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Dredging projects selection when the random shoaling effect is considered

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ABSTRACT

The U.S. inland waterway system has more than 11,000 miles of maintained navigation channel, which carries a significant percentage of the national freight total. Maintenance operations, including dredging and lock and dam maintenance/repair, are important to ensuring the effective and efficient operation of the inland marine transportation system. This study specifically deals with maintenance fund allocation to these projects. It proposes a multimodal approach to formulate the waterway maintenance problem in a network that considers rivers, locks/dams, highways and railways. The random effects of channel infilling known as shoaling are also considered. Maintenance on locks and dams reduces the delay therein, the cost of which is also considered in the model. The solution identifies maintenance projects to fund with an objective to serve the OD demand and minimize the total shipping costs on the network. The model is tested using data from the Ohio River Basin network. The proposed model is effective, and the result indicates a trade-off between lock/dam maintenance versus channel dredging. A distinct feature of this study is its explicit modeling of the interdependency between projects in realizing the system benefits as well as the random shoaling effect. A drawback of the numerical tests is that it does not include railway and highway modes.

***Keywords*:** Multimodal network, Waterway system, Maritime transportation, Maintenance, Dredging, Shoaling

1. Introduction

The marine transportation system is comprised of dredged navigation channels, ports, locks & dams, and other terminals as well as shipping vessels. The marine ports and terminals also transfer domestic freight between the waterway transportation system and the connecting road and rail networks. The vast majority of international trades go through the coastal ports and harbors. The U.S. maritime transportation system carries a significant amount of the national freight. About 600 million tons of commodities are transported through the inland waterway system each year, accounting for about 15 percent of the national freight (Fritelli, 2011; Semonite, 2016; U.S. Department of Transportation, 2017). Therefore, sustained recurring maintenance of the waterway transportation system is important. Regular maintenance dredging ensures enough channel depth, typically 9-ft, for inland waterways while the repair and upkeep of locks and dams reduce the likelihood of vessel delay due to unscheduled service outages. These maintenance operations are critical to the waterway system shipping efficiency and safety, which has rich implications for regional economies and environmental sustainability. The limited waterway maintenance funding comes from the Harbor Maintenance Trust Fund (HMTF), which had more than $8.5 billion at the beginning of the fiscal year 2017 (United States Government Accountability Office, 2017) as an example. The HMTF only applies to coastal ports, and the only funds from this account spent on the inland system go to ports and rivers that are not along federally designated fuel-taxed waterways.

The U.S. Army Corps of Engineers (USACE) is responsible for maintaining commercial ports, harbors, and navigable waterways. Maintenance dredging accounts for the vast majority of Corps' total harbor and channel operations and management costs, which was more than 1.1 billion dollars annually as of 2017 (Frittelli, 2019). Major rehabilitations of the Corps' aging inventory of inland locks and dams is paid for by the Inland Waterway Trust Fund (IWTF), which is collected from a fuel tax levied on commercial vessels operating along federally designated inland rivers, however these IWTF outlays do not cover maintenance dredging of federal inland rivers. Dredging in coastal and inland ports as well as along non-fuel-taxed inland waterways is paid for through outlays from the Harbor Maintenance Trust Fund (HMTF), whereas dredging of fuel-taxed inland rivers is covered by annual appropriations designated in the U.S. federal budget. At the highest levels of federal policy making, the outlays from each respective fund are dependent to some degree on the overall levels of commitment to the national marine transportation system generally. And even if they are covered by different funding accounts, the Corps leadership still has a keen interest in understanding the proper levels of investment required to keep channels dredged and locks reliable. So, a model that balances these tradeoff decisions is providing value. As a result, our study problem as defined later assumes a budget cap for the combined dredging and lock/dam repair maintenances. As readers can easily find, by replacing the total budget constraint with separate budget constraints, one may readily address the situation that has separate budget caps.

Nevertheless, given that the backlog of identified waterway maintenance needs exceeds the funds available, how to select dredging projects remains an interesting and significant problem. In the following, both channel dredging and lock/dam repair will be discussed. Without losing generality, readers may conceive the research problem in the context of inland waterway maintenance only.

Channel depth is necessary to safe and efficient shipping. Dredging is the primary means for draft maintenance. It removes the sediments that regularly settle within the designated navigation channel, a process known as shoaling. And the U.S. Army (Corps of Engineers provides for a 9-ft minimum sailing draft (the vertical distance from the keel of the vessel to the water surface) for vessels operating throughout the inland waterway system. Without regular maintenance dredging, shoaling in navigation channels would lead to draft restrictions for transiting barges requiring that some cargo be offloaded to reduce the sailing drafts, thereby necessitating additional barge transits (and associated shipping costs) to transport the same overall amounts of cargo.

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this includes the Ohio
River, dredging is not required to maintain the 9’ channel because the dams maintain a much deeper pool.

Another important waterway maintenance is on locks and dams. Locks and dams must function reliably to avoid lengthy delays for ships and barges. Even a fairly brief operational failure on the order of a few hours of a navigation lock can cause extensive delays as barge tows queue up on either side, negatively affecting the waterway system efficiency. This paper positions the waterway operations in a context that also involves landside transportation. An important factor in freight shipping is the integration of modes through a multimodal network, consisting of the waterway, railroad, and trucking for efficiency and mobility by leveraging the unique advantages of each mode (Gabriel Crainic and Bektas, 2007; Murphy and Hall, 1995).

This paper deals with the optimization of the waterway maintenance project selection, including dredging and lock/dam maintenance. The Corps, as the administrator of maintenance projects, allocates the available funds to maintenance projects in order to maximize the total system benefits, typically measured by increased shipping capacity compared to a do-nothing option or by the total shipping cost and delay reduction. To accomplish that, the Corps conventionally evaluates the candidate projects based on different measures such as cargo tonnage, project ton-miles, and cargo value in dollars (Mitchell et al., 2013). A report by National Research Council (National Research Council, 2015) suggested that the Corps should not consider the project backlog or the age of inland waterway infrastructure to prioritize the funds, and they should develop an Economically Efficient Asset Management (EEAM) program for this purpose. This report says that USACE has a similar program that considers risks of failure in infrastructure, the economic consequence of having such failures, and the traffic demand to assign the funds (National Research Council, 2015). A report by the Governmental Accountability Office in 2017 (United States Government Accountability Office, 2017) states that the Corps should allocate the budget based on the harbor's use and benefit. Based on this report, the Corps considers the regional importance of a port in assigning the budget; however, the officials stated that they did not perform statutorily required evaluations of the national and regional importance of harbors (United States Government Accountability Office, 2017). The national and regional impact can only be assessed on the accordingly scaled networks.

This conventional process of budget allocation does not consider the interdependent effects of projects on the transportation network but rather only considers the isolated, individual measures such as traffic volumes. The simple rationale is that sailing a larger vessel at one location depends on a channel depth at all the locations of the shipping route that accommodate this larger vessel draft. In addition, the waterway origin-destination routes are intertwined. For instance, the inland marine transportation network on a single river is equivalently a series of segments on a line, and a single weak segment due to an insufficient draft because of shoaling or an out-of-service lock can result in severe disruptions to shipping activity for the origin-destination flows trespassing it. Another example, the Tennessee-Tombigbee waterway located in the northern regions of Alabama and Mississippi got closed in 2019 as a response to shoaling that was caused by heavy localized rain events. The high water level and the sediment that blocked the entrance to a lock chamber closed the system to through traffic for several months (U.S. Army Corps of Engineers Mobile District Website, 2019; US New, 2019). One may easily see that maintaining all but one segment in the system to sufficient levels may produce negligible additional benefits compared to a strategy that maintains none of those same segments. So, using a system-based approach has significant implications when seeking to optimally allocate limited funds across the network for the associated maintenance activities. A system-based approach, which can capture the interdependencies between different maintenance projects in collaboratively supporting origin-destination freight shipping, proves to be a necessary and appropriate approach.

This research aims at developing an operational research model necessary to choose the waterway maintenance projects to increase the minimizing the shipp
system. As mentioned earlier, multiple factors are considered such as the interdependency between project benefits, dredging and shoaling effects, delay due to lock and dam reliability and capacity, and the multimodal connections. A special consideration here is focused on the treatment of the shoaling effect after dredging.

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2. Literature review

The literature review here concerns several areas. Budget allocation is the final decision and, therefore, is the primary focus of this study. Ford (1984) was one of the first who applied operation research techniques to the waterway dredging maintenance. He minimized the excavation and material transportation costs in a network. He also considered the benefit of reusing the dredged materials (Ford, 1986, 1984). Hochstein (1975), and Lund (1990) considered dredging operations on a single route on a river, without considering the connectivity. Mitchell et al. (2013) developed a mixed-integer programming model that did account for the connectivity between projects to optimize the benefit gained from the dredging operations. The benefit was estimated by using the historical tonnage flows at 1-ft increments of vessel sailing draft. They developed a binary model, wherein projects were either fully funded or not funded at all. Some sorting algorithms were proposed based on heuristic criteria and were tested and compared. Khodakarami et al. (2016; 2014) proposed partial funding to the dredging projects requested. A project of a particular budget request is treated as different dredging depth requests, each depth justifying a proportionate portion of the total requested funding. For example, a project that requests to restore 3 ft. of draft via dredging is allowed to dredge from 1 up to 3 ft, but might also be deferred and receive no dredging fund depending on the optimal system-level result. The project may be approved to dredge 1 foot with a third of the total requested budget granted. This treatment allowed a more granular allocation of the limited dredging funds compared to the binary model introduced by Mitchell et al. (2013). They formulated the cost as a linear function of the dredging depth and tried to maximize the tonnage flow on routes. However, neither the shoaling effect nor the multimodal network was considered.

Scully and Mitchell (2017) also studied dredging project selection by considering shoaling effect. The way it considered stochastic shoaling effect is through randomized simulation by generating a large number of scenarios under a probability distribution of shoaling. In each scenario, an optimization is conducted. Each individual optimal result is aggregated in the end to reach a final recommendation. Our paper here instead uses expected shoaling.

Shoaling and dredging are two critical factors that determine the channel depth evolution through time. Shoaling happens due to the natural settling of sediments transported by river flows, with high-water flow events causing elevated suspension and subsequent transport of large quantities of sand, silt, and fine-grain sediment. This natural phenomenon reduces the navigable depths of waterways, and therefore USACE periodically addresses it via dredging. The shoaling process is very complex and highly sensitive to localized factors. In general, there is a lack of available data to enable robust forecasting of localized shoaling rates and patterns (Sullivan and Ahadi, 2017). Nevertheless, there are methods in some cases for estimating shoaling based on historical data and experiential knowledge. For instance, dredging an upstream part of a river might increase shoaling at downstream locations depending on how the dredged material is handled and where it is placed. Ratick and Morehouse Garriga (1996) developed a mixed-integer programming model in order to maximize the achievable reliability of dredging activities for all locations and all periods.

Mitchell et al. (2015) developed a mixed integer programming model to find the optimal combination of ports and channels for dredging/maintenance to have the maximum tonnage throughput in the waterway system subject to a limited budget. They formulated the model and repeatedly apply it over a 20-year duration in the numerical test, though each year was optimized based only on the present shoaling condition and impacts to depth-increment throughput totals (from historical data). It added random parameters at the end of each period to represent the shoaling effect. A genetic algorithm is proposed to solve the formulation. Shoaling effect is a difficult task. However, in recent years, the Corps has established an enterprise capability for managing the tens of thousands of hydrographic channel surveys needed to measure conditions and ultimately to make informed shoaling projections (Dunkin et al., 2018; US Army Corps of Engineers, 2019).

Ahadi et al. (2018) developed a two-stage stochastic model using mixed-integer programming solved by a genetic algorithm for dredging project selection, its goal is to maximize the cargo value through the inland waterway system. To keep the problem tractable, they considered only the important O-D pairs since about 85% of the total tonnage was on about 20% of O-D pairs. In that study, a set of discrete scenarios were generated in which the shoaling effects follow given probability distribution. Those scenarios were able to reflect the correlation of shoaling on different inland waterway segments due to correlated weather and other conditions. However, Ahadi et al. (2018) does not consider the lock and dam effect. Furthermore, it does not mention the scenario size in order to avoid bias.

Lock and dam maintenance is another aspect of the waterway maintenance. The delay there can disrupt commodity flow and therefore add to the shipping cost. Curlee et al. (2004) developed a simulation model called ORNIM that directly considers outages at locks. Wang and Schonfeld (2005) specially optimized the rehabilitation of locks in a separate environment by using the genetic algorithm (G.A.). They considered shipping delay in each lock and dam project and developed maintenance schedules through simulation; however, as they stated, the model was not computationally efficient. The dredging of waterway and repair at locks/dams can be treated in an integrated manner mathematically. Wilson et al. (2011) analytically considered the delay costs by considering the entry into the rivers, import and export ports, crop transfer between production and export zones. A multimodal network was developed comprising trucks, rail, and barges. The delay was also considered in a freight system.

This research follows the authors' earlier effort along the line of modeling the shoaling effect for dredging project selection in Khodakarami et al. (2014). In this research, we develop a two-stage model. The first stage chooses the dredging projects and the depth of the dredging for each project, and the second stage decides on the expected depth due to shoaling. In other words, by clarifying the expected depth of the projects, the throughput maximization problem is solved by choosing the most beneficial projects. The problem is therefore modeled in a deterministic approach by using the expected shoaling effect in the second stage. In other words, the sum of the system benefits over the first year and the expected benefit over the second year is maximized. Additionally, the effect of locks and dams and the network connectivity are considered in this model.

3. The problem description and modeling

The study problem can be described as follows: Given an integrated transport network of rivers, locks/dams, roadways and railways, there is a set of origin-destination demands to ship over this network, each having a specific volume. There is a shipping cost associated with each shipping route due to vessel size and delay at locks/dams. The study problem concerns the waterway system maintenance, in which a set of maintenance projects, each having a particular budget, is proposed. A maintenance project may be for dredging of a particular waterway segment or repair of a lock/dam. A dredging project has a depth of dredging proposed for the budget. The lock/dam repair projects each have a full amount of work. Each project can be approved for partial funding to carry out partially the proposed amount of work proportional to the funding amount. Regarding locks/dams, the partial maintenance is defined as 10, 20, 30, …percent of the full proposed maintenance. Each level of maintenance incurs a different expected delay known at the lock/dam locations to the vessels. About dredging, partial dredging depth may be approved for an accordingly partial budget. This study assumes that the needed budget is linearly related to the approved depth of dredging. For example, an initial proposal of $5 million for a dredging depth of 4 feet may get approved at $3.75 million for a dredging depth of 3 feet. To allow approval of partial funding is based on the fact that a full requested dredging depth may not be more needed than a partial depth at a location after considering the overall system effect.

Each year, only a finite amount of budget is available for the dredging and lock/dam maintenance. Selection of the projects to fund is subject to this budget cap. This study also considers the subsequent shoaling effect in stage two from the stage one dredging decision. Each dredging depth is subject to a shoaling process at a location that follows a particular probability distribution. Therefore, the shoaling at stage two has an expected effect, which is used in the modeling here. A common sense is that a deep dredging in stage one at some locations may be quickly offset to a large degree by a resulting expedited shoaling in stage two. This study considers the system benefits in both stage one (dredging) and stage two (shoaling). The objective is to decide on a subset of the projects to fund so that the commodity shipping cost is minimized over the two-stage period.

Worthy of a notion, the shipping cost is a function of the navigable channel draft allowed. The rationale is that larger depth sails larger vessels, which decreases the unit cost of cargo shipping. Therefore, this study adopts a given cost structure that reduces the unit shipping cost with channel depth. This cost structure was based on the cargo record and cost estimate maintained within the USACE.

Additionally, repair and maintenance of lock and dam improves on the transit efficiency of vessels through them by reducing the vessel waiting time. The reduced waiting time may be due to a more efficient operation or by less frequent lock/dam outages because of breakdown or failure after maintenance (Gambucci, 2010; HDR Engineering, 2013). The waiting and delay at locks/dams is translated into monetary cost in this paper. The level of maintenance and repair can also be approved with partial funding, which also accordingly results in proportionately partial benefits. Of course, the delay is random, but we use an expected value for its cost in the problem formulation. In this way, the shipping cost and the waiting/delay cost at locks/dams are unified in the objective function. The objective function is therefore defined as minimizing the total shipping cost of commodities on the network.

Again, a distinct feature here is that sail of a vessel along a waterway route requires all segments of the channel to meet the draft requirement. The notations, variables, parameters, objective functions and constraints used are specifically defined below.

3.1. NOTATIONS

The later notations are used in developing the model:

LL = Set of all locks

WW = Set of all origin-destination pairs

RR = Set of all routes

$RR(mm)$ = Set of routes on OD m, $RR(mm) \subset RR$

SS = Set of all waterway segments

$SS(rr)$ = Set of waterway segments on route r, $SS(rr) \subset SS$

ZZ = Integer set $\{3,4,5,\ldots,13\}$. Discrete dredging depth of projects allowed with 13 ft being the full depth proposed.

N = Integer set $\{1,2,3,4,5,6\}$. The lock/dam improvement level.

H= Integer set $\{0,20,40,60,80,100\}$. The lock/dam improvement value according to levels. For example, level 4 maintenance carries out 80% of the proposed full amount.

3.2. VARIABLES

$dd_{ii}^{kk} =$ � $1,$ If segment *i* is dredged by *k* feet, $\mathrm{k} \subset ZZ$
$0,$ Other

$ww_{jj,nn} =$ � $1,$ If lock *j* is selected for maintenace (when the degree of h_{nn} is increased)
$0,$ Other

$x_{rr}^{kk,1} =$ � $1,$ If all the segments on route *r* are dredged by *k* feet or more in the first stage
$0,$ Other

$x_{rr}^{kk,2} =$ � $1,$ If all the segments on route *r* remain *k* feet or more in the second stage
$0,$ Other

$ll_{jj} =$ Amount of improvement (i.e. maintenance) determined on lock *j* (in percentage), $ll_{jj} \subset HH$

$CC_{jj} =$ Cost of maintenance of lock *j*

$yy_{jj} =$ Total reduction of expected delay at lock *j* using the linear approximation

$CC_r^{mmmmmm1} =$ shipping cost of route *r* in the first stage

$CC_r^{mmmmmm2} =$ shipping cost of route *r* in the second stage

3.3. PARAMETERS

$CC_i^{kk} =$ Cost of dredging segment *i* by *k* feet

$BB_r^{kk} =$ The tonnage capacity of route *r* after dredging by *k* feet

$NN_r^{kk} =$ The required number of vessels to meet the demand after dredging route *r* by *k* feet

$PP_{r,mm} =$ The portion of the tonnage of route *r* allocated to the total OD of *m* *, where*

$$\sum_{m \in W} P_{r,m} = 1, \forall r \in R \,.$$

Preset volume split between alternative routes.

$cc_{rr} =$ Average shipping cost per vessel on route *r*

$DD_{mm} =$ The freight demand on OD *m*

$bb_{nn} =$ Cost of maintenance level-n

$\beta\beta_{jj} = UUUUUUUU\ cc$ost of improvement for lock j

$VV =$ Delay value (i.e. cost) per hour per vessel

h_{nn}= Alternative amount of improvement on a lock. It is one of the values in H, e.g.), $h_{nn} \subset HH$
where $UU \in NN$. Here $h_1 = 0, h_2 = 20, \ldots, h_6 = 100$

$ff_{jj}(h_{nn})$ =The amount of delay reduction for lock *j* resulting from level-*n* maintenance

$TT =$ Total budget available for all the maintenances.

$MM =$ Big M, a large number

$UU =$ Upper limit of the mean reduced delay of all locks. *It May be a large enough number to make the formulation work.*

3.4. FORMULATION

Obj: $MM\square\square UU \; \sum_{rr\in RR} CC_r^{\max 1} + CC_r^{\max 2}$

Subject to:

$$\text{�}_{ii\in SS}\,\text{�}_{kk\in ZZ}\, dd_{ii}^{kk} CC_{ii}^{kk} + \text{�}_{jj\in LL} CC_{jj} \le TT \qquad (1)$$

$$\text{�}_{kk\in ZZ}\, dd_{i}^{kk} \le 1 \qquad (\forall \square \in SS) \qquad (2)$$

$$\text{�}_{kk\in ZZ}\, xx_{r}^{kk,1} = 1 \qquad (\forall rr \in RR) \qquad (3)$$

$$\text{�}_{kk\in ZZ}\, xx_{r}^{kk,2} = 1 \qquad (\forall rr \in RR) \qquad (4)$$

$$\text{�}_{kk\in ZZ}\, kk\,xx_{rr}^{kk,1} \le \text{�}_{kk\in ZZ}\, kk\,dd_{ii}^{kk} \qquad \text{�}\forall rr \in RR, \forall \square \in SS(rr)\text{�} \qquad (5)$$

$$\text{�}_{kk\in ZZ}\, kk\,xx_{rr}^{kk,2} \le \text{�}_{kk\in ZZ}\, EE(kk)\,dd_{ii}^{kk} \qquad \text{�}\forall rr \in RR, \forall \square \in SS(rr)\text{�} \qquad (6)$$

$$\text{�}_{rr\in RR(mm)}\,\text{�}_{kk\in ZZ}\, xx_{rr}^{kk,1} BB_{rr}^{kk} PP_{rr,mm} = DD_{mm} \qquad (\forall mm \in WW) \qquad (7)$$

$$\text{�}_{rr\in RR(mm)}\,\text{�}_{kk\in ZZ}\, xx_{rr}^{kk,2} BB_{rr}^{kk} PP_{rr,mm} = DD_{mm} \qquad (\forall mm \in WW) \qquad (8)$$

$$\text{�}_{kk\in ZZ}\,\text{�} xx_{rr}^{kk,1} NN_{rr}^{kk} cc_{rr} + \text{�}_{jj\in LL}\,\text{�} UU_{jj} - yy_{rr}\,\text{�} NN^{kk} VV + \text{�} xx_{rr}^{kk,1} - 1\text{�} MM\text{�} \le CC_r^{mmmmmm1} \qquad (\forall rr \in RR) \qquad (9)$$

$$\text{�}_{kk\in ZZ}\,\text{�} xx_{rr}^{kk,2} NN_{rr}^{kk} c_{rr} + \text{�}_{jj\in LL}\,\text{�} UU_{jj} - yy_{rr}\,\text{�} NN^{kk} VV + \text{�} xx_{rr}^{kk,2} - 1\text{�} MM\text{�} \le CC_r^{mmmmmm2} \qquad (\forall rr \in RR) \qquad (10)$$

Linearization of lock maintenance costs where each lock can take one improvement value.

$$yy_{jj} = \text{�}_{nn\in NN}\, ww_{jj,nn}\, ff_{jj}(h_{nn}) \qquad (\forall jj \in LL, \forall h_{nn} \in HH) \qquad (11)$$

$$l_j = \sum_{n\in N} w_{j,n} h_n \qquad (\forall j \in L, \forall h_n \in H) \tag{12}$$

$$\sum_{n\in N} w_{j,n} = 1 \qquad (\forall j \in L) \tag{13}$$

$$c_j = \begin{cases} \beta_j l_j & (14.1) \text{ or,} \\ \beta_j l_j + \sum_{n\in N} w_{j,n} h_n b_n & (14.2) \end{cases} \qquad (\forall j \in L)$$

$$d_i^k, w_{j,n}, x_r^{k,1}, x_r^{k,2} \in \{0,1\} \qquad (\forall k \in Z, \forall r \in R, \forall i \in S, \forall j \in L, \forall n \in N) \tag{15}$$

$$c_j, l_j, y_j, C_r^{m1}, C_r^{m2} \geq 0 \qquad (\forall j \in L, \forall r \in R) \tag{16}$$

The mixed-integer model attempts to use a deterministic approach to minimize the total transportation costs across the network, by selecting the optimal dredging projects and the lock and dam maintenance operations. The total cost includes the shipping cost as a function of the shipping distance plus a delay cost at the locks and dams due to lack of maintenance. The objective function adds all costs along each route to measure the cost of vessel-hour on that route. The required dredging for having the lowest navigable depth (i.e. draft) in all segments along each route, and the amount of delays on the locks and dams measure the total waterside transportation costs. In other words, the cost minimization gives rise to increasing the drafting depth and reducing the delay.

In the above, the objective function contains the costs for two years. Our model considers the cost from two stages. The first stage determines the dredging projects to fund (including the dredging depth). The shoaling in the second stage is conditional on the depth of dredging in the first stage. The expected shoaling is calculated by following a preset probabilistic distribution maintained within USACE. A stage may be a year or longer depending on how accurate the approximate costs are based on the stages. In our study here, a stage is a year for the numerical test.

Constraint (1) limits the total cost of dredging and lock/dam maintenance to the available budget. The lock/dam maintenance cost is associated with the total amount of improvement *l,* which is evaluated in Constraints (11) to (14), and the dredging cost is calculated with the indicator variable *d.* Constraint (2) prescribes that there can only be one dredging depth per segment. Constraint (3) states that there is only one depth increase from dredging in the channel on each path of OD flow. Constraint (4) is similar to (3), but for year two after shoaling. Constraints (5) mandates that the effective, increased depth of each path from dredging be determined by the dredging depth of each segment in the first stage, essentially meaning that the smallest depth increase among the segments along a route becomes the depth increase of the entire route. Constraint (6) is similar to (5), but is based on the remaining depth after shoaling in stage two. The dredging depth in the first stage is selected to minimize the expected value of the total cost over the period of two years. The expected depth is calculated based on historical data and the probability of shoaling after dredging. Constraints (2) to (6) prescribe a relationship that an entire route is dredged to depth k if and only if the smallest dredging depth of all segments along this route is *k*.

Constraints (7) and (8) ensure that the demand for each OD commodity stream can be met. Constraints (9) and (10) specify the cap of the total cost on each stage to be minimized in the objective function. The cost of each route is calculated based on the number of vessels of according size allowed on the route in order to meet the demand. Here the number of vessels NN^{kk}_{rr} is the total capacity BB^{kk}_{rr} divided by the vessel capacity, both NN^{kk}_{rr} and BB^{kk}_{rr} being constant for given *k* and *r*. The vessel capacity and per vessel cost cc_{rr} here are approximate estimates based on subjective judgment by using prevailing vessel size available to each draft depth available based on experiences. It should be mentioned that the number of vessels required to deliver the demand are relatively large for low drafting depths, so these four constraints work altogether to make sure that the demand is met by lowering the shipping costs.

Constraints (11) to (14) implies a relationship between maintenance costs and delays of the dam. Constraint (13) only allows to choose one of the maintenance levels for each lock or dam. Constraint (12) translates a level of maintenance/improvement to the exact percentage, such as 30 percent improvement from the discrete set H. We assume that the maximum level of improvement for a lock is 50 units. Constraint (11) translates the percentage of improvement at a lock/dam into the expected waiting time/delay cost reduction (in time) per vessel. The delay reduction is first calculated in hours before converting into dollars by multiplying it into the delay cost parameter available in Constraints (9) and (10). The relationship between the level of maintenance at each dam and the vessel delay reduction depends on the dam failure probability. A failure may be simply a shutdown for a short period of time due to needed repair to some failed components. The delay may also be due to reduced capacity for lack of sufficient maintenance. The USACE proprietary history data helps determine quantitatively. Qualitatively, the relationship is monotonic, implying a decreasing rate of delay reduction with repair intensity (Khodakarami, 2016) as is represented by function $ff_{jj}(h_{nn})$, where h_{nn} is improvement level. In this paper, we adopt a piece-wise linearization method to approximate the original function. This idea is also suggested in literature where a constant failure rate is observed (Baranov and Ermolin, 2017; Ermolin, 2007). In this paper, we only allow five discrete points to choose for the improvement level decision. Constraints (14.1) and (14.2) are two alternatives for translating the magnitude of improvement into unit improvement cost for each particular lock/dam. (14.1) uses a linear function at a fixed rate while the alternative, (14.2) adopts a linear way to approximate an increasing rate of cost with maintenance. Each time the model is run, only one of the two constraints is chosen. The rationale for exploring (14.2) is that for larger scale improvement, larger equipment may be needed to rent and use, therefore incurring larger cost per unit improvement. Both functions are tested in this paper, respectively. By testing (14.1) and (14.2), a proxy sense of sensitivity of the final recommendation to the lock/dam maintenance cost structure may be achieved, as indicated in the results in Table 1. Constraints (15) and (16) are the standard binary and non-negativity constraints.

4. Test case and data description

The model is tested using data for the Ohio River Basin from historic waterborne cargo flow data maintained by the USACE. The Ohio River plays an important role in the waterway system of the United States, especially in the upper Mid-US region. It connects six states of Illinois, Indiana, Kentucky, Ohio, West Virginia, and Pennsylvania. Major cargo shipped through the Ohio River Basin is coal for the rich reserve in this area as well as petroleum, chemicals, and grains (Wilson and Henrickson, 2007). The model in this study considers the main stem of the Ohio River, which has 700 miles and 21 locks and dams. This study divides the main stem into 51 segments, each segment being a basic funding unit considered for dredging. By going through the dataset, 440 routes are generated from a pool of 51 waterway segments and 21 locks/dams. Figure 1 shows the geographic layout of the river while Figure 2 illustrates the topological connectivity of its components, including the waterway segments, highways and railways serving the OD demand of commodities. Note that not all locations need a 9 feet dredging. For simplicity of the numerical test, 9 feet dredging is assumed for a full project request.

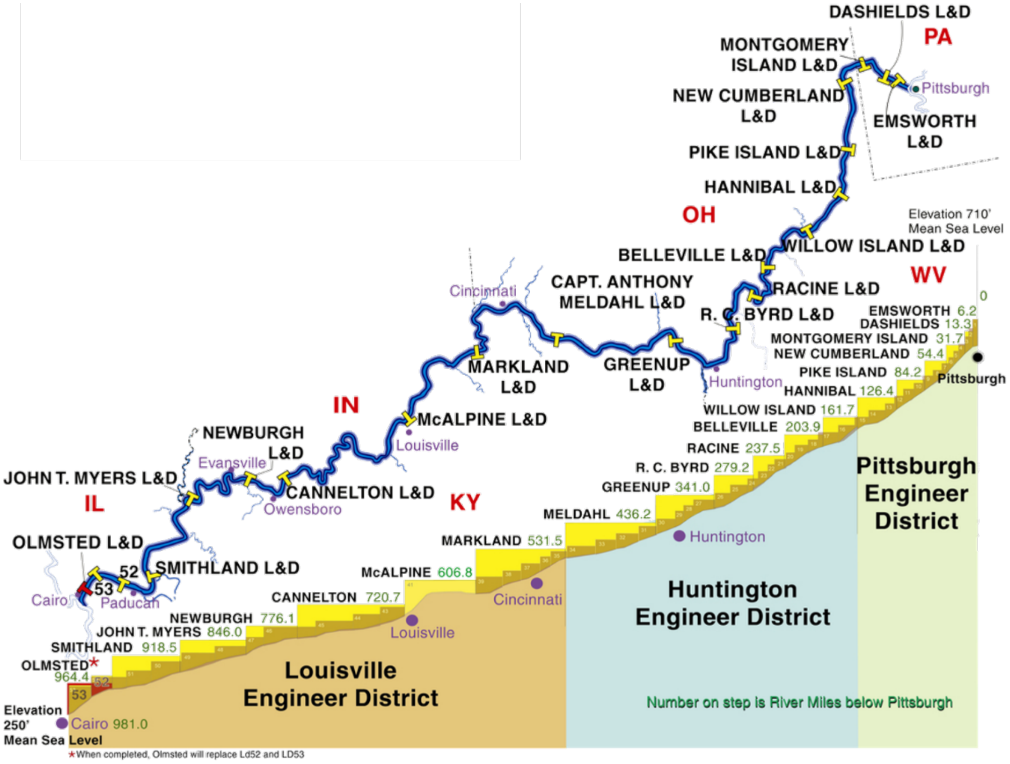

Figure 1 The Ohio River Corridor (Source: (U.S. Army Corps of Engineers, 2012))

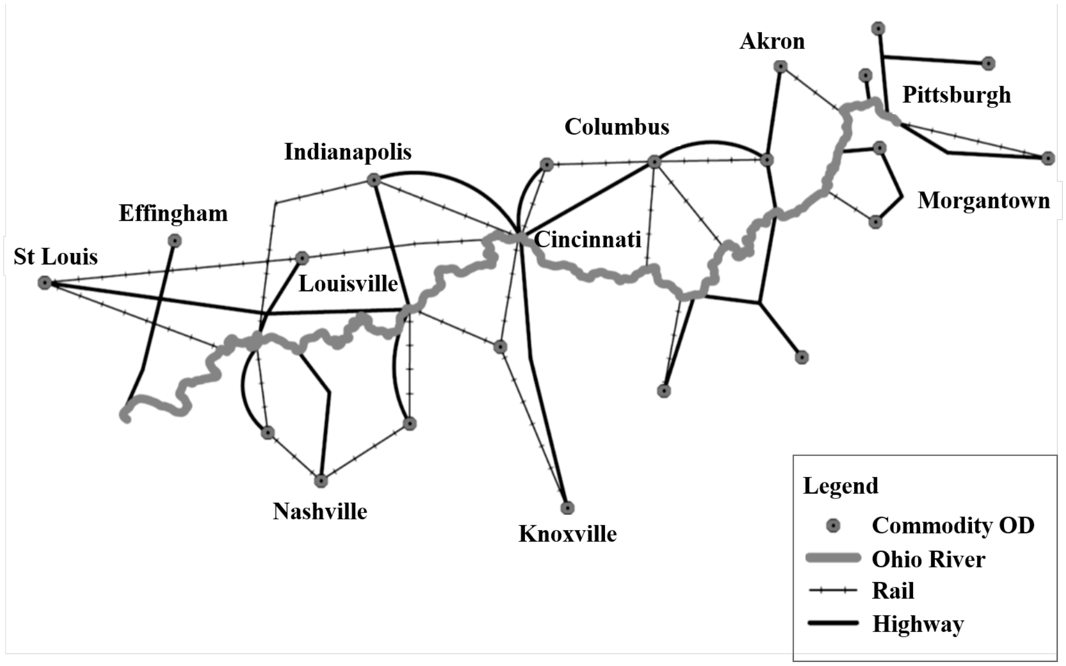

Figure 2 Schematic Multimodal Network In the Ohio River Basin (Source: (Wang and Mahmoudzadeh, 2018))

The USACE maintains the historical cargo data, which includes each vessel's detailed information such as commodities, cargo tonnage, load factor, draft, route, etc. The according channel information such as depth and lock/dam conditions and operations is archived in house and may be retrieved. The historical data is used to derive the efficiency of vessel shipping of sizes as needed for the model, which is conducted in house of the USACE. Figure 2 is the imbedded multimodal network serving the Ohio River Basin OD commodities. This paper takes as given the spatial distribution of OD demands based on historical data extracted from the Corps' waterborne commerce database using the Channel Portfolio Tool that is developed and maintained by the USACE. The origins and destinations are connected to the waterway through highways and railways. The capacities of landside connections are not constraining usually. Therefore, we assume sufficient capacities for the landside links and mainly test on the network effect of waterway maintenance projects. As a special instance, when the waterway capacity falls in shortage due to too small dredging, the commodity flows would be forced onto the landside links. Of course, the proposed model has the potential capability of examining the effect from the landside links as well.

5. Results and findings

In this section, numerical tests are conducted and summarized using the Ohio River Basin data, which also include a sensitivity test to the dam maintenance cost parameter.

5.1. Budget allocations

In solving the model, this paper considers five levels of total available budget as the percentage of the initially requested total by the projects. The initial total allows full funding to every maintenance project, an ideal situation. Note that a lower percentage budget means a tighter budget. Table 1 summarizes the test results.

Table 1. Test results with varying budget

Budget scenario	Total budget ($)	Objective value ($)	Allocated budget to lock/dams ($)	Lock/Dam budget share
Under constraint (14.1)				
0.2	$473,813	$94,706,653	$7,862	1.66 %
0.4	$947,626	$78,905,067	$453,154	47.82 %
0.6	$1,421,439	$74,927,125	$897,552	63.14 %
0.8	$1,895,252	$74,625,598	$1,260,000	66.48 %
1	$2,369,065	$74,307,763	$1,260,000	53.19 %
Under Constraint (14.2)				
0.2	$473,813	$135,603,533	$0	0.00 %
0.4	$947,626	$126,828,910	$392,838	41.45 %
0.6	$1,421,439	$119,684,094	$894,076	62.90 %
0.8	$1,895,252	$113,768,892	$1,366,405	72.10 %
1	$2,369,065	$109,015,375	$1,845,179	77.89 %

In Table 1, the budget scenario refers to how much the total project budget is available as a percentage of the total requested. For example, 1.0 means that the budget is enough to exactly cover all the dredging projects at their full requested amounts plus the fixed amount which is less than the total requested for lock/dam maintenance; In other words, the total budget here is not sufficient to fund all the projects at their fully requested amount. 0.2 means that only 20% of the total budget is available, the amount of which is indicated in the second column. The fourth and fifth columns show the amount allocated to lock/dam maintenance in the absolute total and percentage, respectively. The third column is for the calculated objective value from the optimal solution to the model. Constraint (14.1) and (14.2) are tested, respectively.

The test results show that when the total available budget is extremely tight, an extreme situation, such as when only 20% of the requested budget is available, very little budget would be allocated to the lock/dam maintenance, and the very limited budget would be spent on dredging a few bottleneck river segments. The shoaling made a few river segments constraining on the network, which shall be first addressed. On the other hand, as in the literature, the lock/dam maintenance is highly costly (HDR Engineering, 2013), and the small amount of budget available might not yield meaningful improvement to network efficiency through lock/dams. However, a larger budget available implies a larger proportion of it may possibly be allocated for lock/dam maintenance. The reason for this is that a lock/dam failure can hold up all the vessels, adding to the delay cost. Additionally, by checking on the objective values, Table 1 shows a diminishing rate of return for funding dam maintenance and for the overall operations alike. Note that Constraint (14.2) implies a higher cost for lock/dam maintenance, which explains the difference between the two sections of Table 1.

The formulation has 7,960 variables and is solved on a Windows operating System with a 16 GB of random-access memory on an Intel Core i7 -8650 Central Processing Unit with 1.9 GHz within a time that ranges from approximately 10 seconds to 5,410 seconds. In addition, the model is tested with varying values of the input setups including the average shipping cost per vessel and the delay cost per hour (c_r and V, respectively) in order to show the robustness of the final result. The results indicate that the final solutions are not much sensitive to them.

5.2. Sensitivity analysis of the dam maintenance cost parameter

This section presents the results of sensitivity analysis of the maintenance cost of lock/dam. We multiple the righthand side of constraint (14.2) by a fractional number from 0.5 to 1.5 with an increment of 0.2 to generate a new 14.2 constraint in each test, the cases of which are denoted by $0.5C_j$, $0.7C_j$, $0.9C_j$, $1.1C_j$, $1.3C_j$, and $1.5C_j$, respectively (with slight notational abuse). For example, $0.5C_j$ here represents a new constraint (14.2) constraint as follows,

$$C_j = 0.5 * (\beta_j l_j + \sum_{n \in N} w_{j,n} h_n b_n) \qquad (\forall j \in L)$$

Each fractional number is referred to as a maintenance cost rate in Table 2. We compare the objective value and the share of budget allocated to lock/dams in each of these scenarios with the corresponding values in the scenario using just C_j. The results are provided in Table 2.

Table 2. Lock/Dam budget allocation with maintenance cost rate

Budget scenario	Total budget ($)	Objective change	Dam budget share	Dam budget change
Cost = 0.5C_J				
0.2	$473,813	0.46%	0.00%	
0.4	$947,626	-4.63%	45.90%	10.80%
0.6	$1,421,439	-7.98%	62.20%	-1.12%
0.8	$1,895,252	-6.51%	70.30%	-2.49%
1	$2,369,065	-2.59%	63.40%	-18.56%
Cost = 0.7C_J				
0.2	$473,813	0.41%	0.00%	
0.4	$947,626	-1.94%	43.00%	3.78%
0.6	$1,421,439	-3.56%	60.70%	-3.44%
0.8	$1,895,252	-3.81%	74.90%	3.87%
1	$2,369,065	-2.39%	76.10%	-2.27%
Cost = 0.9C_J				
0.2	$473,813	0.55%	0.00%	
0.4	$947,626	-0.49%	43.90%	5.85%
0.6	$1,421,439	-0.72%	60.40%	-3.98%
0.8	$1,895,252	-0.78%	70.50%	-2.21%
1	$2,369,065	-0.69%	72.30%	-7.14%
Cost = 1.1C_J				
0.2	$473,813	0.23%	0.00%	

0.4	$947,626	0.32%	43.60%	5.22%
0.6	$1,421,439	1.30%	60.20%	-4.25%
0.8	$1,895,252	1.67%	70.50%	-2.19%
1	$2,369,065	2.05%	77.30%	-0.80%
Cost = 1.3Cj				
0.2	$473,813	0.20%	0.00%	
0.4	$947,626	1.51%	46.50%	12.29%
0.6	$1,421,439	2.57%	63.80%	1.36%
0.8	$1,895,252	3.70%	70.40%	-2.40%
1	$2,369,065	4.52%	76.40%	-1.89%
Cost = 1.5Cj				
0.2	$473,813	0.26%	0.00%	
0.4	$947,626	1.69%	40.60%	-2.07%
0.6	$1,421,439	3.59%	60.50%	-3.79%
0.8	$1,895,252	5.22%	70.30%	-2.49%
1	$2,369,065	6.48%	76.50%	-1.82%

In Table 2, objective change refers to the percentage change of the objective value as compared to that using just CC_{jj}. Dam budget share means the percentage of the total budget allocated to lock/dam maintenance. Dam budget change similarly indicate the percentage change of the allocated budget to lock/dam maintenance compared with that scenario of using just CC_{jj}. It shows that the objective function values and the share of budget allocated to lock/dams with the unit maintenance cost. It appears that the percentage changes of the dam allocation share are almost all less than 10% for the varying maintenance cost rates. Table 2 indicate that the lock/dam maintenance budget does not seem sensitive to the lock/dam maintenance cost rate, except for one case when unit cost is $1.3CC_{jj}$ and the budget scenario is 0.4, which does not appear to be a significant outlier.

6. Tests with conventional approaches and managerial insights

The conventional way for maintenance project selection is through reference to the total throughput tonnage over the project segment. A larger annual tonnage would put a project request in high priority. The conventional way seems reasonable on the surface and may get to the right decision for many, if not most cases. But our proposed model has the advantage of revealing why it works or not in the perspective of system optimization. The value of our MIP model resides in the fact that it considers the entire network effect in satisfying the shipping demand at the lowest cost. This section examines two typical common sense and conventional approaches to compare against our MIP model. The first approach considers the benefit and costs in two ways: the benefit cost ratio (B/C) and the local net benefit respectively. A larger B/C ratio or a larger total benefit means a more favored project. The second approach only considers tonnage throughput over the segment of interest in ranking dredging projects, a typical conventional approach. Note that the conventional way only applies to dredging projects and does not apply to lock/dam maintenance. Therefore, in what follows, the project selection under conventional ways only includes those dredging projects. The conventional selection is compared to the selection determined by our MIP model from the network cost perspective. The tests are described in details and numerical results are summarized.

6.1. Benefit/cost approach

The benefit of each project is the total *increased* tonnage that *can* pass through the project location (e.g. the lock/dam or a river segment) *locally,* not accounting for restraints at other locations along OD paths. In other words, the benefit is the resulting potential capacity local to the waterway segment due to the requested project, for the case of dredging. As an example, the potential tonnage of a waterway segment is the sum of the gained (or incremental) traffic for all the OD itineraries that trespass the segment, as referred to as the total benefit of a project. The cost is the project budget requested for the according level of maintenance; again, here the tonnage used corresponds to the level of maintenance. First, we test using the B/C ratio. The ratios are ranked in a descending order. Each of the waterway segments at each of the dredging depths is considered as an alternative project. Note that projects over the same segment represent different depths and are mutually exclusive, where no more than one of them can be selected.

As described earlier, two approaches are experimented: selecting the projects that have the highest B/C ratio and selecting the projects that have the maximum benefit, respectively. In both of the two approaches, the most rewarding project is selected to fund. Each step, the selected project along with other alternative projects on the same segment is removed from a pool of candidate projects, the remaining budget is updated, and the process of selection is repeated. If the remaining budget is not enough to fund a project on the project list, the project is removed from consideration. The process continues until the budget depletes to a level insufficient for any project.

We test both approaches at different budget levels and assessed the network cost for the selected projects as a given solution through our MIP model's objective function, referred to as obj value later. Table 3 and Table 4 summarize the results. In the Table 3 and Table 4, gap means the percentage difference of network shipping costs between the solutions from out MIP model and the B/C approach.

Table 3. Network performance between MIP model and the B/C approach

Budget scenario	Total budget ($)	MIP cost ($)	B/C	Gap (%)
0.2	$473,813	$135,603,533	Not feasible	-
0.4	$947,626	$126,828,910	$129,407,503	2 %
0.6	$1,421,439	$119,684,094	$125,774,602	5 %
0.8	$1,895,252	$113,768,892	$122,465,820	8 %
1	$2,369,065	$109,015,375	$118,079,629	8 %

Table 4. MIP model vs. the max benefit approach

Budget scenario	Total budget ($)	MIP cost ($)	Max Benefit ($)	Gap (%)
0.2	$473,813	$135,603,533	Not feasible	-
0.4	$947,626	$126,828,910	Not feasible	-
0.6	$1,421,439	$119,684,094	$126,980,965	6 %
0.8	$1,895,252	$113,768,892	$122,225,850	7 %
1	$2,369,065	$109,015,375	$119,279,624	9 %

The results show that the shipping costs are lower from using our MIP model compared to using the conventional B/C and max benefit approaches by a significant margin. Naturally, the conventional methods tend to favor fund to the segments at higher depth since the segment usually gets more benefit in this case. This change can cause the optimality gap between our MIP model and the conventional methods.

The gap between our MIP model and the conventional methods increases when the budget availability increases; however, both of them provide reasonable solutions. It should be mentioned that the maximum benefit approach has a slightly larger gap with our MIP model compared to the maximum benefit-cost ratio approach. This is related to the fact that dredging to the max is not always a good option to follow. In the case of using the maximum benefit-cost ratio approach, the system does not always choose to dredge a segment to its maximum depth since the realized benefit might not worth the cost in a network context. Additionally, tables show that when the budget becomes more constraining, the solutions resulting from maximum benefit and max B/C ration methods may not be feasible to our MIP model anymore because they do not consider the network capacity in satisfying the OD demand.

6.2. Through-tonnage approach

This approach tabulates the actual through tonnage on each segment of the waterway for which dredging and maintenance projects are requested and then rank order the projects according their *actual* through tonnages. As an example, the through tonnage of a waterway segment is the sum of the traffic for all the OD itineraries that *currently* trespass the segment. This method funds the projects according to the rank order based on the tabulated total through tonnage. A project on the top of the rank order is removed from consideration when it is either chosen to fund or when the remaining fund is insufficient for it. Each time when a project is chosen to fund, the remaining budget and the pool of candidate projects are updated. And the process repeats until the total available budget is maxed out or when the remaining budget is insufficient to fund any project. The results were identical to the max benefit approach defined in 6.1, which seems reasonable.

6.3. Managerial insights

The major difference between the tests for our MIP model and the conventional methods is the fact that the MIP model considers the costs of locks and dams in its budget allocation as well as the network effect. Conventional methods only consider the dredging projects *locally*. Therefore, the conventional approaches tend to allocate budget to larger dredging depths as much as possible.

To illustrate this difference, we are going to increase the budget level, and see how the budget that can be allocated to deeper dredging in the conventional approaches are shifted from dredging to maintaining locks and dams in the MIP model. We have selected a route that has 21 segments including a single locks and Dam called 07 Aux (Willow Island) located between Mile 160.1 to Mile 161.0 of the Ohio River. This lock segment is located within Washington and Pleasants counties, and acts as a bottle neck in the Ohio river network as 135 waterway itineraries trespass it on the network.

Our model suggests that by changing from budget scenario 0.6 to 0.8, the dredging depth of segments along this route would get deeper by 2 ft according to the conventional approaches while in contrast, the MIP model shows a higher priority on improving the lock within this segment. When continue to increase the budget scenario to 1.0, the MIP solution suggests to continue to increase the level of maintenance of the lock in this segment. The difference from the MIP is due to how the network (or system wide) effect is considered.

To further show this point, we compare the routes that go through funded projects selected by the through tonnage approach and those recommended by the MIP model in the case of having full budget available. Again, the full budget means full amount enough to cover all the dredging projects at full level plus a fixed total below the total requested amount for lock/dams full maintenance. As an interesting result, we find that the MIP model is more likely to fund projects on segments at junctions of routes that connect many other routes/segments.

Table 5 shows the top 20 OD pairs selected to fund using each of these methods. The first column has the list of ranked routes based on the through tonnage, and the second column listed the routes based on the objective value achieved through solving our MIP model in the case of having full budget available. the number in parenthesis indicates the number of segments in each route.

As Table 5 shows, it is less likely for the through tonnage approach to fund routes that are not at the junctions of the network. The routes funded through the MIP model each include multiple segments, each of which could likely becomes a bottleneck in the network and serves a large number of other routes.

Table 5 Routes funded by the through tonnage approach vs. those by the MIP

Conventional Method **Route (Number of segments)**	**MIP Model** **Route (Number of segments)**
61 (10)	430 (66)
427 (15)	431 (62)
53 (5)	410 (60)
58 (2)	411 (58)
149 (17)	6 (59)
237 (0)	412 (56)
262 (0)	432 (55)

64 (21)	413 (54)
132 (16)	375 (53)
396 (25)	356 (50)
405 (7)	349 (49)
363 (21)	357 (47)
421 (27)	392 (47)
144 (8)	34 (45)
416 (41)	358 (45)
287 (2)	414 (52)
66 (23)	393 (45)
63 (19)	359 (41)
289 (5)	299 (45)

In summary, our model is capable of considering both dredging and lock/dam maintenance and making system decisions. The MIP model may help develop or improve the conventional methods towards considering more and more systems effect. This would require a careful diagnosis of the conventional method particularly in how the system effect may be better reflected.

7. Conclusion

The U.S. waterway system carries a large amount of cargo, and plays an important role in international trade and the economy. Dredging at ports and harbors and along the navigable waterways as well as lock and dam maintenance are two important types of projects that ensure the effective functioning of the entire waterway system. There are a fairly large number of maintenance project requests each year, but the budget available is always finite and appears always constraining. Today's typical level of annual budget is at about 1.5 billion dollars. The study specifically optimizes the selection and funding of the maintenance projects by considering budget limit, system randomness (e.g., shoaling), and network connectivity with an objective to reduce the overall multimodal network shipping cost. Two notable features of this paper include establishing a model that considers the interdependence of maintenance projects in terms of realizing their network benefits and the shoaling effect. The method of dealing with random shoaling in this paper is through approximation using a deterministic model. Lock and dam maintenance projects are complicated to consider in the network flow model, but this paper makes a first step towards incorporating it. The numerical test uses the Ohio River Basin network, whose historical Waterborne Commerce data and historical annual tonnage data is provided by the USACE. The proposed model effectively makes meaningful recommendations regarding the maintenance project funding. The MIP model proposed in this paper represents a much-needed effort to facilitate the system wide decision making in the context of multimodal transportation. Many interesting research topics may ensue by building on the MIP model here. Additionally, the random shoaling may warrant further studies by considering the correlation with dredging between segments.

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