Resources

Navigation channel design:

- Canadian Coast Guard Guidelines for the Safe Design of Commercial Shipping Channels: www.ccg-gcc.gc.ca/folios/00020/docs/gdreport01-eng.pdf
- U.S. Army Corps of Engineers Deep-Draft Coastal Navigation Entrance Channel Practice: http://chl.erdc.usace.army.mil/library/publications/chetn/pdf/cetn-i-63.pdf

Managing boat wakes:

- International Navigation Association Guidelines for Managing Wake Wash from High-Speed Vessels:
  http://www.pianc.us/workinggroups/docs_wg/marcom-wg41.pdf

Navigation aids:

- U.S. Coast Guard Aids to Navigation System: https://www.uscgboating.org/images/486.PDF

River training structures:

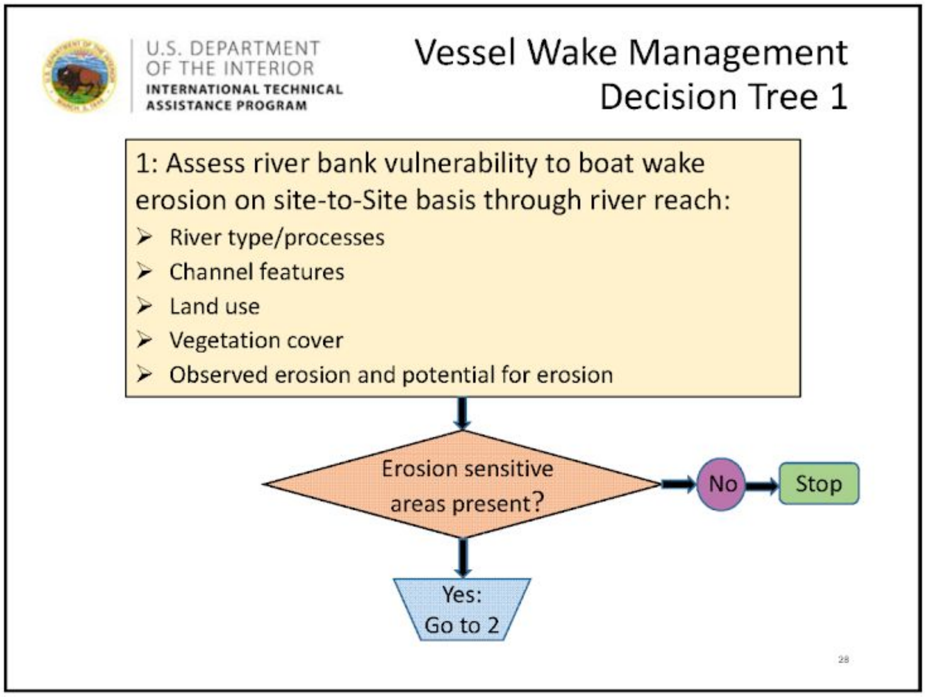
- American Society for Civil Engineers Inland Navigation Channel Training Works: http://www.engr.colostate.edu/~pierre/ce_old/classes/ce717/MOP%20Inland_Navigation_ASCE%20FINAL%20DRAFT.pdf

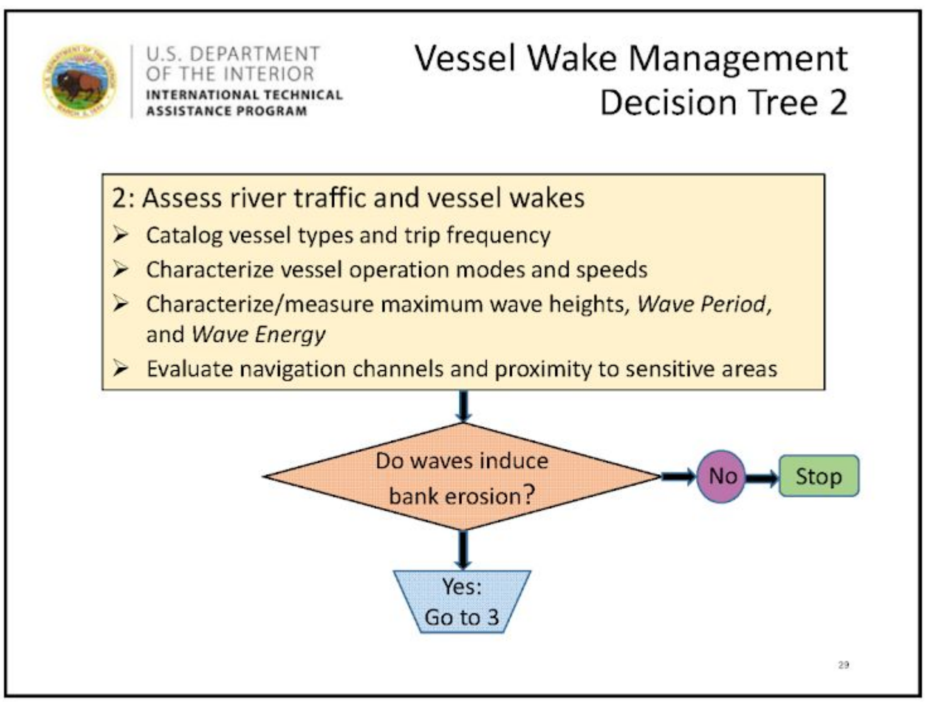
Dredging:

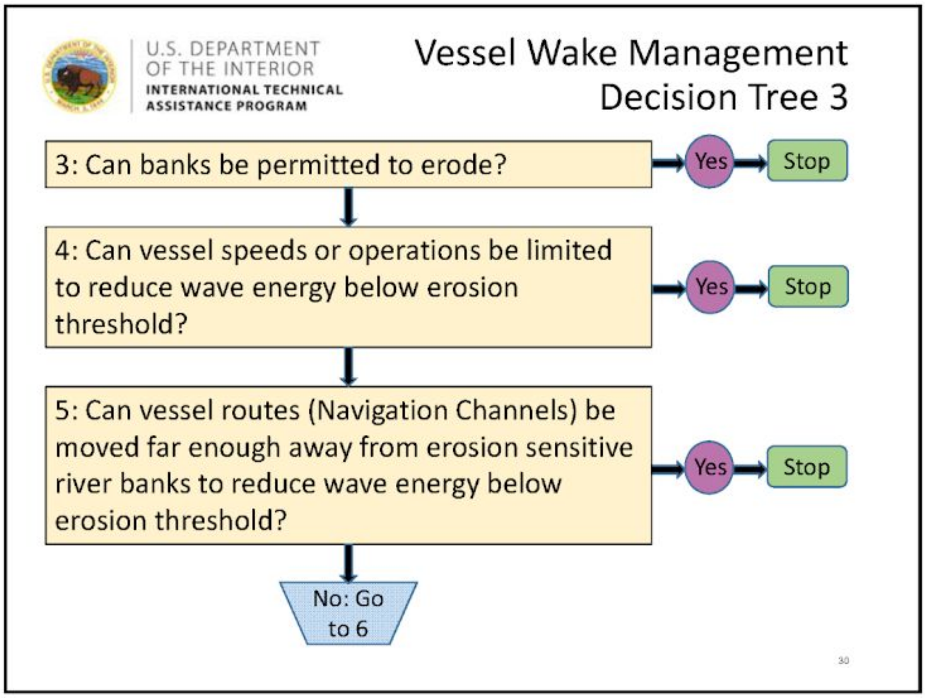
- State of New Jersey Dredging Technical Manual:
  www.nj.gov/dep/cmp/analysis_dredging.pdf
- U.S. Army Corps of Engineers Dredging and Dredged Material Management: http://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-5025.pdf
- U.S. Army Corps of Engineers Overdepth Dredging and Recommendations: http://el.erdc.usace.army.mil/elpubs/pdf/eedp04-37.pdf

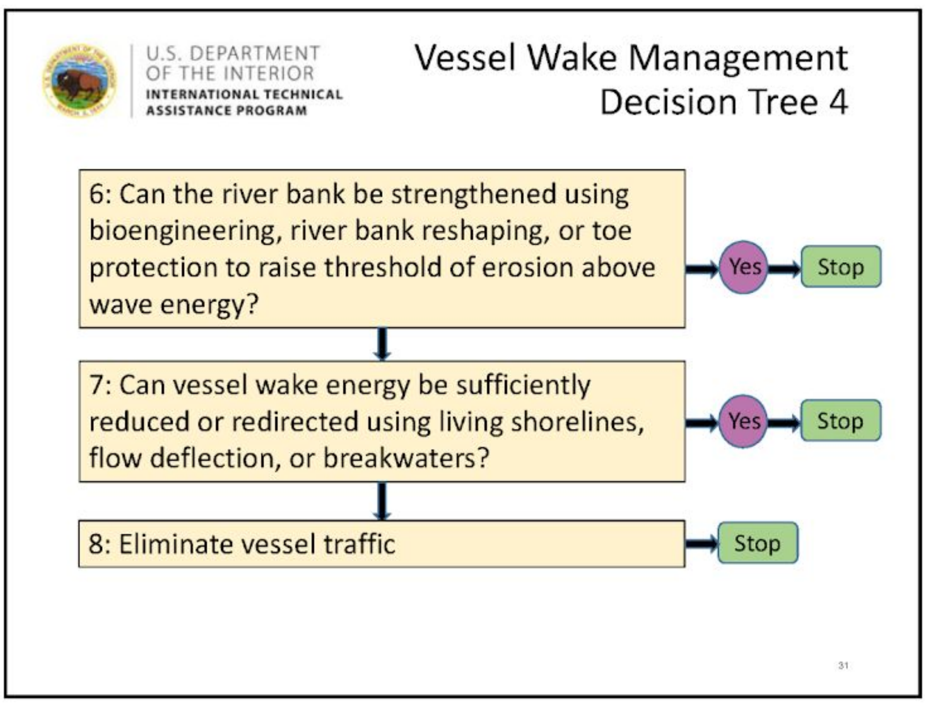
APPENDIX C: Decision Tree for Assessing Bank Stability.

Developed by Conor Shea, US Fish and Wildlife Service, Arcata, California, USA.






U.S. DEPARTMENT
OF THE INTERIOR
INTERNATIONAL TECHNICAL
ASSISTANCE PROGRAM
Vessel Wake Management
Decision Tree 3
3: Can banks be permitted to erode?
Yes
Stop
4: Can vessel speeds or operations be limited to reduce wave energy below erosion threshold?
Yes
Stop
5: Can vessel routes (Navigation Channels) be moved far enough away from erosion sensitive river banks to reduce wave energy below erosion threshold?
Yes
Stop
No: Go to 6
30


U.S. DEPARTMENT
OF THE INTERIOR
INTERNATIONAL TECHNICAL
ASSISTANCE PROGRAM
Vessel Wake Management
Decision Tree 4
6: Can the river bank be strengthened using bioengineering, river bank reshaping, or toe protection to raise threshold of erosion above wave energy?
Yes
Stop
7: Can vessel wake energy be sufficiently reduced or redirected using living shorelines, flow deflection, or breakwaters?
Yes
Stop
8: Eliminate vessel traffic
Stop
31