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Multi-year planning for optimal navigation channel dredging and dredged material management

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ABSTRACT

Navigation channels are critical maritime infrastructure that supports economic and recreational activities and intermodal freight supply chains, impacting broad areas of the hinterland. Maintenance of the maritime infrastructure is vital to the operations of the transportation system. This paper studies a strategic-level maritime infrastructure asset management problem: multi-year planning of navigation channel maintenance dredging and dredged material management. A mathematical model called dredging planning optimization model (DPOM) is developed to optimize channel dredging planning and dredged material management in confined disposal facilities (CDFs), accounting for practical constraints and considerations, including channel linkage and dependency, channel bundling, CDF accessibility and capacity, shoaling and navigability deterioration over time, reimbursable costs, channel economic values, etc. The problem is formulated as a mixed integer nonlinear programming (MINLP) model, with the objective of maximizing the total economic-value-weighted average navigability under fixed budget. The model can be reformulated as an equivalent mixed integer programming (MIP) model, which can be solved by the CPLEX solver, using the branch and bound algorithm. A heuristic algorithm called the dynamic planning prioritization (DPP) algorithm, is proposed in order to solve large-scale problems due to the computational complexity. DPP incorporates a dynamic ranking criterion to overcome the challenge of simultaneously handling all of the practical constraints and considerations, as well as the impact of channel prioritization on future year decisions. Finally, a real-world case study is proposed to illustrate the model results and demonstrate the effectiveness of the MIP model and the DPP algorithm.

1. Introduction

The marine transportation system expands significantly each decade, with rapid growth in freight and passenger cargo as well as commercial fishing and recreational use. Based on the data provided by the USDOT Maritime Administration (2020) about 99% of overseas trade value enters or leaves the U.S. by ship, and waterborne cargo and associated activities contribute more than 500 billion dollars to the U.S. GDP, generating over 200 billion dollars in annual taxes and sustaining over 10 million jobs. Navigation channels are among the most vital infrastructure for maritime transportation. In the U.S., the marine transportation system includes

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approximately 25,000 miles of navigable channels (Bureau of Transportation Statistics, 2020), sustaining maritime commerce and providing access for recreational boaters, commercial vessels, and the transportation of people and goods.

Channel dredging is critical to maintaining maritime transportation systems and providing efficient and reliable service (Islam and Parks, 2014; Vogt et al., 2018; Cohen et al., 2019). For example, New Jersey Department of Transportation Office of Maritime Resources (NJDOT/OMR) conducts maintenance dredging projects throughout the state of New Jersey (NJDOT, 2020) to support the estimated 50-billion-dollar maritime industry in the State of New Jersey, USA, and maintain safe and navigable waterways. Maintenance dredging of navigation channels removes sediment and accumulated debris from the bottom of the channels and waterways and places the dredged material in an approved location, usually a “confined disposal facility” (CDF). CDF is an area specifically designed for disposal of contaminated sediments dredged for purposes of sediment remediation and is one of the most common solutions to managing contaminated sediments for navigation dredging projects (Palermor and Bosworth, 2008). Dredged materials are used beneficially (e.g., for beach replenishment), or more recently, are used in efforts to restore and enhance coastal marshes.

Agencies (e.g., state DOT) face the big challenge of optimally allocating a limited budget while maintaining operations and achieving the desired level of service, given the complexity of spatially and temporally managing the hundreds of miles of navigation channels and CDFs in their jurisdiction. Channels have varied attributes, such as shoaling rate, sediment volume, location, and cost of dredging. Furthermore, there are many practical considerations in the decision-making process. For example, certain channels are considered more important than others in that they have different levels of usage and economic impact (e.g., traffic type and volume, resilience criticality); some channels bear a certain percentage of debris from natural disasters (e.g., hurricanes, coastal flooding) and need to be dredged with higher priority, the costs of which are sometimes reimbursable by Federal partners. Channels are also linked and dependent upon one another: a main channel has to be navigable before its spur channels can be reached, and thus has a higher priority. Furthermore, dredging can only be performed at a relatively low cost if there is available capacity in nearby CDFs. Especially for hydraulic dredging through pipelines, disposal sites must be within a reasonable distance; otherwise, dredged materials have to be transported to distant facilities at a much higher cost. Given limited budgets and several practical constraints, decision makers (e.g., state DOT) will need to balance various factors in the most cost-efficient manner.

Traditionally, planning decisions are based on expert experience, which is labor-intensive and difficult to transfer. As dredging and dredged material management is a very specialized engineering subject, when experienced engineers retirement, it poses vast challenges for their successors to gain the same level of institutional knowledge (which requires years of experience to develop). More importantly, empirical planning may not necessarily optimally achieve specific performance objectives (e.g., maximized navigable miles) while satisfying all constraints. It is also hard to meet the needs for performance-based asset management, e.g., strategic capital planning, life cycle cost analysis, quantitative performance and condition assessment, scenario comparison, etc. Dredging and dredged material management planning is by nature an operations research problem that has not been extensively studied. Recognizing these challenges, we aim to build a comprehensive mathematical model to quantify all practical concerns and optimally address the dredging resource allocation problem. The model can augment or ultimately replace existing experience-based approaches.

This paper studies a maritime asset management problem to answer the following questions: (1) how to plan and prioritize the navigation channel dredging activities within a multi-year time horizon? and (2) how to assign confined disposal facilities (CDFs) for disposing of dredged sediment? A dredging planning optimization model (DPOM) is formulated as a mixed integer nonlinear programming (MINLP) model. The objective of the optimization model is to maximize the economic-value-weighted average navigability. We also formulate some practical characteristics of the problem, including channel dependency (main channels versus linked branch channels), channel spatial clustering, CDF accessibility, evolution of navigability and dredging volume over time, user’s requirements, potential for reimbursement, interest rate of dredging cost, and channel economic values (the formulation is detailed in Section 3). Then, we propose a method to reformulate the original MINLP model to an equivalent mixed integer linear programming (MIP) model, which can be exactly solved by the CPLEX solver. However, the MIP model is still NP hard (Roy et al., 1987). As the problem scale increases beyond a certain level (i.e., length of planning time or number of channels and CDFs increases), the CPLEX solver (using the branch and bound algorithm for MIPs) struggles to obtain the optimal solution within reasonable amount of time. Therefore, we develop an efficient heuristic algorithm, called a dynamic planning prioritization (DPP) approach, which incorporates a dynamic ranking criterion for prioritizing the channels to dredge in different years. The DPP algorithm is not only designed for its computational speed, but also for determining the priority of candidate channels for dredging in each year, which cannot be directly determined by the MIP model and the CPLEX solver. With the optimization model and the DPP heuristic algorithm, this paper then develops a synergetic strategic-operational planning method to address the uncertainty of channel navigability deterioration process. In order to verify the effectiveness of the proposed model and algorithm, we perform a real-world case study using New Jersey’s maritime infrastructure network and masked cost data. The analysis results of the case study demonstrate that the proposed model and the algorithm can effectively assist decision makers in dredging planning and dredged materials management and performance evaluation.

The remainder of the paper is organized as follows: Section 2 reviews related literature on the planning problem of navigation channel dredging and Section 3 builds the mathematical model of the planning problem. The prioritization algorithm is explained in Section 4. Section 5 proposes a synergetic strategic-operational planning method for implementation of the dredging activity and dredged material disposal activity. Section 6 introduces the real-world case study. Conclusions are drawn and future work is introduced in Section 7.

Table 1
Selected references on channel dredging planning and dredged material management.

Research focus		References	Methodologies	Main characteristics of the studied problem
Plan for navigation channel dredging	Time independent	Mitchell et al. (2013)	MIP, prioritization heuristics	• Interdependence of the individual projects
		Khodakarami et al. (2014)	MIP, prioritization heuristics	• Stochastic channel shoaling rate • Interdependencies between elements of waterway segments, ports, navigation locks, highways, and railway sections
		Jeong et al. (2016)	Multi-Criteria Decision Analysis	• Multi-objective optimization covering dredging cost and social and environmental impacts
		Sullivan and Ahadi (2017), Ahadi et al. (2018)	Stochastic program, genetic algorithm	• Budget uncertainty due to emergency dredging
		Mahmoudzadeh et al. (2021)	MIP	• Multimodal network covering rivers, locks/dams, highways and railways • Stochastic channel shoaling rate • Interdependency between projects
	Time dependent	Ratick et al. (1992)	Simulation-optimization approach	• Stochastic channel conditions
		Ratick and Garriga (1996)	Risk-based spatial decision support system, MIP	• Stochastic shoaling and scouring rates
		Nachtmann et al. (2014)	MIP	• Optimal dredge fleet scheduling problem • Practical constraints including environmental restrictions of dredging, dredging equipment availability, and varying equipment productivity rates
Dredged sediment management		Bailey et al. (2010)	Descriptive analysis	• CDF management strategies to maximize the useful life of the facilities, as well as economic, material, and manpower resources
		Williams et al. (2005)	Nonlinear programming model	• Optimizing the disposal of dredged material at offshore disposal sites
		Bates et al. (2012)	Multi-criteria decision analysis, multi objective optimization	• Assignment of dredged materials

2. Literature review

2.1. *Existing research*

Researchers have been aware of the indispensability and importance of maritime port network resiliency and reliability (Asadabadi and Miller-Hooks, 2017, 2020). Maritime asset management enables the marine transportation system to provide the best level of service via developing, operating, maintaining, upgrading, and disposing of assets in the most cost-effective manner (including all costs, risks and performance attributes), sustaining a high level of reliability and resiliency. The problem studied in this paper belongs to the category of “optimal transportation infrastructure investment planning” (Ting and Schonfeld, 1998; Wang and Schonfeld, 2005; Tao and Schonfeld, 2006; Asadabadi and Miller-Hooks, 2017; Zhang et al., 2017; Nur et al., 2020) in the context of maritime asset management focusing on coastal structures and engineered channels (Eruguz et al., 2017; Dunkin and Mitchell, 2015; Mazaheri and Turner, 2019; Mitchell, 2010; Mitchell, 2012, etc.).

Navigation channel dredging activities are of critical importance to sound maritime asset management. Researchers have proposed many optimization methodologies, including deterministic models (e.g., mixed integer programming), stochastic models, prioritization heuristic algorithms, metaheuristic algorithms (e.g., Genetic Algorithm), decision analysis, etc., to plan navigation channel dredging activities.

Some researchers developed time-independent planning methodologies for navigation channel dredging activities. Mitchell et al. (2013) studied an optimization problem to select maintenance dredging projects given a budget. They considered the interdependence of the individual projects: because of the origin–destination cargo flow between and across multiple projects, only when interdependent dredging projects were selected, could the benefit be achieved. They modeled the problem as a mixed integer programming model and proposed six prioritization algorithms based on six different ranking criteria. Khodakarami et al. (2014) attempted to maximize the benefits brought by the maintenance projects in a multimodal transportation network. The model is further extended to account for the random nature of shoaling and subsequent vessel draft restrictions after dredging to maximize the expected capacity over a multiyear study period. The model is formulated as a mixed integer programming. Two prioritization algorithms were developed based on two ranking criteria, benefit and benefit-cost ratio, respectively. Jeong et al. (2016) applied the MCDA (Multi-Criteria Decision Analysis) technique for an optimal river dredging management model, specifically in Korea where river dredging research is scarce. Their model supports decision making by providing weight factors covering dredging cost and social and environmental impacts. Sullivan and Ahadi (2017) considered maximizing the expected commodity tonnage that can be transported through the inland waterway system by implementing a subset of maintenance dredging projects. The budget required for emergency dredging is assumed to be unpredictable and thus the uncertainty of the total budget is considered. This problem is modeled as a two-stage stochastic program and a genetic algorithm is developed as a solution approach. Ahadi et al. (2018) modeled the problem of selecting inland maintenance dredging projects with the objective of maximizing commodity values. Their model considered uncertainty in the amount of reactive (i.e., emergency) dredging. A customized genetic algorithm is developed to solve realistically sized instances. Recently, Mahmoudzadeh et al. (2021) developed a multimodal approach to formulate the waterway maintenance problem in a network that considers rivers, locks/dams, highways and railways. They explicitly modeled the interdependency between projects to address the trade-off between lock/dam maintenance and channel dredging as well as the channel random shoaling effect.

A few researchers developed time-dependent planning methodologies for navigation channel dredging activities. Ratick et al. (1992) proposed a reliability-based dynamic dredging decision model then used simulation–optimization approach to schedule the optimal deployment and activity levels for dredgeing. Ratick and Garriga (1996) presented the development of a risk-based spatial decision support system, intended to assist in the planning of maintenance dredging activities for navigation channels. They developed Reliability Based Dynamic Dredging Decision model (a mixed integer programming) that accounts for variations in shoaling and scouring rates due to river conditions and dredging activity to plan dredging activities with the objective of maximizing the total benefit. Nachtmann et al. (2014) sought to examine the decision to allocate dredge resources, with the objective of maximizing the total cubic yards of material dredged over the planning horizon. They considered some practical constraints, including environmental restrictions of dredging, dredging equipment availability, and varying equipment productivity rates that affected project completion times. The multi-year optimization model proposed in this paper belongs to this category of time-independent planning methodologies.

The above reviewed references optimize the selection of dredging projects that achieves certain objectives. It is indispensable to manage the disposal of the dredged sediment and debris from dredging activities. Dredged materials are commonly placed at confined disposal facilities (CDF) (Bailey et al., 2010; Lunemann et al., 2017). CDF management is another essential aspect of maritime asset management that has attracted important research. For example, Bailey et al. (2010) proposed CDF management strategies to maximize the useful life of the facilities, as well as economic, material, and manpower resources; Williams et al. (2005) developed an improved method for optimizing the disposal of dredged material at offshore disposal sites; Bates et al. (2012) conducted geospatial optimization and planning for dredged materials management. They used multi-criteria decision analysis (MCDA) to determine the assignment of dredged materials to disposal sites, considering complex environmental problems.

The existing work, which are summarized in Table 1, exclusively focuses on either optimization of navigation channel dredging plan or dredged material management. We are not aware of any literature that simultaneously optimize the plan of channel dredging activities and dredged material disposal activities.

Several other researchers developed asset management tools for implementation of these methodologies to support decision makers' planning for channel dredging and disposal activities. Maher (2004) provided a dynamic decision support tool with a step-by-step list of action items in the form of a decision support flow-chart covering planning, engineering and management of harbor dredging. Skibniewski and Vecino (2012) developed a project management framework for dredging projects (PMFD) to facilitate better performance of dredging projects. The framework was implemented in a web-based project management system (WPMS) environment, to analyze and optimize project management processes in dredging operations. In addition, Loney et al. (2019) provided a comprehensive optimization strategy via a few computer program tools for the U.S. Army Corps of Engineers (USACE)'s dredging program, which is aligned with the existing rolling budget development cycle employed by the USACE.

Another related work reviewed in this section is roadway maintenance planning problems that aim to use optimization techniques to sustain satisfactory infrastructure condition by prioritizing roadway assets and allocating the budget. Planning of maritime navigation channel dredging and roadway maintenance on network level have similar features and considerations, including infrastructure condition deterioration, maintenance cost subject to a budget, economic value of each road segment, asset bundling for easier management, etc. Plenty of research has proposed advanced methodologies for roadway maintenance planning problems, such as mathematical programming (e.g., mixed integer programming), dynamic programming, Markov chain, and heuristic algorithms (e.g., prioritization and *meta*-heuristic algorithms) (Golabi et al., 1982; Morcous and Lounis, 2005; Zhang and Gao, 2012; Gao and Zhang, 2013; Binhomaid and Hegazy, 2014; Ma et al., 2018). However, these methodologies cannot be directly applied in maritime channel maintenance planning problem that is studied in this paper. A key difference is the disposal of dredged material in maritime channel maintenance planning projects that must be considered in the planning stage (Bailey et al., 2010; Lunemann et al., 2017). In addition, maritime channel maintenance planning problem has two other unique features, including linked channel and reimbursable cost (detailed in Section 3.1) that do not need to be considered in roadway maintenance planning problems.

2.2. Knowledge gaps and intended contributions

Despite all the existing modeling efforts, there are still large research gaps with regard to the following two aspects: (1) Most of the existing research separately studies the planning of navigation channel dredging activities and the management of dredged material disposal activities. They lack an integrated methodology for optimal multi-year planning of dredging and disposal activities at the same time. In addition, existing work has not simultaneously studied many practical considerations (e.g., channel spatial clustering/bundling, channel linkage and dependency, CDF accessibility and capacity, channel shoaling (dynamic dredging volume increment), navigability deterioration, user's requirement, etc.), when planning dredging and disposal activities. (2) Although optimization modeling and prioritization algorithms have been used for the deployment of channel dredging activities, most of the existing

Table 2
Navigability levels by condition index.

Navigability index	Description
0	The channel does not have any shoaling and is at maximum navigability. It is in very good condition and does not require any dredging action.
1	The channel has some shoaling, but is still reasonably navigable for the designed vessel at most tide stages. It is still in a state of good repair and does not need dredging action immediately.
2	The channel has shoaling which reduces navigation for larger, less maneuverable vessels and under low tide conditions. The channel is still able to be used, but it is no longer in a state of good repair and needs dredging action.
≥ 3	The channel has severe shoaling and is either closed or has limited navigability under high tide conditions. The channel is in poor condition and needs immediate dredging action.

prioritization algorithms are static and difficult to apply to a strategic, time-dependent (multi-year) planning problem. They do not have a mechanism to account for the impact of near-term planning decisions on the future conditions of the system and thus the life cycle cost of maintaining the infrastructure. Additionally, there are few effective solution algorithms that can deal with large scale problems to prioritize channels in a multi-year planning horizon.

The intended contributions of this paper to the literature are summarized in the following three aspects: (1) This paper achieves multi-year planning of navigation channel dredging activities and assignment of CDFs for disposing of dredged sediment or debris, simultaneously considering practical characteristics, including linked channels (main channels versus linked branch channels), channel spatial clustering/bundling, CDF accessibility and capacity, channel condition deterioration (e.g., evolution of navigability and dredging volume over time), reimbursable cost (that can be applied to next year's budget), interest rate of dredging cost, user requirements, and channel economic values. The DPOM is formulated as a mathematical program, and a method is proposed to re-formulate the model into a mixed integer program, which can be exactly solved by algorithms such as branch and bound. (2) We also develop an efficient heuristic algorithm, called the dynamic planning prioritization (DPP) approach, for large-scale problems, which determines not only which channels should be dredged, but also the priorities of dredging different channels in a specific year. By incorporating a dynamic ranking criterion with multiple hierarchies of priorities for dredging channels, the developed algorithm overcomes the challenge of simultaneously handling channel clustering/bundling groups, channel linkage, CDF accessibility/capacity, as well as the impact of channel selection in one year on future decisions. (3) The methodologies developed are ready to be applied to solve practical problems. The optimization model and the prioritization algorithm (DPP) have already been embedded in the planning tool Maritime Asset Management System (MAMS) that NJDOT/OMR is developing.

3. Mathematical modeling

This section defines the problem under study, describes practical considerations and user requirements, and introduces the mathematical formulation of the DPOM.

3.1. Problem statement

The basic problem studied in this paper is to determine which channels should be dredged, in which year they should be dredged, and into which CDFs the dredged material should be disposed. When making the decision, the objective is to maximize the economic value weighted navigability over the whole planning horizon given that the cost of dredging activity is limited by the annual budget. The following practical characteristics of the problem are considered.

A channel's navigability condition can be categorized in a set of levels, which is defined as "navigability condition index". The levels are defined in Table 2: the lower the condition index value, the higher the navigability. If a channel's navigability condition index ≤ 1, the channel is considered as being in a "state of good repair", aka, SGR. The navigability of a channel will worsen over time without dredging as sediments accumulate over time (i.e., shoaling). We assume that the navigability index increases (i.e., navigability decreases) at a constant rate if not dredged. For example, a channel takes fixed "n" years for its navigability index to increase by "1" if no dredging activity is performed; n could be different for each channel. If the channel is dredged, we assume that the dredging activity is thorough, and the navigability index is reset to "0" immediately after dredging. The navigability index used in the case study is simple. However, the developed model and heuristic algorithm in Section 3.3 and Section 4 are not limited by the current navigability index because the definition of navigability index in these two methods is universal, which can have more levels to be defined. Thus, the developed model and heuristic algorithm are still applicable for the case with more complex definition of navigability condition.

There are two types of dredging volume: template volume (the volume that is required for a contractor to dredge) and over dredge volume.[1] In this paper, we assume that only the template volume will be dredged and the over dredge volume is fixed and will not be included in the dredged volume. This is an approximation of the actual dredging volume – an underestimation, as template volume is the minimum volume that has to be dredged. The ratio between template volume and over dredge volume is used to roughly estimate

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[1] Over dredge volume is the dredging volume that is taken outside the required authorized dimensions to compensate for physical conditions and inaccuracies in the dredging process and to allow for efficient dredging practices (Tavolaro et al., 2007). It is usually defined as the volume between the design depth (template) and the over dredge depth, e.g., one foot below the design depth.

navigability in their practice. When the template volume of a channel is less than its over dredge volume, the channel is deemed likely to have low shoaling and will generally not be considered for dredging.[2] This practice of screening eligible channels will be incorporated in the model as a constraint.

In light of the strategic level planning problem that we are solving, a simplified, linear shoaling model is used in this problem. Each channel has a specific, constant shoaling rate, indicating that the template volume of each channel increases incrementally a certain amount each year. Note that the linear and deterministic shoaling model is only valid for short-term (e.g., five years or less) based on the data provided by NJDOT. This assumption for short-term planning is also verified by some studies in the literature that the shoaling rate can be predicted with small error (Sterling, 2003; Johnston, 2003). As the planning horizon increases to a longer time, there will be larger uncertainty of the shoaling process, and the shoaling model may need to be revised to nonlinear or stochastic formulas, given which the optimization model in Section 3 will be modified to non-linear and/or stochastic programming. Due to data limitation, this paper does not develop a more complex shoaling model.

We also need a "deterioration model" to predict the future condition of the assets. In this context, we use the number of years for the navigability index to increase by 1 (if not dredged) to calculate how each channel's navigability index evolves over time. This parameter is channel specific and can be pre-determined based on shoaling rate and expert judgement.

The economic value of a channel is used to measure its importance, which can be determined by its affiliated facilities or industries, including marinas, emergency services, ferry terminals, restaurants, industrial factories, construction sites, and its contribution to charter, commercial fishing, and other water related business, as well as the usage value. The economic value of the New Jersey channels in this problem is used as an input parameter for the model, which can be pre-determined by subject matter experts.

The concept of a "linked channel" is similar to the "interdependent channels" discussed in Mitchell et al. (2013). There are two types of channels: main channels and branch channels (e.g., spur channels). The geographical relationship is described as a main channel "carrying" one or more branch channels, or a branch channel "being linked to" a main channel. In practice, a main channel should have higher priority over its branch channels if both main channel and the linked channel have poor navigability, because the main channel connects to the entry of branch channels and when the main channel has shoaling and is not in a "state of good repair," it will be difficult for the dredging ship to reach the branch channel. Thus, there exists interdependent relationship between the main channel and linked branch channel: If a branch channel will have a failure and must be dredged, then the decision whether a main channel will be dredged is determined by the navigation condition of the main channel. If the main channel also has a poor navigability condition, then the main channel must be dredged first. If the main channel is in a "state of good repair", then it does not need to be dredged even if the linked branch channel will have a failure. To model this relationship, we use a constraint to impose that the main channel must be selected for dredging if at least one of its branch channels is selected except that 1) the main channel is already in a state of good repair (i.e., navigability index < 2 or the ratio of its template volume to the over dredge volumes is < 1); 2) the main channel is specifically selected by the user not to be dredged.

Channels can be clustered into pre-defined groups based on their spatial location. These channels' dredging activities can be centralized for management considering "the economy of scale". The clustering method can be based on the spatial distance as well as some practical concerns. For example, the channel clustering could be required by the dredging company that bids for the dredging activities. If a dredging company conducts the dredging project for a bundle of channels, there will be engineering cost and oversight cost associated with this bundled dredging activity that occurs only once. Dredging each individual channel will have a marginal cost depending on dredging volume, which we model as a "variable cost". Thus, it is preferable that channels in the same group be dredged together to save fixed costs.

Most of the dredged materials are disposed in a nearby CDF. Based on the geographic information, a CDF is practically accessible by a channel if it is within a certain distance (e.g., 5 miles). CDFs also have limited capacities.[3] Therefore, there may exist channels with no available capacity to accommodate the volume of dredged material. These channels, if they have to be dredged, will require additional funds for dredged material management, e.g., specialized processing followed by upland beneficial use. We model this using a "penalty cost" which is, for example, twice as high as the normal disposal cost to accessible CDFs.

As mentioned earlier, the dredging cost is classified into three categories: fixed cost, variable cost, and "penalty" disposal cost. As long as at least one channel in a group is selected for dredging, a fixed cost needs to be paid. The fixed cost, including costs of engineering and oversight, is counted only once per group and is independent of the dredging volume. The variable dredging cost is proportional to the dredging volume, which equals a unit cost multiplied by the dredging volume. The additional "penalty" disposal cost is the extra cost for disposing the dredged volume when there is no available CDF capacity to accommodate the volume. We consider the inflation of the dredging cost over years, indicating that the dredging cost will increase at a specific interest rate.

In the case of a disastrous natural event, such as flooding or storm surge, that produces large amounts of debris (and sediment) in navigation channels, extra funds need to be allocated to dredge these channels in high priority, and the cost can sometimes be reimbursed from special funds. The total reimbursable cost is usually paid after dredging and can be added to the next year's dredging

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[2] This pre-screening criterion is a simplified assumption and used only as a rough way to narrow down the channel pool for selection in high level dredging planning. There could be channels, especially long ones, which will need dredging in limited reaches despite their total over dredge volume exceeding the total template volume. Visual evaluation of survey data is still necessary as a QA/QC check to the model outputs to ensure that these relatively small volume navigation hazards are properly considered.

[3] We assume fixed current capacities for CDFs in the scope of this study. However, the current capacity of a CDF may be structurally expanded (e.g., by raising berms or increasing footprints) up to its maximum allowed capacity. The option of expanding CDFs and the associated engineering aspect could be considered in future research.

Table 3
Notation of sets, variables, and input parameters.

Sets	
CH	Set of channels, indexed by i. $CH = \{1, 2, \dots, n_C\}$
G	Set of channel groups, indexed by k. $G = \{1, 2, \dots, n_G\}$.
Y	Set of years for planning, indexed by w. $Y = \{1, 2, \dots, n_Y\}$.
$\overline{Y}$	Set of years for observing, indexed by w as well. After the last year of planning, we need to observe the navigability of all channels in the next year. Thus, $\overline{Y}$ has one more year than Y. That is $\overline{Y} = \{1, 2, \dots, n_Y, n_Y + 1\}$.
CDF	Set of CDFs, indexed by c. $CDF = \{1, 2, \dots, n_{CDF}\}$.
Variables	
$x_{i,w,c} = \begin{cases} 1, & \text{if Channel } i \text{ is dredged in Year } w \text{ and the dredged volume is disposed at CDF } c \\ 0, & \text{otherwise} \end{cases}$	
$z_{i,w} = \begin{cases} 1, & \text{if Channel } i \text{ is dredged in Year } w, \text{ but the dredged volume is disposed at a high penalty cost because no CDF capacity is available to accommodate the dredged volume.} \\ 0, & \text{otherwise} \end{cases}$	
$y_{k,w} = \begin{cases} 1, & \text{if at least one channel in Group } k \text{ is dredged in Year } w \\ 0, & \text{otherwise} \end{cases}$	
$Nav_{i,w}$	Channel i's navigability index in year w, which is an integer based on Table 2. Note that the navigability index of each channel in the first year is a known input parameter.
$Navp_{i,w}$	"$Navp_{i,w}$" is a set of newly introduced variables to aid to formulate the deterioration of navigability as linear equations. "$Navp_{i,w}$" itself does not have practical meaning, but is used as an ancillary variable to formulate evolution of the navigability index.
$V_{i,w}$	Template volume in cubic yards that needs to be dredged for Channel i in Year w. Note that the volumes in the first year are known as parameters.
SC_w	Total reimbursed cost in Year w generated from the previous year.
$X_{i,w}$	An intermediate binary variable indicating if the template volume is larger than the over dredged volume: if $V_{i,w} < OD_i$, $X_{i,w} = 0$, otherwise $X_{i,w} = 1$.
Input parameters	
B_w	The budget in Year w.
uc_i	Variable cost per unit of volume to dredge Channel i in the first year. We assume that the cost for dredging per unit of volume of material in each channel increases at a yearly rate of IR considering the inflation of the dredging cost over years.
upc_i	Unit penalty cost to dispose per unit of volume from Channel i, when no CDF is accessible for this volume or the accessible CDFs do not have enough capacity to accommodate the volume.
fc_k	The fixed cost if at least one channel in Group k is dredged.
$Nav_{i,1}$	The initial navigability index of Channel i in the first year.
$V_{i,1}$	Channel i's initial volume to be dredged in the first year.
$\sigma_{i,j}$	The link relation indicator parameter. If Channel i carries Channel j, $\sigma_{i,j} = 1$; otherwise $\sigma_{i,j} = 0$.
$\delta_{i,k}$	Channel grouping indicator parameter. If Channel i is in Group k, $\delta_{i,k} = 1$; otherwise $\delta_{i,k} = 0$.
$\lambda_{i,c}$	The CDF accessibility indicator parameter. If $\lambda_{i,c} = 1$, CDF c is accessible for Channel i, i.e., the dredged volume from Channel i can be disposed at CDF c; otherwise, $\lambda_{i,c} = 0$.
N_k	Number of channels in Group k.
INV_i	Increasing rate of Channel i's dredging volume (i.e., shoaling rate).
$INav_i$	Number of years needed by Channel i to increase its navigability index by "1" if not dredged.
$Lnav$	The largest allowable navigability index, which is 3 in this problem.
OD_i	The surpassed over dredged volume. In this paper, we assume that this portion of volume is never dredged.
EV_i	The normalized economic value of Channel i.
p_i	The percentage of reimbursable volume in total dredged volume of Channel i.
ps	The portion of the cost that is reimbursable.
CP_c	The capacity of CDF c.
$UP_{i,w}$	The user option parameter. $UP_{i,w} = \begin{cases} 0, & \text{Channel } i \text{ cannot be dredged in Year } w \\ 1, & \text{Channel } i \text{ can be dredged in Year } w \\ 2, & \text{Channel } i \text{ must be dredged in Year } w \end{cases}$
$up_{i,w}$	A logic parameter based on $UP_{i,w}$ satisfying $up_{i,w} = \begin{cases} 0, & UP_{i,w} = 0 \text{ or } 1 \\ 1, & UP_{i,w} = 2 \end{cases}$. Alternatively, $up_{i,w} = 1$ indicates that Channel i must be dredged in Year w, as required by the user; otherwise $up_{i,w} = 0$.
$up'_{i,w}$	A logic parameter based on $UP_{i,w}$ satisfying $up'_{i,w} = \begin{cases} 0, & UP_{i,w} = 0 \\ 1, & UP_{i,w} = 1 \text{ or } 2 \end{cases}$. Alternatively, $up'_{i,w} = 1$ indicates that Channel i can be or must be dredged in Year w; $up'_{i,w} = 0$ indicates that Channel i cannot be dredged in Year w, as required by the user.
IR	The interest rate of cost
θ	A number slightly less than "1" (e.g., 0.99) used in Formulas (13), (14)

budget. For example, many channels still bear a certain percentage of sediment caused by Superstorm Sandy, and the cost for dredging this portion of the volume is reimbursable; thus, sandy sediment volume is an important factor when prioritizing the channels. For each channel, we model the reimbursable cost to be the total variable cost (for dredging all volume) multiplied by the percentage of reimbursable volume.

The agency will allocate a budget each year for maintenance dredging. The total usable budget includes the budget allocated by the agency and the reimbursed cost generated from the previous year. Note that this paper focuses on a routine maintenance planning problem. In case of emergency dredging needs, such as a flood event, extra emergency funds need to be allocated in each year. The deterministic model developed in this paper can be extended to a stochastic model in future research by incorporating the uncertainties in dredging planning.

Sometimes the user may have some special requirements for the channel dredging plan. The developed model should be flexible so that decision makers can accommodate such requirements. For example, users should be able to prescribe that some channels must be dredged, can be dredged, or cannot be dredged in specific years.

3.2. Nomenclatures

The notation of the DPOM model is presented in Table 3.

3.3. Model formulation – DPOM

The multi-year capital planning problem for dredging and dredged material disposal is formulated into the DPOM as a mixed integer non-linear program, as follows:

$$Min\ \underset{w\in\overline{Y}}{mean}\left(\frac{\sum_{i\in CH} EV_i \times Nav_{i,w}}{\sum_{i\in CH} EV_i}\right) \tag{1}$$

Subject to

$$\sum_{c\in CDF} x_{i,w,c} + z_{i,w} \leqslant 1 \quad for\ any\ \ i \in CH, w \in Y \tag{2}$$

$$Nav_{i,w} \leqslant Lnav\ \ for\ any\, i \in CH, w \in \overline{Y} \tag{3}$$

$$\sum_{c\in CDF} x_{i,w,c} + z_{i,w} \leqslant Nav_{i,w}/2 + up_{i,w}\ \ for\ any\, i \in CH, w \in Y \tag{4}$$

$$\sum_{c\in CDF} x_{i,w,c} + z_{i,w} \leqslant \frac{V_{i,w}}{OD_i} + up_{i,w}\ for\ any\ \ i \in CH, w \in Y \tag{5}$$

$$\sum_{c\in CDF} x_{i,w,c} + z_{i,w} \geqslant UP_{i,w} - 1\ \ for\ any\, i \in CH, w \in Y \tag{6}$$

$$\sum_{c\in CDF} x_{i,w,c} + z_{i,w} \leqslant UP_{i,w}\ \ for\ any\, i \in CH, w \in Y \tag{7}$$

$$y_{k,w} \geqslant \frac{\sum_{i\in CH}\left(\sum_{c\in CDF} x_{i,w,c} + z_{i,w}\right)\delta_{i,k}}{N_k}\ \ for\ any\ k \in G,\ \ w \in Y \tag{8}$$

$$x_{i,w,c} \leqslant \lambda_{i,c},\ \ for\ any\, i \in CH, w \in Y, c \in CDF \tag{9}$$

$$\sum_{w\in Y}\sum_{i\in CH} x_{i,w,c} V_{i,w} \leqslant CP_c\ \ for\ any\, c \in CDF \tag{10}$$

$$SC_{w+1} = ps \times (1 + IR)^{w-1} \times \sum_{i\in CH}\left(\sum_{c\in CDF} x_{i,w,c} + z_{i,w}\right) V_{i,w} uc_i p_i\ \ for\ any\, w \in Y \tag{11}$$

$$V_{i,w+1} = V_{i,w}\left(1 - \left(\sum_{c\in CDF} x_{i,w,c} + z_{i,w}\right)\right)\ +\ INV_i\ \ for\ any\, i \in CH, w \in Y \tag{12}$$

$$Navp_{i,1} = Nav_{i,1} - \theta\ \ for\ any\, i \in CH \tag{13}$$

$$Navp_{i,w+1} = Navp_{i,w}\left(1-\left(\sum_{c\in CDF}x_{i,w,c}+z_{i,w}\right)\right)-\theta\left(\sum_{c\in CDF}x_{i,w,c}+z_{i,w}\right)\ +\ 1/INav_i\ \ for\ any\, i\in CH, w\in Y \tag{14}$$

$$Nav_{i,w}\geqslant Navp_{i,w}\ \ for\ any\, i\in CH, w\in \overline{Y} \tag{15}$$

$$Nav_{i,w}\leqslant Navp_{i,w}+1\ \ for\ any\, i\in CH, w\in \overline{Y} \tag{16}$$

$$\left(\sum_{c\in CDF}x_{j,w,c}+z_{j,w}\right)+\frac{Nav_{i,w}}{Lnav}\ +\ X_{i,w}+up^{'}_{i,w}-\left(3+\frac{1}{Lnav}\right)\leqslant\left(\sum_{c\in CDF}x_{i,w,c}+z_{i,w}\right)\sigma_{i,j}+(1-\sigma_{i,j})M\ for\ all\ i,j\in CH, w\in Y \tag{17}$$

$$X_{i,w}\leqslant\frac{V_{i,w}}{OD_i}\ \ for\ any\, i\in CH, w\in Y \tag{18}$$

$$X_{i,w}\geqslant\frac{V_{i,w}+M}{OD_i+M}-1\ \ for\ any\, i\in CH, w\in Y \tag{19}$$

$$(1+IR)^{w-1}\times\left(\sum_{i\in CH}\left(\sum_{c\in CDF}x_{i,w,c}+z_{i,w}\right)V_{i,w}uc_i+\sum_{k\in G}y_{k,w}fc_k+\sum_{i\in CH}z_{i,w}V_{i,w}upc_i\right)\leqslant B_w+SC_w\ \ for\ any\, w\in Y \tag{20}$$

$$x_{i,w,c}\in\{0,1\}\ \ for\ any\, i\in CH, w\in Y, c\in CDF \tag{21}$$

$$y_{k,w}\in\{0,1\}\ \ for\ any\, k\in G, w\in Y \tag{22}$$

$$z_{i,w}\in\{0,1\}\ \ for\ any\, i\in CH, w\in Y \tag{23}$$

$$Nav_{i,w}\ are\ integers\ for\ any\ i\in CH, w\in \overline{Y} \tag{24}$$

The objective function (Formula (1)) aims to minimize the economic-value-weighted average navigability index, which is equivalent to maximizing the economic value weighted average navigability.

Formula (2) ensures that each channel can be dredged at most once each year. $\sum_{c\in CDF}x_{i,w,c}+z_{i,w}$ represents whether Channel *i* is dredged in Year *w*. If $\sum_{c\in CDF}x_{i,w,c}+z_{i,w}=1$, Channel *i* is dredged in Year *w*; if $\sum_{c\in CDF}x_{i,w,c}+z_{i,w}=0$, Channel *i* is not dredged in Year *w*.

Formula (3) prescribes that each channel's navigability index should not exceed the allowable upper limit *Lnav*. If the navigability index of a channel will increase to $Lnav+1$ in the next year without dredging, then the indication is that this channel has been in critical condition for a certain amount of time and thus constraint (3) will enforce it to be dredged this year.

Formula (4) formulates the following logic: if a channel is in a "state of good repair" (i.e., the navigability index is less than or equal to "1"), this channel will not be dredged this year unless the user requires it. If the user does not require to dredge Channel *i* in Year *w*, then $up_{i,w}=0$ and Formula (4) is equivalent to $\sum_{c\in CDF}x_{i,w,c}+z_{i,w}\leqslant Nav_{i,w}/2$. If Channel *i* is in a "state of good repair" in Year *w*, then $Nav_{i,w}=0$ or 1 and thus $Nav_{i,w}/2=0$ or 0.5. Since $\sum_{c\in CDF}x_{i,w,c}+z_{i,w}$ is binary, representing whether Channel *i* is dredged in Year *w*, $\sum_{c\in CDF}x_{i,w,c}+z_{i,w}$ must be "0" if $Nav_{i,w}/2=0$ or 0.5. This indicates that if Channel *i* is in "state of good repair" in Year *w* and the user does not force to dredge it, then this channel will not be dredged. On the other hand, if $Nav_{i,w}\geqslant 2$ indicating that the channel is not in a "state of good repair", then $Nav_{i,w}/2\geqslant 1$ and thus $\sum_{c\in CDF}x_{i,w,c}+z_{i,w}$ could be 0 or 1. The constraint is then satisfied for any decision variable, indicating that the channel may or may not be dredged when the channel is not in a "state of good repair". If the user requires that the Channel *i* must be dredged in Year *w*, then $up_{i,w}=1$. Thus, Formula (4) becomes $\sum_{c\in CDF}x_{i,w,c}+z_{i,w}\leqslant Nav_{i,w}/2+1$, which is naturally satisfied and does not affect the model in this case. We need to use another constraint (Formula (6)) to ensure that Channel *i* must be dredged in Year *w* when the use requires to.

Formula (5) ensures that if the template volume is less than the surpassed over dredged volume, the channel will not be dredged in the current year unless the user requires it. Similar to Formula (4), Formula (5) is equivalent to $\sum_{c\in CDF}x_{i,w,c}+z_{i,w}\leqslant V_{i,w}/OD_i$ if the user does not require that Channel *i* must be dredged in Year *w*. If the template volume is less than the surpassed over dredged volume, then $0<V_{i,w}/OD_i<1$, and thus $\sum_{c\in CDF}x_{i,w,c}+z_{i,w}=0$, indicating that the channel will not be dredged. Only when $V_{i,w}\geqslant OD_i$, is the Channel *i* qualified to dredge in Year *w*.

Formulas (6) and (7) specify user requirements. Formula (6) signifies that if $UP_{i,w}=2$, the Channel *i* must be dredged in Year *w*. If $UP_{i,w}=2$, $UP_{i,w}-1=1$, then $\sum_{c\in CDF}x_{i,w,c}+z_{i,w}\geqslant 1$. Since $\sum_{c\in CDF}x_{i,w,c}+z_{i,w}$ is binary representing whether Channel *i* is dredged in Year *w*, $\sum_{c\in CDF}x_{i,w,c}+z_{i,w}$ must equal "1″ and Channel *i* should be dredged in Year *w*. Formula (7) signifies that if $UP_{i,w}=0$, the Channel *i* cannot be dredged in Year *w*. If $UP_{i,w}=0$, then $\sum_{c\in CDF}x_{i,w,c}+z_{i,w}\leqslant 0$. Since $\sum_{c\in CDF}x_{i,w,c}+z_{i,w}$ is binary, $\sum_{c\in CDF}x_{i,w,c}+z_{i,w}$ must equal "0" and Channel *i* cannot be dredged in Year *w*.

Formula (8) models the relationship between $\left(\sum_{c\in CDF}x_{i,w,c}+z_{i,w}\right)$ and $y_{k,w}$, indicating that if at least one channel in Group *k* is dredged, then $y_{k,w}$ must be equal to "1" and the fixed cost of dredging Group *k* should be added to the total cost. If at least one channel in Group *k* is selected to dredge, then $\sum_{i\in CH}\left(\sum_{c\in CDF}x_{i,w,c}+z_{i,w}\right)\delta_{i,k}$ is a positive number less than the number of channels in Group *k* (N_k). Thus, $\sum_{i\in CH}\left(\sum_{c\in CDF}x_{i,w,c}+z_{i,w}\right)\delta_{i,k}/N_k$ is greater than "0" and less than or equal to "1". Since $y_{k,w}$ is binary, $y_{k,w}$ must be "1", representing that at least one channel in Group k is dredged in Year w.

Formula (9) indicates that a channel's dredged volume cannot be disposed at CDFs that are not accessible by the channel. If $\lambda_{i,c} = 0$ representing that CDF c is not accessible for Channel i, then $x_{i,c,w} \leqslant 0$. Since $x_{i,c,w}$ is binary, $x_{i,c,w}$ must be "0". Thus, this constraint can model that Channel i's dredged volume will not be disposed at CDF c if CDF c is not accessible for Channel i.

Formula (10) is to ensure that the capacity of each CDF cannot be exceeded.

Formula (11) is used to calculate the reimbursable cost generated in the previous year. $\sum_{i\in CH}\left(\sum_{c\in CDF} x_{i,w,c} + z_{i,w}\right) V_{i,w} uc_i p_i$ is the reimbursable cost generated by the dredging activity in Year w. It is the present value of the reimbursable cost at the first year. Then, the value of the reimbursable cost at Year w is $\sum_{i\in CH}\left(\sum_{c\in CDF} x_{i,w,c} + z_{i,w}\right) V_{i,w} uc_i p_i \times (1 + IR)^{w\text{-}1}$. This reimbursable cost will be reimbursed in the next year (Year $w + 1$). SC_{w+1} is the total cost reimbursed in Year $w + 1$ generated from the previous Year w. Thus, $SC_{w+1} = ps \times (1 + IR)^{w\text{-}1} \times \sum_{i\in CH}\left(\sum_{c\in CDF} x_{i,w,c} + z_{i,w}\right) V_{i,w} uc_i p_i$.

Formula (12) is used to model the change of dredging volume from one year to the next year. We assume that dredging volume increases linearly each year. If Channel i is dredged in Year w ($\sum_{c\in CDF} x_{i,w,c} + z_{i,w} = 1$), the dredging volume in Year $w + 1$ will be INV_i; otherwise ($\sum_{c\in CDF} x_{i,w,c} + z_{i,w} = 0$), the new shoaling volume will be added onto the previous dredging volume in the next year, i.e., $V_{i,w} + INV_i$.

Formulas (13–16) are used to model the change in navigability index over years. $Nav_{i,w}$ is an integer number between $Navp_{i,w}$ and $Navp_{i,w} + 1$ based on Formulas (15) and (16). In the first year, $Navp_{i,1}$ is a number equal to $Nav_i - \theta$, where θ is a number slightly smaller than "1" (e.g., 0.99), according to Formula (13). Then, the evolution of $Navp_{i,w}$ over years is modeled by Formula (14). If there is no dredging activity on Channel i in Year w, then $\sum_{c\in CDF} x_{i,w,c} + z_{i,w} = 0$ and Formula (14) is $Navp_{i,w+1} = Navp_{i,w} + 1/INav_i$. This means that $Navp_{i,w}$ increases by $1/INav_i$ each year if there is no dredging activity, where $INav_i$ is the number of years to increase Channel i's navigability index by "1". If Channel i is planned to dredge in Year w, then Formula (14) is $Navp_{i,w+1} = -\theta + 1/INav_i$. If the channel's navigability index needs two years or more to increase by "1" ($INav_i \geqslant 2$), then $-1 < Navp_{i,w+1} = -\theta + 1/INav_i < 0$, so that the navigation index is "0" in the next year ($Nav_{i,w+1} = 0$). If the channel's navigability index needs one year to increase by "1" ($INav_i = 1$), then $0 < Navp_{i,w+1} = -\theta + 1/INav_i < 1$, and thus $Nav_{i,w+1} = 1$, representing that the navigation index becomes "1" in the next year after it is dredged in the current year.

Formula (17) models the following logic: if Channel j is dredged in Year w and Channel i carries Channel j (i.e., Channel j is linked to Channel i), then Channel i must be dredged as well, unless at least one of the following conditions is satisfied: 1) the navigability index ($Nav_{i,w}$) of Channel i in Year w is less than or equal to "1" (i.e., Channel i is in a state of good repair), 2) Channel i's template volume ($V_{i,w}$) in Year w is less than the surpassed over dredged volume (OD_i) (i.e., the shoaling is low), or 3) the user requires that Channel i cannot be dredged. In Formula (17), "M" is a sufficiently large positive number, and $X_{i,w}$ is the variable indicating whether the second condition is satisfied. That is if $V_{i,w} < OD_i$, $X_{i,w} = 0$, otherwise $X_{i,w} = 1$, which is formulated together with Formulas (18) and (19).

Formula (20) ensures that each year's total cost should not exceed the budget and the reimbursed cost from the previous year. The total cost includes the variable cost for dredging individual channels, the fixed cost for dredging groups, and the extra cost of disposing the volume when there are no accessible CDFs.

Formulas (21–24), respectively, specify that $x_{i,w,c}$, $y_{k,w}$, $z_{i,w}$, and $X_{i,w}$ are binary variables, and $Nav_{i,w}$ is an integer variable.

3.4. Re-formulation

The constraints formulated by Formulas (10–12), (14), and (20) are nonlinear because of the following nonlinear terms: $x_{i,w,c} \times V_{i,w}$, $z_{i,w} \times V_{i,w}$, and $\left(\sum_{c\in CDF} x_{i,w,c} + z_{i,w}\right) \times Navp_{i,w}$. However, because variables $x_{i,w,c}$ and $z_{i,w}$ are binary, and $\left(\sum_{c\in CDF} x_{i,w,c} + z_{i,w}\right)$ is binary as well based on Formula (2), all of these formulas can be reformulated as linear constraints by introducing new variables, $xv_{i,w,c}$, $xnavp_{i,w}$, and $zv_{i,w}$, which will be formulated to satisfy $xv_{i,w,c} = x_{i,w,c} \times V_{i,w}$, $zv_{i,w} = z_{i,w} \times V_{i,w}$, and $xnavp_{i,w} = Navp_{i,w}\left(\sum_{c\in CDF} x_{i,w,c} + z_{i,w}\right)$ via the following additional constraints.

Reformulation of $xv_{i,w,c} = x_{i,w,c} \times V_{i,w}$:

$$xv_{i,w,c} \geqslant V_{i,w} - M\left(1 - x_{i,w,c}\right) \text{ for any } i \in CH, w \in Y, c \in CDF \tag{25}$$

$$xv_{i,w,c} \leqslant M \times x_{i,w,c} \text{ for any } i \in CH, w \in Y, c \in CDF \tag{26}$$

$$xv_{i,w,c} \leq V_{i,w} \text{ for any } i \in CH, w \in Y, c \in CDF \tag{27}$$

$$xv_{i,w} \geq 0 \text{ for any } i \in CH, w \in Y \tag{28}$$

where "M" is a sufficiently large number.

Reformulation of $zv_{i,w} = z_{i,w} \times V_{i,w}$:

$$zv_{i,w} \geqslant V_{i,w} - M\left(1 - z_{i,w}\right) \text{ for any } i \in CH, w \in Y \tag{29}$$

$$zv_{i,w} \leqslant M \times z_{i,w} \text{ for any } i \in CH, w \in Y \tag{30}$$

$$zv_{i,w} \leqslant V_{i,w} \text{ for any } i \in CH, w \in Y \tag{31}$$

$$zv_{i,w} \geq 0 \; for \; any \; i \in CH, w \in Y \tag{32}$$

where “*M*” is a sufficiently large number.

Reformulation of $xnavp_{i,w} = Navp_{i,w}\left(\sum_{c \in CDF} x_{i,w,c} + z_{i,w}\right)$:

$$xnavp_{i,w} \geqslant Navp_{i,w} - M\left(1 - \left(\sum_{c \in CDF} x_{i,w,c} + z_{i,w}\right)\right) \; for \; any \, i \in CH, w \in Y \tag{33}$$

$$xnavp_{i,w} \leqslant M \times \left(\sum_{c \in CDF} x_{i,w,c} + z_{i,w}\right) \; for \; any \, i \in CH, w \in Y \tag{34}$$

$$xnavp_{i,w} \geqslant -M \times \left(\sum_{c \in CDF} x_{i,w,c} + z_{i,w}\right) \; for \; any \, i \in CH, w \in Y \tag{35}$$

$$xnavp_{i,w} \leqslant Navp_{i,w} + M\left(1 - \left(\sum_{c \in CDF} x_{i,w,c} + z_{i,w}\right)\right) \; for \; any \, i \in CH, w \in Y \tag{36}$$

where “*M*” is a sufficiently large number.

Then Formula (10) can be reformulated as Formula (37) and Formulas (25)–(28)

$$\sum_{w \in Y} \sum_{i \in CH} xv_{i,w,c} \leqslant CP_c \; for \; any \, c \in CDF \tag{37}$$

Formula (11) can be reformulated as Formula (38) and Formulas (25)–(32)

$$SC_{w+1} = ps \times (1 + IR)^{w-1} \times \sum_{i \in CH} \left(zv_{i,w} + \sum_{c \in CDF} xv_{i,w,c}\right) uc_i p_i \; for \; any \, w \in Y \tag{38}$$

Formula (12) can be reformulated as Formula (39) and Formulas (25)–(32)

$$V_{i,w+1} = V_{i,w} - \sum_{c \in CDF} xv_{i,w,c} - zv_{i,w} \; + \; INV_i \; for \; any \, i \in CH, w \in Y \tag{39}$$

Formula (14) can be reformulated as Formula (40) and Formulas (33)–(36)

$$Navp_{i,w+1} = Navp_{i,w} - xnavp_{i,w} - \theta\left(\sum_{c \in CDF} x_{i,w,c} + z_{i,w}\right) \; + \; 1/INav_i \; for \; any \, i \in CH, w \in Y \tag{40}$$

Formula (20) can be reformulated as Formula (41) and Formulas (25)–(32)

$$(1 + IR)^{w-1} \times \left(\sum_{i \in CH} \sum_{c \in CDF} \left(xv_{i,w,c} uc_i + zv_{i,w} uc_i\right) + \sum_{k \in G} y_{k,w} fc_k + \sum_{i \in CH} zv_{i,w} upc_i\right) \leqslant B_w + SC_w \; for \; any \, w \in Y \tag{41}$$

In summary, the multi-year channel dredging optimization model, DPOM, is formulated by Formulas (1)–(9), (13), (15)–(19), (21)–(41).

4. Heuristic algorithm: dynamic planning prioritization

The DPOM proposed in Section 3 is a mixed integer programming (MIP) model, which is NP hard. Although the case in the paper can be solved by the commercial solver CPLEX within reasonable amount of time, the computing time increases exponentially as the number of channels, number of CDFs, and number of years for planning increase. It is possible that the exact optimization model cannot obtain a satisfactory solution when more channels and/or CDFs are involved or more years should be planned. Therefore, we further develop a novel and efficient heuristic algorithm, called a dynamic planning prioritization (DPP) algorithm, to efficiently solve large-scale problems. This heuristic DPP algorithm not only specifies which channels should be dredged, but also determines the priorities of the selected channels in each year. Moreover, heuristic methods often do not rely on commercial software such as CPLEX or MATLAB and can be standalone for easy implementation. Also, an efficient heuristic method may produce a high-quality solution that provides a tight bound to the MIP formulation that expedites the branch and bound process for the optimal solution (Mitchell et al., 2013). Thus, prioritization heuristic algorithms are commonly developed by researchers in dredging projects optimization (Mitchell et al., 2013, Khodakarami et al., 2014, Ahadi et al., 2018).

The designed DPP algorithm defines four hierarchies of priorities, within each of which the channels are ranked based on secondary criteria.

Highest priority. The channels, which are required by the user for dredging, and whose navigability index reaches “*Lnav*” (the largest allowable navigability index limit) and will reach “*Lnav* + 1” in the next year if not dredged, should have the highest priority for dredging. These channels must be dredged in the current year.

Second highest priority. The channels, whose navigability index will reach "$Lnav + 1$" before the end of the planning horizon without any dredging activity, have the second highest priority. Among these channels with this hierarchy, there are two extra rules for sub-prioritizing: 1) the channels which take less time to increase their navigability index to "$Lnav + 1$" have higher priority; 2) channels with higher incremental dredging costs (i.e., shoaling rate multiplied by the unit dredging cost) have higher priority. The shoaling rate multiplied by the unit dredging cost represents the yearly increased cost for dredging this channel. If a channel with a high yearly increased cost is not dredged in the current year, then the cost for dredging this channel will increase dramatically in the next few years.

Third highest priority. The channels, whose navigability index will not reach "$Lnav + 1$" at the end of the planning horizon even if they are never dredged, have the third highest priority. These channels' sub-priorities are ranked based on the criterion of economic-value-weighted average navigability index divided by the increased cost of dredging, which represents essentially the benefit cost ratio contributing to the optimization objective. This ranking criterion for the third-highest-priority channels is inspired by a classical greedy approximation algorithm originally proposed by Dantzig (1957) for the knapsack problem. This greedy approximation algorithm sorts the items in the decreasing order of the value per unit of weight. It then proceeds to insert them into the sack, starting with as many copies as possible of the first kind of item until there is no more space in the sack. Provided that there is an unlimited supply of each kind of item, if V^* is the maximum value of items that fit into the sack, then the greedy algorithm is guaranteed to achieve at least a value of $V^*/2$. The economic-value-weighted average navigability index in this problem is as the value in the knapsack problem, and the increased cost in this problem is as the weight in the knapsack problem.

Lowest priority. The channels with lowest priority are those that cannot be dredged in the current year: (1) the user requires that the channel cannot be dredged in the current year, (2) the navigability index of the channel is in a state of good repair (i.e., $Nav_{i,w} \leqslant 1$), or (3) the template volume is less than the over dredging volume.

The next step is to design an effective criterion to rank the channels within each priority hierarchy category. The DPP algorithm only needs to account for channels within the second and third priority hierarchies, because the channels in the highest priority hierarchy must be dredged while those in the lowest priority hierarchy will not be selected for dredging. The biggest challenge of developing such a ranking criterion is to simultaneously consider channel grouping, channel linkage, CDF accessibility, as well as the impact of the channel dredging plan in one year on decisions in future years. Incorporating all these considerations, we propose a dynamic ranking criterion for the DPP algorithm. The ranking criterion is "dynamic" because the value of the ranking criterion of each channel changes after certain channels are selected for dredging in each year (please see how the ranking criterion changes below, particularly the increased cost for dredging Channel i, $ac_{i,w}$ (CS_w)). We use Formula (42) to formulate the ranking criterion.

$$R_{i,w} = \frac{\sum_{g \in Linked_i \cup \{i\}} EV_g \times Nav_{g,w}}{ac_{i,w}(CS_w)} \times \left(INV_i \times uc_i \times \alpha^{n_Y - w + 1 - NY}\right)^{\eta_{i,w}} \tag{42}$$

$ac_{i,w}$ (CS_w) is the increased cost for dredging Channel i and its linked main channels ($Linked_i$) that must be dredged if Channel i is selected for dredging, given that a set of channels CS_w are already selected for dredging in Year w, based on Formula (17). $ac_{i,w}$ should be updated dynamically each year after channels for dredging are selected because of the changing group cost and the extra cost for disposing the volumes that cannot be disposed at any accessible CDF. We give two examples to demonstrate why $ac_{i,w}$ should be updated dynamically. As a first example, Channels 5 and 6, with variable dredging costs of 200 and 300, respectively, are in the same group. The fixed cost for dredging this group is 100. If no other channel in this group is selected for dredging so far, then the increased cost for dredging Channel 5 is $ac_{5,w} = 200 + 100 = 300$. If Channel 6 is already selected for dredging before Channel 5 is selected, then the increased cost of dredging Channel 5 is no longer 300 because the fixed cost (100) has already been added when Channel 6 is selected, and thus $ac_{5,w} = 200$. As a second example, Channel 5's and Channel 6's dredging volumes are 1000 and 2000 cubic yards respectively, and they can access only one CDF with remaining capacity of 2000 cubic yards. If Channel 6 has not been selected for dredging, then Channel 5's volume can be shipped to this CDF and thus there is no extra penalty disposal cost. If Channel 6 is selected for dredging, the CDF's remaining capacity is "0", no longer available for Channel 5's dredged volume and thus inducing an extra penalty disposal cost. As such, we design Algorithm 1 to obtain $ac_{i,w}$ as follows. For the notation, please refer Tables 3, 12 and 13 and Appendix A.

Algorithm 1. Get the increased cost $ac_{i,w}$ for dredging each of the channels in set CNS_w given that the channels in set CS_w are already selected for dredging
$ac_{i,w}$ = **Algorithm 1** (CNS_w, CS_w, GS_w, $Linked_i$, $RCP_{c,w}$, uc_i, $V_{i,w}$, fc_k , $\delta_{i,k}$, $\lambda_{i,c}$)

```
Input $CNS_w$, $CS_w$, $GS_w$, $Linked_i$ (for all $i \in CNS_w$), $RCP_{c,w}(CS_w)$, $uc_i$ (for all $i \in CNS_w$), $V_{i,w}$ (for all $i \in CNS_w$), $fc_k$ (for all $k \in G$), $\delta_{i,k}$, $\lambda_{i,c}$
Output $ac_{i,w}$, for all $i \in CNS_w$
For $i \in CNS_w$
  $ac_{i,w} = V_{i,w} \times uc_i + \sum_{j \in Linked_i \cap CNS_w} V_{j,w} uc_j$;
  $Linked\_group_i = \{k|$ for all $k$ satisfying that $\delta_{j,k} = 1$ for all $j \in \{i\} \cup (Linked_i \cap CNS_w)\}$;
  For $k \in Linked\_group_i$
    If $k \notin GS_w$
      $ac_{i,w} = ac_{i,w} + fc_k$;
    End if
  End for
  For $g \in \{i\} \cup (Linked_i \cap CNS_w)$
```

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(*continued*)

Algorithm 1. Get the increased cost $ac_{i,w}$ for dredging each of the channels in set CNS_w given that the channels in set CS_w are already selected for dredging $ac_{i,w} =$ **Algorithm 1** $(CNS_w, CS_w, GS_w, Linked_i, RCP_{c,w}, uc_i, V_{i,w}, fc_k, \delta_{i,k}, \lambda_{i,c})$

```
        If $\max_{c \in CDF} RCP_{c,w}(CS_w) \times \lambda_{g,c} < V_{g,w}$
            $ac_{i,w} = ac_{i,w} + V_{g,w} \times upc_i$;
        End if
    End for
End for
```

$\eta_{i,w} = 1$, if Channel i's navigability index will increase to greater than or equal to $Lnav + 1$ by the end of the planning horizon, given that it is never dredged after Year w, otherwise, $\eta_{i,w} = 0$.

NY is the number of years needed for the navigability index to increase to $Lnav + 1$, which will lead to infeasible status. Thus, $n_Y - w + 1 - NY$ is the time interval between the year when the navigability index will reach $Lnav + 1$ and the end of the planning horizon, where n_Y is the total number of years in the planning horizon.

α is a positive number large enough to ensure that the channels, whose navigability will reach "$Lnav + 1$" at the end of the planning horizon without any dredging activity, have a high priority.

When $\eta_{i,w} = 1$, the ranking criterion value of Channel i will be higher than those with $\eta_{i,w} = 0$ through being multiplied by a large value $(INV_i \times uc_i \times \alpha^{n_Y - w + 1 - NY})$. Therefore, the term $\left(INV_i \times uc_i \times \alpha^{n_Y - w + 1 - NY}\right)^{\eta_{i,w}}$ given $\eta_{i,w} = 1$ determines the sub-priorities of the channels within the second hierarchy whose navigability index will reach $Lnav + 1$ by the end of the planning horizon without any dredging activity. The factor $\alpha^{n_Y - w + 1 - NY}$ can achieve the goal that channels with less time to reach $Lnav + 1$ navigability index have higher priorities, and the factor $INV_i \times uc_i$ can ensure that a channel with a higher yearly increased cost has a higher priority for dredging.

When $\eta_{i,w} = 0$, the factor $\left(INV_i \times uc_i \times \alpha^{n_Y - w + 1 - NY}\right)^{\eta_{i,w}} = 1$ no longer influences the ranking criterion value. Then, the factor $\sum_{g \in Linked_i \cup \{i\}} EV_g \times Nav_{g,w} / ac_{i,w}$ determines the sub-priorities of the channels within the third hierarchy category. The channels with higher economic-value-weighted average navigability and lower addition dredging costs are ranked higher.

The DPP algorithm is described as follows:

Step 1. For each year, select channels with highest dredging priority into the list, which must be dredged in the current year, as required by the user or the navigability index will exceed the largest allowable navigability index limit in the next year if they are not dredged in this year.

Step 2. For each selected channel for dredging, the CDF with the largest capacity among all accessible CDFs will be selected for disposing the dredged volume. After each channel is assigned to a CDF for disposal, the CDF's capacity is updated by subtracting the dredged volume. If a channel does not have access to any CDF or none of the accessible CDFs' capacities are sufficient to dispose the dredged material, add a penalty disposal cost to the total cost.

Step 3. Calculate the total cost for dredging these channels, including fixed cost, variable cost, and penalty disposal cost, and subtract it from the budget in this year to get the remaining budget.

Step 4. Rank all channels with the second and third highest dredging priority based on the ranking criterion (Formula (42)). Note that the ranking criterion can automatically differentiate the second and third highest priorities, and thus we can simultaneously prioritize all channels with the second and third highest priority.

Step 5. Find the channel with the highest value ($R_{i,w}$) of the ranking criterion. Check if the remaining budget is greater than or equal to the increased cost ($ac_{i,w}$) for dredging and disposing the material of this channel and its linked main channels ($Linked_i$) that must be dredged if it is selected for dredging (these linked channels must be qualified as they are not in a state of good repair, their template volume is greater than or equal to the over dredge volume, and the user does not require that they cannot be dredged in the current year). If yes, select this channel and its linked main channels to the dredging list, determine the CDF assignment plan as in Step 2, update the ranking criterion based on Formula (42), subtract the increased cost from the budget and get the remaining budget, and then repeat Step 5. If not, go to Step 6.

Step 6. Check the next highest value ($R_{i,w}$) of the ranking criterion until we find one channel whose increased cost ($ac_{i,w}$) is less than or equal to the remaining budget or we cannot find any such channel. If we can find one such channel, select this channel and its linked main channels to the dredging list, determine the CDF assignment plan as in Step 2, update the ranking criterion based on Formula (42), subtract the increased cost from the budget and get the remaining budget, and then return to Step 5. If we cannot find any such channel, finalize the channel list for dredging in current year and go to Step 7.

Step 7. Calculate the reimbursable cost generated by the dredging activity in the current year and add it to the next year's budget. Then conduct the same steps for the next year until the end of the planning horizon is reached.

The detailed information pertaining to determining the priority of each channel is given as the pseudocode in Algorithm 2. All additional notations used in these algorithms are presented in Appendix A.

Algorithm 2. Determine the priorities of all channels CS_w within all planning years

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(*continued*)

Algorithm 2. Determine the priorities of all channels CS_w within all planning years
$CS_w =$ **Algorithm 2** (all parameters)

$CS_w =$ **Algorithm 2** (all parameters)

```
Input all parameters
Output $CS_w$
$Nav'_{i,1} = Nav_{i,1}$;
$RCP_{c,1} = CP_c$;
For $w = 1: n_Y$
  $Nav_{i,w} = \lfloor Nav'_{i,w} \rfloor$; % Get the maximum integer less than or equal to $Nav'_{i,w}$
  $RB_w = B_w + SC_w$;
  $CE_w = \{i \mid$for all $i$ satisfying that $Nav_{i,w} \geq 2$, $V_{i,w} \geq OD_i$, and $UP_{i,w} \geq 1\}$;
  $CS_w$ $\{i \mid$for all $i$ satisfying that $Nav'_{i,w} + 1/INav_i = Lnav + 1$ or $UP_{i,w} = 2\}$;
  $CS\_linked_w = \{i \mid$for all $i$ satisfying that $\sigma_{i,j} = 1$ for all $j \in CS_w\} \cap CE_w$;
  $CSv_w = CS_w \cup CS\_linked_w$;
  $GS_w = \{k \mid$for all $k$ satisfying that $\delta_{i,k} = 1$ for all $i \in CS_w\}$;
  $CNS_w = CE_w \backslash CS_w$;
  [$CDF\_plan_{i,w}$ (for all $i \in CS_w$), $RCP_{c,w}$ (for all $c \in CDF$), $NVC_w$] = Algorithm 3 ($CS_w$, $RCP_{c,w}$, $\lambda_{i,c}$, $V_{i,w}$, $uc_i$); % Use Algorithm 3 to obtain the CDF assignment plan, the
    remaining CDF capacity after dredging channels in $CS_w$, and the additional penalty disposal cost.
  $CLC_w = \sum_{i \in CS_w} V_{i,w} uc_i + \sum_{k \in GS_w} fc_k + NVC_w$ ;
  While $|CNS_w| > 0$, do
    $Linked_i = \{j \mid$ for all $j$ satisfying that $\sigma_{j,i} = 1\} \cap CNS_w$, for all $i \in CNS_w$; % Linked main channels
    For all $i \in CNS_w$: $ac_{i,w} =$ Algorithm 1 ($CNS_w$, $CS_w$, $GS_w$, $Linked_i$, $RCP_{c,w}$, $uc_i$, $V_{i,w}$, $fc_k$ , $\delta_{i,k}$, $\lambda_{i,c}$);
    % Use Algorithm 1 to calculate the increased cost for dredging each channel in $CNS_w$
    Use Formula (42) to calculate the values of the ranking criterion: $R_{i,w}$ for all $i \in CNS_w$;
    $i^* = \underset{i \in CNS_w}{argmax}(R_{i,w})$;
    If $ac_{i^*,w} \leq RB_w$
      $I^* = \{i^*\} \cup Linked_{i^*}$;
      $CNS_w = CNS_w \backslash I^*$;
      $CS_w = CS_w \cup I^*$;
      $GS_w = GS_w \cup \{k \mid$for all $k$ satisfying that $\delta_{i,k} = 1$ for all $i \in I^*\}$;
      $CLC_w = CLC_w + ac_{i^*,w}$;
      $RB_w = RB_w - ac_{i^*,w}$;
      [$CDF\_plan_{i,w}$ (for all $i \in I^*$), $RCP_{c,w}$ (for all $c \in CDF$), $\sim$] = Algorithm 3 ($I^*$, $RCP_{c,w}$, $\lambda_{i,c}$, $V_{i,w}$, $uc_i$);
    Else
      $Carrying_{i^*} = \{j \mid$ for all $j$ satisfying that $\sigma_{i^*,j} = 1\} \cap CNS_w$; % The Branch channels carried by the main channel $i^*$
      $CNS_w = CNS_w \backslash (\{i^*\} \cup Carrying_{i^*})$; % In this case, channel $i^*$ cannot be dredged because of insufficient budget, and its branch channels cannot be dredged as
    well, because if any of the branch channels is dredged, the main channel $i^*$ must be dredged, which induces contradiction. Thus, the main channel $i^*$ and its
    branch channels $Carrying_{i^*}$ must be excluded from the set $CNS_w$.
    End if
  End do
  $SC_{w+1} = ps \times \sum_{i \in CS_w} V_{i,w} uc_i p_i$;
  $V_{i,w+1} = V_{i,w} + INV_i$ for all $i \in C$;
  $Nav'_{i,w+1} = Nav'_{i,w} + 1/INav_i$ for all $i \in C$;
End for
```

Given any set of channels C_w to be dredged and the remaining capacities of all CDFs in Year w, Algorithm 3 obtains the CDF assignment plan ($CDF\_plan_{i,w}$, for all channels $i \in C_w$), the remaining capacity of each CDF ($RCP_{c,w}$) after the dredged volumes of the channels in C_w are shipped to the CDFs, and the additional penalty cost for disposing the dredged volume from channels in C_w. Algorithm 3 selects the CDF with the highest capacity among all accessible CDFs for disposing the dredged volume in a channel.

Algorithm 3. Obtain the CDF assignment plan, the remaining capacity of each channel, and the additional non-CDF-volume disposing cost for dredging channels
[$CDF\_plan_{i,w}$, $RCP_{c,w}$, NVC_w] = **Algorithm 3** (C_w, $RCP_{c,w}$, $\lambda_{i,c}$, $V_{i,w}$, uc_i)

```
Output $CDF\_plan_{i,w}$, $RCP_{c,w}$, $NVC_w$
Input $C_w$, $RCP_{c,w}$, $\lambda_{i,c}$, $V_{i,w}$, $uc_i$
$NVC_w = 0$;
For $i = 1 \in C_w$
  $c^* = \underset{c \in CDF}{max}(RCP_{c,w} \times \lambda_{i,c})$;
  If $c^* < V_{i,w}$
    $NVC_w = NVC_w + V_{i,w} \times upc_i$;
    $CDF\_plan_{i,w} =$ NaN;
  Else
    $CDF\_plan_{i,w} = c^*$;
    $RCP_{c^*,w} = RCP_{c^*,w} - V_{i,w}$;
  End if
End for
```

Another advantage of the DPP algorithm is that it does not rely on the assumption that the dredging volume increases linearly. The DPP heuristic algorithm can be modified for nonlinear shoaling model by modifying the ranking criterion. In the ranking criterion, INV_i is the shoaling. If the dredging volume does not increase constantly for each year, we can use "$INV_{i,w}$" to represent the increased dredging volume in Channel i in Year w. Thus, the ranking criterion formula changes over time as the increased dredging volume changes, but the algorithm structure does not need to be changed. Therefore, the DPP algorithm is still applicable for the scenario where the dredging volume does not increase linearly.

5. Methodologies to handle shoaling uncertainty

The proposed optimization model in Section 3 and the DPP heuristic algorithm in Section 4 do not account for the uncertainty of shoaling process and navigability deterioration process. Thus, this section proposes potential methodologies that can handle this uncertainty. One method proposed in this paper is the synergetic strategic-operational planning approach for implementation of the dredging activity and dredged material disposal activity. This method uses the proposed Mixed Integer Programming (MIP) model in Section 3 for strategic multi-year planning and uses dynamic prioritization planning (DPP) approach in Section 4 for each year's operational planning. Specifically, in the beginning of the planning horizon, the MIP plans multi-year (e.g., 3–5 years) dredging and CDF disposal activities; and at the beginning of each year, given the strategic multi-year plan by MIP, the DPP prioritizes the channels in the strategic-planned list and adjusts dredging plan due to uncertainty based on the real-time navigability condition, dredging volume, dredging cost, budget, and user requirement. For example, if in one year, the budget is not sufficient to dredge all channels in the strategic plan by MIP, the DPP selects the highest-ranking channels from the list in the strategic plan as many as possible and removes lowest-ranking channels from the list due to insufficient budget. If the budget is redundant, the prioritization approach will prioritize the channels that are not in strategic plan list and select those in the decreasing order of priority one by one until the budget runs out. For the detailed interpretation of the synergetic strategic-operational planning method, please refer to the case study results in Section 6.2.

Our future work will extend the current methodologies and explore two new methodologies to model the uncertain navigability deterioration process in optimizing the plan of channel dredging and dredged material disposal after collecting more data.

1. Scenario-based optimization. The scenario-based optimization applies the Monte Carlo simulation to generate a series of scenarios of channel navigability deterioration process, which are different combinations of navigability changing parameters. Then, we will build a programming model (e.g., mixed integer programming) with the objective of maximizing the expected economic value weighted average navigability, which is average for all combinations of navigation changing parameters. Alternatively, we would develop an algorithm that generates a solution pool with multiple plans and select the best plan that guarantees certain reliability requirement to achieve the maximum economic value weighted navigability for all combinations of navigation changing parameters.
2. Markov-chain-based optimization. After collecting sufficient data of the navigability deterioration process, we might be able to model the probabilistic distribution of next year's navigability based on the current year's navigability given the decision whether the channel is dredged or not. If the historical data can validate that a channel's navigability only depends on its navigability in the last year, we can build a Markov-chain-based optimization model, which enables decision making based on the navigability condition at a specific time.

6. Case study

This section conducts a real-world case study based on the data provided by NJDOT/OMR to test the model/algorithm's efficiency as well as to demonstrate the application of the developed model/algorithms in decision making in dredging planning and asset condition prediction. We experiment with a set of 5-year scenarios with different annual budgets to compare the performance of the CPLEX solver (implemented on GAMS) and the DPP algorithm.

6.1. Data source

The NJDOT/OMR dataset contains 216 channels clustering into 63 pre-defined groups and 52 CDFs. The data provided for each channel include channel characteristics such as economic value, length, shoaling rate, costs of historical dredging projects, channel linkage relationships, as well as current conditions, such as navigability index, template volume, over dredging volume, and reimbursable volume percentage. In addition to the given data, a constant navigability deterioration rate for each channel is generated based on its shoaling rate, i.e., the number of years it takes for the navigability index to increase by 1. We use the sum of historical engineering cost and oversight cost as each group's fixed cost, and calculate the average unit dredging cost per cubic yard as variable costs for each channel. The information provided for each CDF includes its remaining capacity and GIS location, which we use to calculate the distances between each channel-CDF pair to determine whether a CDF is accessible for each channel.

Both the exact MIP optimization and heuristic DPP algorithm approaches are used to obtain the channel dredging plan and the CDF assignment plan for the DPOM. To evaluate the impact of the annual budget (allocated by the agency), we test for multiple annual budget values from \$20 million to \$60 million with a \$5 million increment, which generates 9 cases. For simplicity, we use the same

Table 4
Comparison between the exact optimization (MIP) by CPLEX solver and the heuristic DPP algorithm.

Annual Budget (USD)	EVWNI		Gap between DPP and exact optimization (%)	Computing time (seconds)	
	Best solution by DPP	Optimal solution by CPLEX solver		DPP	CPLEX solver
20 million	1.422	1.347	5.51	0.056	15,092.050
25 million	1.260	1.202	4.77	0.047	95.835
30 million	1.139	1.110	2.58	0.047	111.841
35 million	1.073	1.042	3.00	0.047	220.814
40 million	1.011	0.989	2.24	0.038	476.080
45 million	0.963	0.947	1.66	0.037	91.824
50 million	0.937	0.918	2.15	0.035	54.006
55 million	0.912	0.895	1.88	0.033	68.490
60 million	0.888	0.887	0.20	0.033	25.906

EVWNI: Economic-value-weighted navigability index.

annual budget throughout the 5-year horizon in each case. The heuristic DPP algorithm is programmed on Matlab 2019a and implemented on a 2.60 GHz Windows 10 PC with 16 GB RAM. The exact MIP optimization model is implemented on the GAMS software solved by the CPLEX solver on the same computer.

6.2. The case study results

Table 4 presents a comparison between the results from the exact optimization and the heuristic DPP algorithm. As expected, the objective function values (i.e., the economic value weighted average navigability index) obtained by the heuristic DPP algorithm are slightly higher than those of the exact optimal solutions obtained by the MIP optimization approach for all cases, while the gaps (defined by Formula (43)) between these two solutions are very small. The largest gap is only 5.51% (the case with an annual budget of $20 million).

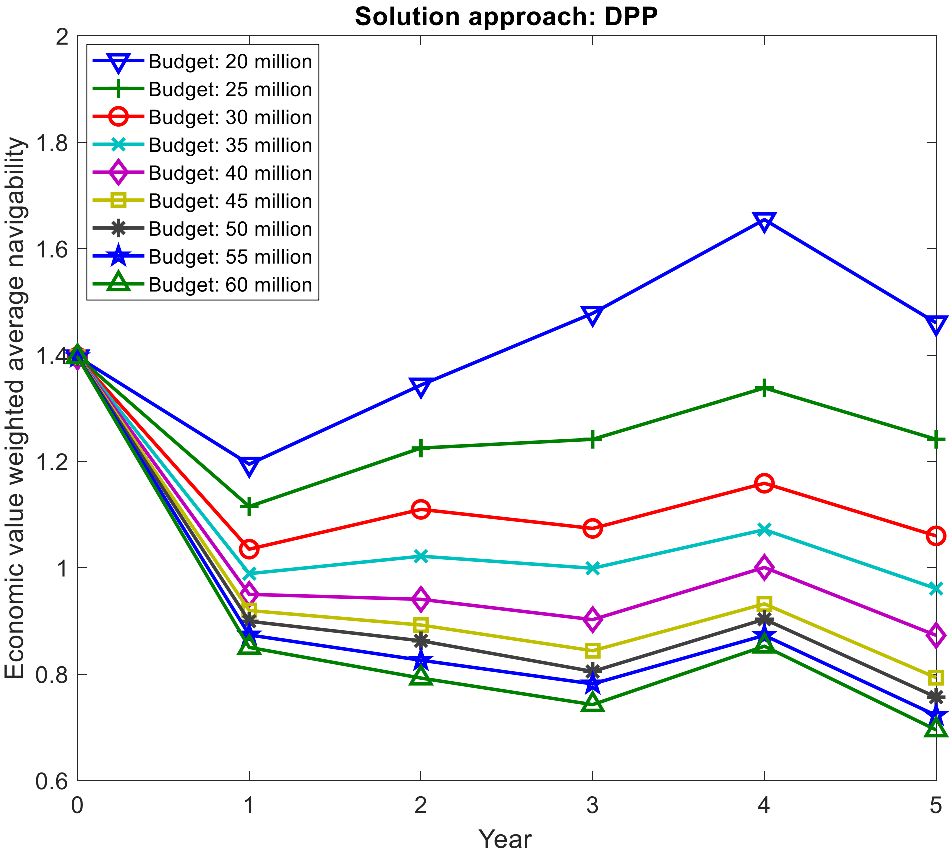

Fig. 1. The change of the objective value – economic value weighted average navigability index – over time given different annual budgets (5 years planning, DPP algorithm).

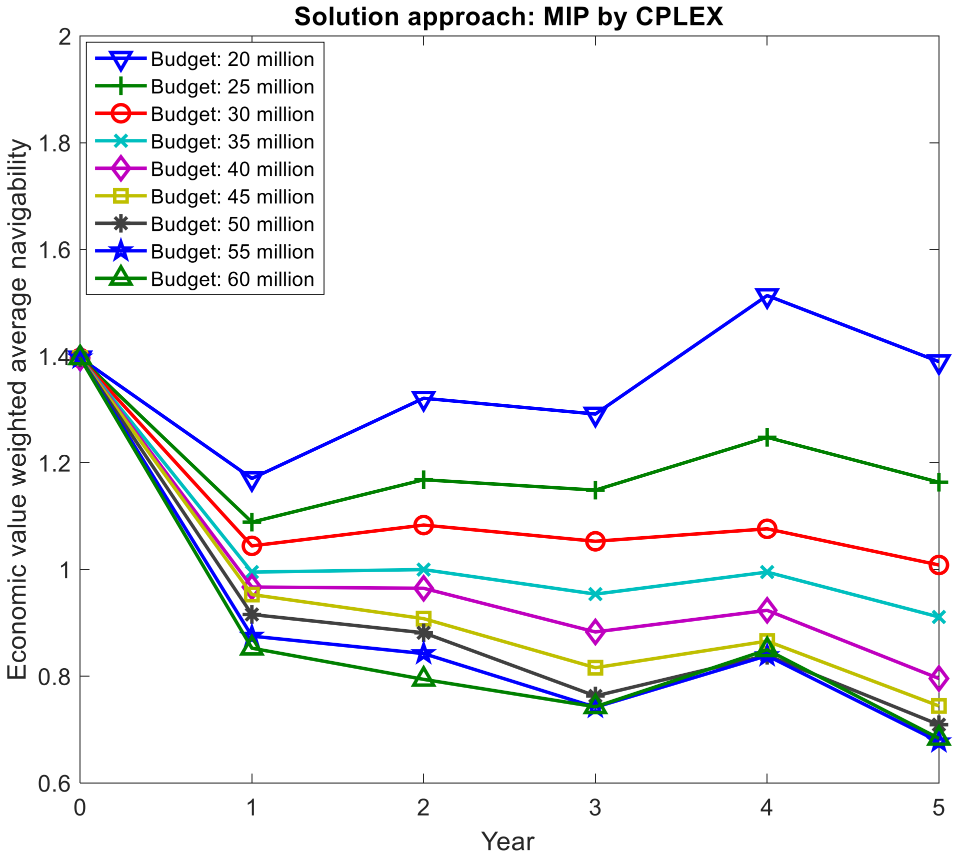

Fig. 2. The change of the objective value – economic value weighted average navigability index over time given different annual budgets (5 years planning, exact optimization).

$$\text{Gap} = \frac{\text{Objective function value of DPP} - \text{objective function value of MIP}}{\text{Objective function value of MIP}} \times 100\% \tag{43}$$

The computing time of the exact MIP optimization by the CPLEX solver varies significantly for the these cases with different annual budgets. The longest computing time among all cases is 15,092.050 s (the case with annual budget of 20 million dollars). In this case with annual budget of 20 million dollars, most of the CPU time is spent on seeking for a feasible solution because 20-million-dollor budget is not sufficiently large that leads to the difficulty finding a feasible solution. In all other cases, the CPLEX solver can solve the MIP model exactly within a reasonable time (within 500 s). In contrast, the heuristic DPP algorithm is much faster than the CPLEX solver for the exact MIP optimization approach. For all of these cases, the DPP algorithm was able to find near optimal solutions within 0.06 s.

Figs. 1 and 2 present the change in the economic value weighted average navigability index over time, given different annual budgets within the 5-year planning horizon, using the heuristic DPP algorithm and the exact MIP optimization approach, respectively.

Table 5
Breakdown of costs.

Annual budget	Total cost (dollars)	Variable cost		Fixed cost		Additional disposal cost	
		Dollars	Percentage of total cost	Dollars	Percentage of total cost	Dollars	Percentage of total cost
20 million	108,536,590	60,225,440	55.49	31,807,897	29.31	16,503,243	15.21
25 million	136,172,440	69,897,582	51.33	46,202,172	33.93	20,072,688	14.74
30 million	161,774,534	79,822,961	49.34	59,355,042	36.69	22,596,532	13.97
35 million	188,118,420	93,271,246	49.58	65,127,498	34.62	29,719,674	15.80
40 million	214,383,850	103,772,711	48.41	75,869,529	35.39	34,741,608	16.21
45 million	239,504,520	118,976,722	49.68	81,678,389	34.10	38,849,409	16.22
50 million	264,193,720	135,695,354	51.36	89,803,297	33.99	38,695,067	14.65
55 million	289,648,410	147,445,460	50.90	95,311,728	32.91	46,891,222	16.19
60 million	302,187,100	148,114,058	49.01	102,488,783	33.92	51,584,271	17.07

The two figures present similar patterns of the changing trend of the economic value weighted average navigability index. Given a smaller annual budget, such as $20 million, the economic value weighted average navigability index gradually increases with time, showing that the system condition deteriorates under insufficient maintenance. As the annual budget increases, the navigability index is sustained stably as time goes on. With the largest annual budgets (e.g., $55 and $60 million), the navigability index is kept at a low level (e.g., below 1), since the budget is sufficient to support the dredging activities to keep the system in a state of good repair.

Table 5 displays the portion of the three types of cost, variable cost, fixed cost, and additional disposal cost, in the total cost for the five-year planning. For the cases with annual budget from 20 million to 60 million, the variable cost accounts for 48.41–55.49% of the total cost, fixed cost accounts for 29.31–36.69% of the total cost, and the additional disposal cost account for 13.97–17.07% of the total cost. All the three types of cost have a significant portion. Note that in maritime channel maintenance project management, disposal of dredged material is a key activity that must be considered for planning after channels are dredged. Since the additional disposal cost accounts for a significant portion of the total cost, we anticipate that dredged material disposal activity has a significant impact on the optimization model and the solution.

Table 6 quantifies the impact of disposal activity on the channel dredging plan, which is reflected by the difference of economic value weighted navigability index between the cases with the additional disposal cost accounted and not accounted. We remove the CDF constraints and the additional disposal cost for the dredged volume, assuming that all dredged materials do not need additional cost to be disposed. Then, for each case with annual budget from 20 million to 60 million, we solve the multi-year optimization model to get the optimal economic value weighted navigability index. The results are compared with those of the original optimization results with additional disposal cost accounted. The comparison results are presented in Table 6. We can observe that when the budget is 20 million, which is relatively small, the objective value of optimal economic value weight navigability index is significantly lower (by 10.08%) than the solution when additional disposal cost is accounted. This indicates that the disposal cost has a significant impact on channel dredging plan in the scenarios with relatively insufficient budget. As the annual budget increases, the impact of additional disposal cost on the channel dredging plan is reduced because sufficient budget allows most channels to be dredged despite the additional disposal cost and thus the difference in economic value weight navigability index diminishes.

Next, we use Table 7, showing the detailed results of an annual budget of $30 million case, as an example to present other performance measures obtained by the two solution approaches. From Table 7, we cannot identify a significant difference between the exact optimization approach and the DPP algorithm in terms of total usable budget, total dredging cost, number of channels to be dredged, economic value weighted average navigability index, average navigability index, or number of channels in states of good

Table 6
Quantification of the impact of disposal activity on economic-value-weighted navigability index.

Annual budget	Optimal EVWNI without additional disposal cost	Optimal EVWNI with additional disposal cost	Degradation of EVWNI with additional disposal cost accounted (%)
20 million	1.224	1.347	10.08
25 million	1.112	1.202	8.13
30 million	1.032	1.110	7.55
35 million	0.972	1.042	7.19
40 million	0.933	0.989	5.96
45 million	0.906	0.947	4.49
50 million	0.893	0.918	2.80
55 million	0.886	0.895	1.05
60 million	0.882	0.887	0.52

EVWNI: Economic-value-weighted navigability index.

Table 7
Planning result under an annual budget of $30 million.

Year		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6 (no dredging, for observation only)	Yearly Average
Given annual budget (million dollars)		30.00	30.00	30.00	30.00	30.00	–	
Reimbursed cost from the previous year (million dollars)	DPP	–	3.60	2.45	3.62	3.57	2.80	
	Optimization	–	4.47	2.03	3.76	2.42	2.67	
Total usable budget (million dollars)	DPP	30.00	33.60	32.45	33.62	33.57	–	
	Optimization	30.00	34.47	32.03	33.76	32.42	–	
Total dredging cost (million dollars)	DPP	29.80	33.09	32.13	33.07	33.12	–	
	Optimization	29.90	34.41	31.99	33.67	32.32	–	
Number of channels to be dredged	DPP	31	13	21	25	28	–	
	Optimization	29	17	20	32	23	–	
Economic value weighted average navigability index	DPP	1.397	1.035	1.110	1.074	1.159	1.060	1.139
	Optimization	1.397	1.044	1.083	1.053	1.076	1.009	1.110
Average navigability index	DPP	1.458	1.083	1.134	1.116	1.167	1.056	1.169
	Optimization	1.458	1.093	1.102	1.093	1.056	1.009	1.135
Number of channels in state of good repair ($Nav_{i,w} \leq 1$)	DPP	118	149	145	144	138	149	140.50
	Optimization	118	147	147	145	147	153	142.83

Table 8
Partial list of solution results (30 million dollars budget).

Channels	Shoaling rate (cubic yards per year)	Number of years to increase navigability index by 1		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
1	308	5	Dredge or not	No	No	No	No	No	No
			Dredging volume	1700	2008	2316	2624	2932	3240
			Navigability index	0	0	0	0	0	1
2	961	2	Dredge or not	No	No	No	No	Yes (CDF: 186)	No
			Dredging volume	200	1161	2122	3083	4044	961
			Navigability index	0	0	1	1	2	0
3	1920	2	Dredge or not	No	No	No	No	Yes (CDF: 187)	No
			Dredging volume	200	2120	4040	5960	7880	1920
			Navigability index	0	0	1	1	2	0
4	1620	9	Dredge or not	No	Yes (CDF: 100)	No	No	No	No
			Dredging volume	52,700	54,320	1620	3240	4860	6480
			Navigability index	3	3	0	0	0	0
5	410	7	Dredge or not	No	No	No	No	No	No
			Dredging volume	4800	5210	5620	6030	6440	6850
			Navigability index	0	0	0	0	0	0

Table 9
Synergetic strategic-operational planning results (only the first-year result is presented for demonstration) (an example for 30 million dollars budget).

Rank	Priority based on DPP	Channel number	Channel group number	Number of years to increase navigability index by 1	Current navigability index before dredging	Economic value	Assigned CDF number for disposal
1	Highest priority (required by the user)	22	8	6	2	2	173
2	Second highest	210	57	2	3	4	No CDF
3	Second highest	174	40	3	3	7	335
4	Second highest	168	38	2	2	9	No CDF
5	Second highest	49	11	3	3	9	24
6	Second highest	143	29	4	3	9	100
7	Second highest	170	40	4	3	6	335
8	Second highest	172	40	4	3	6	335
9	Second highest	182	45	4	3	8	40
10	Second highest	179	45	4	3	5	43
11	Second highest	17	8	4	3	2	173
12	Second highest	188	49	5	3	7	37
13		186 (linked to 188)	47	3	2	8	38
14	Second highest	197	53	5	3	8	13
15		201 (linked to 197)	53	6	3	8	25
16	Second highest	200	53	5	3	6	5
17	Second highest	180	45	5	3	3	61
18	Third highest	173	40	10	3	2	335
19	Third highest	171	40	10	3	2	335
20	Third highest	199	53	6	3	3	19
21	Third highest	20	8	7	2	1	173
22	Third highest	142	29	4	2	9	100
23	Third highest	198	53	4	2	9	6
24	Third highest	100	18	10	3	6	135
25		99 (linked to 100)	18	10	3	9	135
26	Third highest	184	45	3	2	5	40
27	Third highest	25	8	8	2	3	173
28	Third highest	12	8	9	3	8	173
29	Third highest	94	18	9	3	2	No CDF

repair. This also indicates that the DPP algorithm can obtain results close to the exact optimal solutions.

We present a partial list of channels (Table 8) to interpret the solution results that display multi-year plan of channel dredging activities and CDF disposal activities for the end user (annual budget is 30 million dollars). In Table 8, Channel 1 and Channel 5 will not be dredged within the five-year planning horizon because their navigability is anticipated to always be in the state of good repair. Channel 2 will be dredged in Year 4 and the dredged material will be disposed in CDF 186. After Channel 2 is dredged in Year 4, the navigability index immediately becomes to “0” and the template dredging volume decreases to 0 cubic yards in the same year. Then the channel’s deterioration process restarts. In Year 5, one year after dredging, the navigability index is still “0” but the template dredging volume increases to 961 cubic yards since the shoaling rate is 961 cubic yards per year. Channel 3 is planned to dredge in Year 4 and Channel 4 will be dredged in Year 1. The shoaling process and navigability deterioration process of these two channels are similar to those of Channel 2.

The result of the synergetic strategic-operational planning method in Section 5 is presented in Table 9 below. Recall that we have four hierarchies of priorities in the designed DPP algorithm:

(1) Channel 22 has the highest priority to be dredged because the user requires to (as our first priority hierarchy).
(2) Channels whose navigability index will reach to “4” in the next year (not allowed) if they are not dredged immediately also have the highest priority, but in this case, there are no such channels in the list.
(3) For the second priority hierarchy, there are 16 channels because their navigability index will reach to “4” at the end of the planning horizon if they are not dredged during the planning horizon. This information can be implied from the two columns “Number of years to increase navigability index by 1” and “Current navigability index before dredging”. Note that Channel 186’s navigability index will not reach to “4” even without dredging during the planning horizon, but it is still in the second highest priority category. This is because Channel 186 is linked to Channel 188, which is in the second highest priority category, and if Channel 188 is selected for dredging, then Channel 186 must be selected as well. Thus, Channel 186 has the same priority as Channel 188.
(4) For the third priority hierarchy, 12 channels with the third highest priority are selected for dredging.

The remaining 187 channels are not selected for dredging in the first year. The results of the method in other years can be interpreted in the same way. However, the channel selection plan may vary with the real-time condition due to navigability deterioration uncertainty. For example, some low-priority channels will not be selected for dredging when budget is not sufficient to dredge all channels in the strategic-plan list, or some channels that are not in the strategic-plan list may be selected for dredging given redundant budgets. This synergetic strategic-operational planning method can help hedge against this uncertainty by adjusting the prioritization list dynamically (see Table 10).

6.3. *Additional comparison*

This section compares the proposed multi-year optimization by exact solution (MIP by CPLEX solver) and DPP with two additional solution approaches, which are single-year optimization (separate planning for each year) and a static planning prioritization (SPP) heuristic algorithm. The comparison aims to demonstrate that 1) the integrated multi-year optimization planning method and the DPP algorithm outperform the separate single-year optimization planning for each year, and 2) the proposed methodologies significantly improve the dredging plan and the dredged material management by the traditional prioritization heuristic method (SPP) used by the current administration in practice.

The single-year optimization method optimizes the channel dredging plan and dredged material management separately for each year. Different from the integrated multi-year optimization, single-year optimization does not account for the impact of the plan for current year on the decisions in future years, and thus may be myopic to maximize the current year’s benefit only. The myopic consequence can be reflected by the comparison results in Table 10. The single year optimization model is presented in Appendix B.

Table 10
Solution results by single-year optimization, multi-year optimization, SPP, and DPP.

Annual budget	Single-year optimization (separate planning for 5 years)		SPP		DPP		Integrated multi-year optimization (MIP by CPLEX)
	EVWNI	Gap (%)	EVWNI	Gap (%)	EVWNI	Gap (%)	EVWNI
20 million	Infeasible	–	Infeasible	–	1.422	5.51	1.347
25 million	Infeasible	–	Infeasible	–	1.260	4.77	1.202
30 million	Infeasible	–	Infeasible	–	1.139	2.58	1.110
35 million	Infeasible	–	1.281	22.88	1.073	3.00	1.042
40 million	1.043	5.52	1.190	20.33	1.011	2.24	0.989
45 million	0.992	4.68	1.110	17.12	0.963	1.66	0.947
50 million	0.949	3.38	1.043	13.61	0.937	2.15	0.918
55 million	0.919	2.65	0.940	5.00	0.912	1.88	0.895
60 million	0.888	0.20	0.918	3.58	0.888	0.20	0.887

EVWNI: Economic-value-weighted navigability index.
Gap: the gap is calculated by the same method defined in Formula (43) for each solution approach.

Table 11
Computing time of single-year optimization, multi-year optimization, SPP, and DPP.

Annual budget	Computing time			
	Single-year optimization (separate planning for 5 years)	SPP	DPP	Integrated multi-year optimization (MIP by CPLEX)
20 million	Infeasible	Infeasible	0.056	15,092.05
25 million	Infeasible	Infeasible	0.047	95.84
30 million	Infeasible	Infeasible	0.047	111.84
35 million	Infeasible	0.041	0.047	220.81
40 million	11.342	0.035	0.038	476.08
45 million	10.645	0.040	0.037	91.82
50 million	10.487	0.040	0.035	54.01
55 million	10.272	0.041	0.033	68.49
60 million	10.063	0.035	0.033	25.91

The SPP algorithm represents to some extent the decision-making process of the current practice, resembling NJDOT's current planning method. The SPP algorithm ranks channels based on their navigability index and economic value. It uses navigability index as the primary ranking criterion and uses economic value as the secondary criterion. We name it as static planning prioritization algorithm (SPP) because the ranking criterion value of SPP is static, meaning that the ranking criterion value does not change after certain channels are selected for dredging. In addition, the ranking criterion of SPP also does not account for the impact of channel selection in one year on future decisions. Except for the ranking criterion, the algorithm structure of SPP is identical with that of the developed dynamic planning prioritization (DPP). SPP ranks channels in the descending order of navigability index. For those channels with identical navigability index, they are ranked in the descending order of economic value. This SPP algorithm also has the drawback of myopia as the single-year optimization does. In addition, SPP does not account for the cost in the ranking criterion and thus may obtain low-quality solution, as demonstrated in the following results.

In Table 10, the single year optimization and SPP approaches are compared with the developed integrated multi-year optimization and DPP approaches. We have the following observations.

When the budget is less than or equal to 35 million, the single-year optimization cannot get a feasible solution to the five-year planning due to insufficient budget. This is caused by its drawback of myopia. Some channels have large shoaling rate and navigability deterioration rate. Although these channels may not be the most urgent for dredging (navigability index = 2) in a certain year, they will have large dredging volume and poor navigability in the next year due to large shoaling rate and navigability deterioration rate. These channels must be dredged in the next year because of poor navigability. However, since there will be very large dredging volume, the dredging cost might exceed the budget, and thus not all of these urgent channels can be dredged, leading the solution to be infeasible. In contrast, both the integrated multi-year optimization approach and the DPP algorithm can obtain feasible solutions to the five-year planning with an annual budget no less than 20 million. As the annual budget increases to 40 million or larger, although the single-year optimization can obtain feasible solutions, the obtained solution quality is always outperformed by the integrated multi-year optimization as well as the DPP algorithm except for the 60-millon-budget case, an extreme large budget case in which DPP and the single-year optimization get the identical solution quality.

Similarly, the SPP algorithm cannot get a feasible solution when the annual budget is relatively small (⩽30 million) because the SPP algorithm also has the drawback of myopia. As the annual budget is larger than 35 million, we can observe that both the exact optimization approach and the DPP algorithm significantly outperform the SPP algorithm in terms of solution quality. Only when the budget is sufficiently large (e.g., greater than 55 million), the quality of solutions obtained by all approaches are close because almost all channels could be dredged given sufficient annual budget. We can conclude that both the exact optimization approach and DPP algorithm can significantly improve the solution quality compared with the SPP algorithm that follows current administration's approach in practice, particularly in the scenario with relatively insufficient budget (e.g., annual budget <50 million USD). Another interesting finding is that if the decision maker needs to keep economic value weighted navigability index below 1.00, the SPP algorithm needs around 55-million annual budget, while DPP and multi-year optimization (MIP by CPLEX) need only 45 million and 40 million annual budgets, saving approximately 18.18% and 27.27%, respectively.

Table 11 presents the computing time of the four solution approaches. As expected, the integrated multi-year optimization by CPLEX solver spends the longest computing time compared with the other three approaches. The single-year optimization by CPLEX solver takes approximately 10–12 s to get the optimal solutions for the cases with budgets from 40 million to 60 million. SPP and DPP are the fastest algorithms with the computing time <0.06 s for all cases.

7. Conclusions

This paper develops a dredging planning optimization model (DPOM) for multi-year planning of channel dredging and dredged material disposal activities. A heuristic algorithm, called the dynamic planning prioritization (DPP) algorithm, is developed to improve computing efficiency. A real-world case study based on the data in New Jersey is used to verify the effectiveness and efficiency of the model and the algorithm. The results show that the CPLEX solver can successfully obtain exact solutions for five-year planning problems (mixed integer programming) with 216 channels and 52 CDFs within reasonable amount of time (the maximum computing time is 15,092 s). The developed DPP algorithm can solve the same set of problems instantly (within 0.06 s) with <5.51% optimality gaps. Both the multi-year optimization model and the DPP algorithm are compared with a single-year optimization (separate planning for 5 years) and a SPP algorithm which resembles the current administration's approach in practice. The results show that both the exact optimization approach and DPP algorithm can significantly improve the planning solution obtained by the separate single-year optimization model, especially when the budget is insufficient. In addition, with the economic value weighted navigability index being kept below 1.00, the DPP algorithm and multi-year optimization (MIP by CPLEX) can save approximately 18.18% and 27.27% of the annual budget compared with SPP. In conclusion, the proposed methodologies and findings of the paper improve the practice of navigational dredging planning by providing optimized solutions with significantly better quality, efficiency, and reliability. The model and algorithm have been implemented in a maritime asset management system as an effective tool to support asset management decision making.

There are some limitations in the paper which may be addressed in future research. For example, we do not account for the change of ship size that may affect the navigability, considering it may not be a significant factor within short-term planning horizon (e.g., less than or equal to 5 years). As a strategic planning model, we assume a simplified navigability deterioration curve (i.e., based on historic shoaling depth, average per channel), and the detailed navigability quantification is out of the scope of this study. In addition to draught of ships, navigability of a channel is also dependent on the shoaling profile both across and along the channel. In our future research, we plan to work with the industry experts to develop detailed rules to define navigability, as well as incorporate of hydrodynamic and/or data-driven models to predict the "deterioration" of channel navigability accounting for stochastic factors. Given that the change of ship size in the next few years is not random, it can be easily incorporated as a parameter in our future research. In addition, our future work will extend the current model and explore the two proposed stochastic programming methodologies to model the uncertain navigability deterioration process in optimizing the plan of channel dredging and dredged material disposal after collecting more data.

CRediT authorship contribution statement

Zheyong Bian: Methodology, Writing – original draft. **Yun Bai:** Conceptualization, Methodology, Writing – review & editing, Project administration. **W. Scott Douglas:** Conceptualization, Investigation, Writing – review & editing. **Ali Maher:** Conceptualization, Writing – review & editing, Funding acquisition, Project administration. **Xiang Liu:** .

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 12
Notation used in the algorithms.

CE_w	Set of channels that are eligible for dredging in Year w. These channels satisfy three conditions: 1) the user specifies that the channels can be dredged or must be dredged ($UP_{i,w} = 1$ or 2); 2) the navigability index of each channel is greater than or equal to 2 ($Nav_{i,w} \geq 2$); 3) the template volume is greater than or equal to the over dredging volume ($V_{i,w} \geq OD_i$).
CS_w	Set of channels that are already selected for dredging in Year w in the current step of the prioritization algorithm.
C_w	Any set of channels that may be dredged, which is an input of Algorithm 3.
CNS_w	For Year w, CNS_w is the set of channels that are prioritized to be selected for dredging in the current step of the prioritization algorithm, excluding the channels that have already been selected for dredging. Only those channels which are eligible for dredging are in CNS_w. Thus, $CE_w = CS_w \cup CNS_w$.
GS_w	For Year w, GS_w is the set of groups that are already selected for dredging. This means that at least one channel in each group in GS_w is selected in CS_w.
$RCP_{c,w}$	For Year w, $RCP_{c,w}$ is the remaining capacity of CDF c.
RB_w	The remaining budget in Year w after some channels are selected for dredging.
$ac_{i,w}$	Increased cost to dredge each channel in CNS_w (for all $i \in CNS_w$}.
$Nav'_{i,w}$	Since the navigability index of each channel is an integer, $Nav'_{i,w}$ represents the decimal format of the Channel i's navigability index in Year w, indicating how long it will take for the channel's navigability to increase by "1" from Year w. For example, in Year w, if $Nav'_{i,w} = 1.25$ and $INav_i = 4$ (total number of years to increase the navigability index by "1"), then 3 years are needed to increase its navigability to "2".
$CLC_w(CS_w)$	Cumulative cost given the channels that are already selected for dredging in Year w (CS_w) in the current step of the prioritization algorithm.
$Linked_i$	The set of channels carried by Channel i.
$Linked\_group_i$	The set of groups of the channels carried by Channel i.
$Carrying_i$	The set of main channels carrying Channel i.
$CDF\_plan_{i,w}$	The CDF assignment plan of Channel i's dredged volume in Year w.
$NY_{i,w}$	The number of years needed by Channel i in Year w to increase the navigability to "$Lnav$" if the channel is never dredged.
NVC_w	Additional disposing cost, i.e., the total cost for disposing the volume that cannot be shipped to any CDF, given that a set of channels are selected for dredging.

Table 13
Notation used in single-year optimization.

Sets

CH	Set of channels, indexed by *i*. $CH = \{1, 2, \ldots, n_C\}$
G	Set of channel groups, indexed by *k*. $G = \{1, 2, \ldots, n_G\}$.
CDF	Set of CDFs, indexed by *c*. $CDF = \{1, 2, \ldots, n_{CDF}\}$.

Variables

$$x_{i,c} = \begin{cases} 1, & \text{if Channel } i \text{ is dredged and the dredged volume is disposed at CDF } c \\ 0, & \text{otherwise} \end{cases}$$

$$z_i = \begin{cases} 1, & \text{if Channel } i \text{ is dredged , but the dredged volume is disposed at a high penalty cost because no CDF capacity is available to accommodate the dredged volume.} \\ 0, & \text{otherwise} \end{cases}$$

$$y_k = \begin{cases} 1, & \text{if at least one channel in Group } k \text{ is dredged} \\ 0, & \text{otherwise} \end{cases}$$

Input parameters

Nav_i	Channel *i*'s navigability index before dredging in the current year.
V_i	Template volume in cubic yards that needs to be dredged for Channel *i* in the current year.
SC	Total reimbursed cost generated from the previous year.
B	The budget allocated for the current year.
uc_i	Variable cost per unit of volume to dredge Channel *i* in the first year.
upc_i	Unit penalty cost to dispose per unit of volume from Channel *i*, when no CDF is accessible for this volume or the accessible CDFs do not have enough capacity to accommodate the volume.
fc_k	The fixed cost if at least one channel in Group *k* is dredged.
$\sigma_{i,j}$	The link relation indicator parameter. If Channel *i* carries Channel *j*, $\sigma_{i,j} = 1$; otherwise $\sigma_{i,j} = 0$.
$\delta_{i,k}$	Channel grouping indicator parameter. If Channel *i* is in Group *k*, $\delta_{i,k} = 1$; otherwise $\delta_{i,k} = 0$.
$\lambda_{i,c}$	The CDF accessibility indicator parameter. If $\lambda_{i,c} = 1$, CDF *c* is accessible for Channel *i*, i.e., the dredged volume from Channel *i* can be disposed at CDF *c*; otherwise, $\lambda_{i,c} = 0$.
N_k	Number of channels in Group *k*.
Lnav	The largest allowable navigability index, which is 3 in this problem.
OD_i	The surpassed over dredged volume. In this paper, we assume that this portion of volume is never dredged.
EV_i	The normalized economic value of Channel *i*.
CP_c	The remaining capacity of CDF *c* in the current year before dredging.
γ_i	A parameter to indicate whether a channel to be dredged in the current year: $\gamma_i = \begin{cases} 0, & \text{Channel } i \text{ cannot be dredged} \\ 2, & \text{Channel } i \text{ must be dredged} \\ 1, & \text{Otherwise} \end{cases}$. If the following events occur, then Channel *i* cannot be dredged in the current year ($\gamma_i = 0$): (1) the navigability index (Nav_i) of Channel *i* is less than or equal to "1" (i.e., Channel *i* is in a state of good repair), (2) Channel *i*'s template volume (V_i) is less than the surpassed over dredged volume (OD_i) (i.e., the shoaling is low), or (3) the user requires that Channel *i* cannot be dredged. If the following conditions are satisfied, then Channel *i* must be dredged in the current year ($\gamma_i = 2$): (1) the user requires that Channel *i* must be dredged in the current year, or (2) the navigability index of Channel *i* will exceed the maximum allowable value (*Lnav*) in the next year if it is not dredged in this year.

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Appendix

A. Additional notation used in the algorithms (See Table 12)

B. Single-year optimization model (For the notation, see Table 13)

$$Min\frac{\sum_{i\in CH}EV_i\times Nav_i}{\sum_{i\in CH}EV_i} \tag{44}$$

Subject to

$$\sum_{i\in CH}\left(\sum_{c\in CDF}x_{i,c}+z_i\right)V_iuc_i+\sum_{k\in G}y_kfc_k+\sum_{i\in CH}z_iV_iupc_i\leqslant B+SC \tag{45}$$

$$y_k\geqslant\frac{\sum_{i\in CH}\left(\sum_{c\in CDF}x_{i,c}+z_i\right)\delta_{i,k}}{N_k}\ for\ any\ k\in G \tag{46}$$

$$\sum_{c\in CDF}x_{i,c}+z_i\leqslant\gamma_i\ for\ any\ i\in CH \tag{47}$$

$$\sum_{c\in CDF}x_{i,c}+z_i\geqslant\gamma_i-1,\ for\ any\ i\in CH \tag{48}$$

$$\left(\sum_{c\in CDF}x_{j,c}+z_j\right)\times\frac{\gamma_i}{2}\leq\left(\sum_{c\in CDF}x_{i,c}+z_i\right)\times\sigma_{i,j}+(1-\sigma_{i,j})\times M\ for\ any\ i,j\in CH \tag{49}$$

$$\sum_{i\in CH}x_{i,c}V_i\leqslant CP_c\ for\ any\ c\in CDF \tag{50}$$

$$\sum_{c\in CDF}x_{i,c}+z_i\leqslant 1\ for\ any\ i\in CH \tag{51}$$

$$x_{i,c}\in\{0,1\}\ for\ any\ i\in CH, c\in CDF \tag{52}$$

$$y_k\in\{0,1\}\ for\ any\ k\in G \tag{53}$$

$$z_i\in\{0,1\}\ for\ any\ i\in CH \tag{54}$$

Formula (44) is the objective function that minimizes the economic value weighted navigability index. Formula (45) ensures that the annual cost, including fixed cost, variable cost, and "penalty" disposal cost cannot exceed the allocated budget plus the reimbursed cost generated from the last year's dredging activity. Formula (46) models the relationship between $\left(\sum_{c\in CDF}x_{i,c}+z_i\right)$ and y_k, which is similar to Formula (8). Formula (47) and (48) respectively model the conditions under which channels cannot be dredged and must be dredged. Table 13 presents the detailed conditions under which channels cannot be dredged, can be dredged, and must be dredged in explaining the indicator parameter γ_i. Formula (49) models the same logic as Formula (17). Formula (50) represents that the disposed material is limited by CDF's remaining capacity. Formula (51) indicates that each channel cannot be dredged repeatedly. Formula (52)–(54) signify that decision variables $x_{i,c}$, y_k, z_i are all binary.

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