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Enhanced Maritime Asset Management System (MAMS)

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16. 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. Agencies like New Jersey Department of Transportation (NJDOT) 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.

This project studies the strategic level maritime infrastructure asset management problem for planning of navigation channel maintenance dredging and dredged material management. Mathematical models and solution algorithms have been developed to prioritize channels and optimize channel dredging planning and dredged material management in confined disposal facilities (CDFs). In addition, a software called maritime asset management system (MAMS) has been developed to implement the methodological framework with analytical models. This report presents the mathematical model framework and introduces the details about the MAMS software. The MAMS has been in use by NJDOT and is expected to significantly save the dredging cost and facilitate the planning and management practice.

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1 Introduction

National and state navigation channels are critical maritime infrastructure that supports economic and recreational activities and intermodal freight supply chains. Agencies like NJDOT spend millions of dollars annually to dredge the navigation channels in their jurisdiction and maintain the disposal facilities to support the maritime operations (e.g., a $50 billion industry in New Jersey). This project aims to design and develop a first-of-its-kind Maritime Asset Management System (MAMS) which includes a methodological framework and a decision support software tool. The MAMS addresses strategic level maritime asset management: single and multi-year planning of navigation channel dredging, dredged material placement and disposal facility maintenance. The methodological framework defines and integrates concepts, principles, input-output relationships, models, algorithms, as well as business processes. Innovative mathematical models and algorithms are developed to optimize planning decisions, accounting for practical constraints and considerations, including channel linkage and network dependency, project bundling, CDF accessibility and capacity expansion, deterioration (i.e., shoaling and navigability condition over time), reimbursable costs, economic values, etc. The software tool implements the framework to integrate data, enable parameter adjustment, visualize analytical results, and produce asset management reports. This outcome of this research is practically valuable for agencies in terms of 1) save dredging cost with system optimal solutions; 2) comply with regulatory requirements for performance-based asset management; 3) improve the efficiency, accuracy and accountability of the planning process; 4) facilitate communication and knowledge transfer among engineering and management personnel.

Current practices are using empirical experience for their maritime asset management of channel dredging, which may not be necessarily be the optimal and most cost-justified. The existing approach heavily reply on senior engineer's knowledge and experience and thus hard to transfer to other personnel. The methodology (and the software) can lead to the optimal decisions (the least cost or the best performance result). For example, the potential saving by using an optimal solution for achieving a same performance objective, to improve the state of good repair ratio from 30% to 60%, would be around $60 million compared to the case using a naive solution obtained by purely ranking the channels by navigability index. In addition, the existing approach heavily replies on senior engineers' knowledge and experience, who have to manually assemble data from different databases, calculate results, and produce tables and charts. The process is labor intensive, prone to errors, and hard to be transferred to less experienced personnel. The MAMS tool automates the process and utilizes computer power to search for optimal solutions. It can accurately calculate results and enable advanced input and output features. For example, it allows user to save their previous inputs and outputs for fast reload in later times and compare results of different scenarios in the same charts and tables. It also produces standardized reports and facilities communications among management units.

A novel mathematical model dredging planning optimization model (DPOM) is developed which optimizes single and multi-year planning decisions including yearly dredging list, dredged material assignment to disposal facilities or sites. DPOM is formulated as a nonlinear mixed integer programming (NMIP) model with the objective of maximizing one of the performance measures or minimizing cost. The model incorporated all essential business rules and constraints in dredging operation, and concerns in strategic capital planning, such as reimbursable cost, budget, economic benefit, etc.

We also developed a novel solution algorithm, dynamic planning prioritization (DPP), to solve the DPOM. 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. The DPOM can be solved by commercial optimization solvers but only when problem size is small. The DPP algorithm can effectively solve the DPOM by when the problem size is large (i.e., numbers of channels or years are large).

A software called maritime asset management system (MAMS) has been developed to implement the methodological framework with analytical models. The input includes channel and disposal facility data as well as user input/selection/specification (e.g., performance objective, budget level). The output includes the optimal dredging plan for different years including channel bundle plan, yearly project selection, project priority list, material disposal plan to facilities, maintenance plan for disposal facilities, as well as condition forecast for channels and disposal facilities. In addition, the tool can output a number of performance results, including group fixed cost, variable cost, disposal cost, system navigability index, economic value, state of good repair status, budget needed, reimbursable cost, in total and annual average values. The tool also enables scenario analysis and comparison and outputs formatted asset management reports with charts, tables and summaries of the maritime system, as needed by agencies to fulfill the asset management requirements.

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 project 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 (Dunkin and Mitchell, 2015; Mazaheri and Turner, 2019; Mitchell, 2010, 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, meta heuristic 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 dredges. 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 study 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.

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

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. 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 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 study to the literature are summarized in the following three aspects: 1) This study 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 Methodology

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 in this study 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.

Navigability condition index

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 in some year, 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.

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 design 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.

Dredging volume, shoaling, and navigability deterioration

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 study, 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 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

[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.

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 study 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.

Economic value

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, and 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.

Linked channels

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

[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.

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 between its template and over dredge volumes is < 1); 2) the main channel is specifically selected by the user not to be dredged.

Channel spatial clustering/bundling
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 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 occur 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.

Confined disposal facility (CDF)
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.

Cost (considering interest rate)
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.

Reimbursable cost
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 budget. For example, many channels still bear a certain percentage of sediment caused by

[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.

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.

Budget
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 study 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 study can be extended to a stochastic model in future research by incorporating the uncertainties in dredging planning.

User requirement
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.

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	
$x_{i,w,c} = \begin{cases} 1, & \text{if Channel } i \text{ is dredged in Year } w \text{ and the dredged volume is disposed at CDF } c \\ 0, & \text{otherwise} \end{cases}$	
$z_{i,w} = \begin{cases} 1, & \text{if Channel } i \text{ is dredged in Year } w\text{, but the dredged volume is disposed at a high penalty} \\ & \text{because no CDF capacity is available to accommodate the dredged volume.} \\ 0, & \text{otherwise} \end{cases}$	
$y_{k,w} = \begin{cases} 1, & \text{if at least one channel in Group } k \text{ is dredged in Year } w \\ 0, & \text{otherwise} \end{cases}$	

$Nav_{i,w}$	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.
$Navp_{i,w}$	This is an ancillary continuous variable used to formulate Channel i's navigability index in year w. "$Navp_{i,w}$" is the newly introduced variable 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 context, 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)

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:

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

Subject to

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

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

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

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

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

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

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

$x_{i,w,c} \le \lambda_{i,c}$, for any $i \in CH, w \in Y, c \in CDF$ (9)

$\sum_{w \in Y} \sum_{i \in CH} x_{i,w,c} V_{i,w} \le CP_c$, for any $c \in CDF$ (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 $w \in Y$ (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 $i \in CH, w \in Y$ (12)

$Navp_{i,1} = Nav_{i,1} - \theta$, for any $i \in CH$ (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 $i \in CH, w \in Y$

(14)

$Nav_{i,w} \ge Navp_{i,w}$, for any $i \in CH, w \in \overline{Y}$

(15)

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

(16)

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

(17)

$X_{i,w} \le \frac{V_{i,w}}{OD_i}$ for any $i \in CH, w \in Y$ (18)

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

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

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

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

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

$Nav_{i,w}$ are integers, for any $i \in CH, w \in \overline{Y}$ (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 must 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 $\sum_{c \in CDF} x_{i,w,c} + z_{i,w} \le Nav_{i,w}/2$. 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 $Nav_{i,w} \ge 2$ indicating that the channel is not in a "state of good repair", then $Nav_{i,w}/2 \ge 1$ 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 $\sum_{c \in CDF} x_{i,w,c} + z_{i,w} \le Nav_{i,w}/2 + 1$, 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 $\sum_{c \in CDF} x_{i,w,c} + z_{i,w} \le V_{i,w}/OD_i$ 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 $V_{i,w} \ge OD_i$, 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 $\sum_{c \in CDF} x_{i,w,c} + z_{i,w} \ge 1$. 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 $\sum_{c \in CDF} x_{i,w,c} + z_{i,w} \le 0$. 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 $x_{i,c,w} \leq 0$. 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 $\sum_{i\in CH}\left(\sum_{c\in CDF} x_{i,w,c} + z_{i,w}\right)V_{i,w}uc_i p_i \times (1 + IR)^{w-1}$. 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, $SC_{w+1} = ps \times (1 + IR)^{w-1} \times \sum_{i\in CH}\left(\sum_{c\in CDF} x_{i,w,c} + z_{i,w}\right)V_{i,w}uc_i p_i$.

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" ($INav_i \geq 2$), 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 $xv_{i,w,c} = x_{i,w,c} \times V_{i,w}$:

$$xv_{i,w,c} \geq V_{i,w} - M\left(1 - x_{i,w,c}\right) \text{ for any } i \in CH, w \in Y, c \in CDF \quad (25)$$
$$xv_{i,w,c} \leq M \times x_{i,w,c} \text{ for any } i \in CH, w \in Y, c \in CDF \quad (26)$$
$$xv_{i,w,c} \leq V_{i,w} \text{ for any } i \in CH, w \in Y, c \in CDF \quad (27)$$
$$xv_{i,w} \geq 0, \text{ for any } i \in CH, w \in Y \quad (28)$$

where "M" is a sufficiently large number.

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

$$zv_{i,w} \geq V_{i,w} - M\left(1 - z_{i,w}\right) \text{ for any } i \in CH, w \in Y \quad (29)$$
$$zv_{i,w} \leq M \times z_{i,w} \text{ for any } i \in CH, w \in Y \quad (30)$$

$zv_{i,w} \le V_{i,w}$ for any $i \in CH, w \in Y$ (31)

$zv_{i,w} \ge 0$, for any $i \in CH, w \in Y$ (32)

where "*M*" is a sufficiently large number.

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

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

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

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

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

where "*M*" is a sufficiently large number.

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

$$\sum_{w\in Y}\sum_{i\in CH} xv_{i,w,c} \le CP_c, \text{ for any } c \in CDF \quad (37)$$

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

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

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

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

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

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

Formula (20) can be reformulated as Formula (33) and Formulas (25-32)

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

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

3.5 Heuristic Algorithm: Dynamic Planning Prioritization

The DPOM proposed in Section 2 is a mixed integer programming (MIP) model, which is NP hard. Although the case in the study 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 not 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., $Nav_{i,w} \leq 1$), 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 the changes below, particularly the increased cost for dredging Channel i, $ac_{i,w}(CS_w)$). We use Formula (42) to formulate the ranking criterion.

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

$ac_{i,w}(CS_w)$ 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 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 to Table 2 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 $g \in \{i\} \cup (Linked_i \cap CNS_w)$
        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 $\sum_{g \in Linked_i \cup \{i\}} EV_g \times Nav_{g,w} \big/ ac_{i,w}$ 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 are 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' capacity 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 dredged 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
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 $Nav'_{i,w}$
    $RB_w = B_w + SC_w$;
    $CE_w = \{i$ |for all i satisfying that $Nav_{i,w} \geq 2$, $V_{i,w} \geq OD_i$, and $UP_{i,w} \geq 1\}$;
    CS_w $\{i$ |for all i satisfying that $Nav'_{i,w} + 1/INav_i = Lnav$ or $UP_{i,w} = 2\}$;
    $CS\_linked_w = \{i$ |for all i satisfying that $\sigma_{i,j} = 1$ for all $j \in CS_w\} \cap CE_w$;
    $CS_w = CS_w \cup CS\_linked_w$;
    $GS_w = \{k$ |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**
        $Linked_i = \{j|$ 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 $i \in CNS_w$;
        $i^* = \arg\max_{i \in CNS_w} \left(R_{i,w} \right)$;
        If $ac_{i^*,w} \leq RB_w$
            $I^* = \{i^*\} \cup Linked_{i^*}$;
            $CNS_w = CNS_w \backslash I^*$;
            $CS_w = CS_w \cup I^*$;
            $GS_w = GS_w \cup \{k$ |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 $c \in CDF$), ~] = **Algorithm 3** (I^*, $RCP_{c,w}$, $\lambda_{i,c}$, $V_{i,w}$, uc_i);
Else
$Carrying_{i*} = \{j|$ 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)

Input C_w, $RCP_{c,w}$, $\lambda_{i,c}$, $V_{i,w}$, uc_i
Output $CDF\_plan_{i,w}$, $RCP_{c,w}$, NVC_w
$NVC_w = 0$;
For $i = 1 \in C_w$
$c^* = \max_{c \in CDF} (RCP_{c,w} \times \lambda_{i,c})$;
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.

4 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.

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

4.2 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).

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

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 seconds (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 seconds). 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 seconds.

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

Figure 1 and Figure 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. 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.

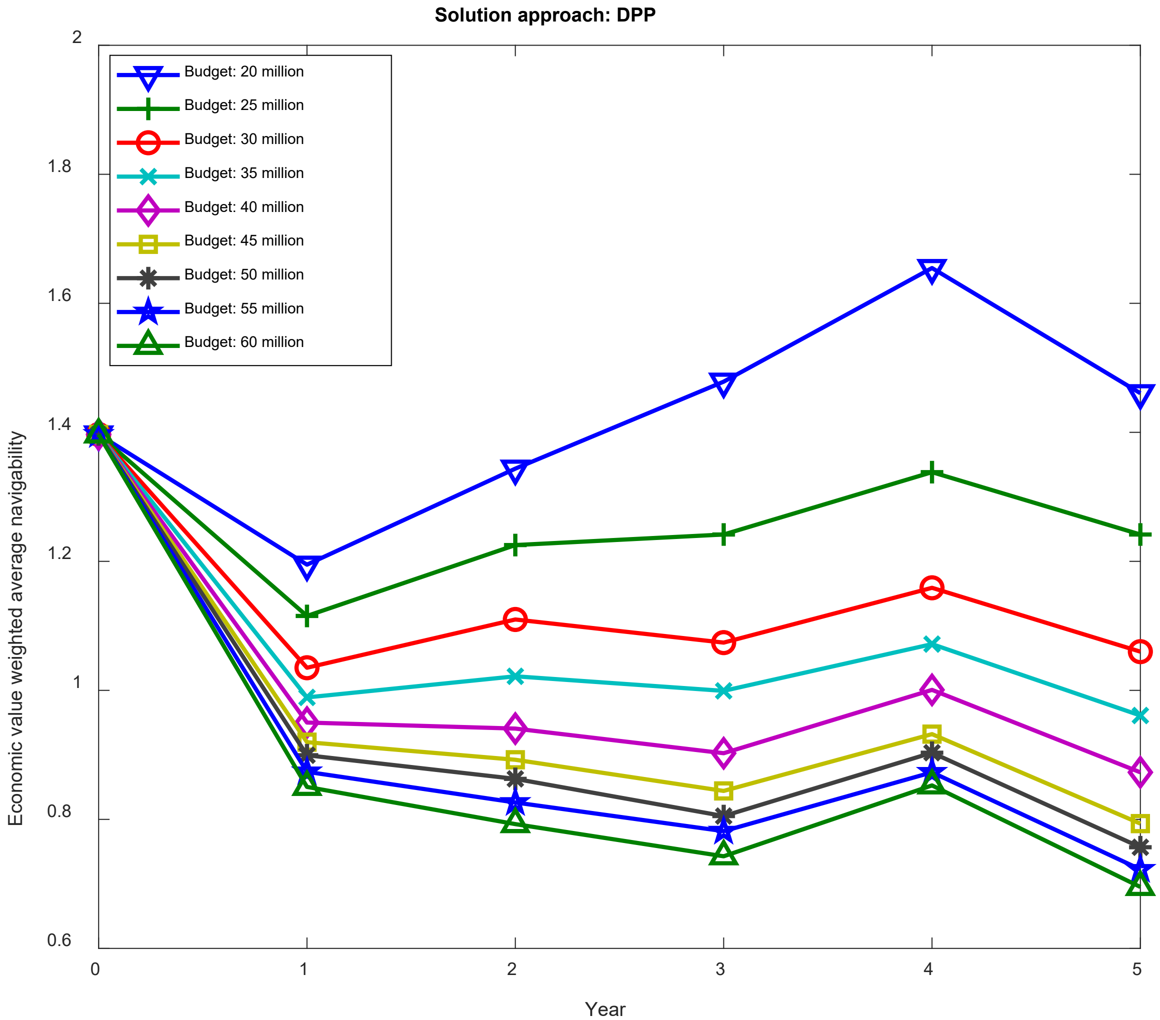


Figure 1 The change of the objective value - economic value weighted average navigability index - over time given different annual budgets (5 years planning, DPP algorithm)

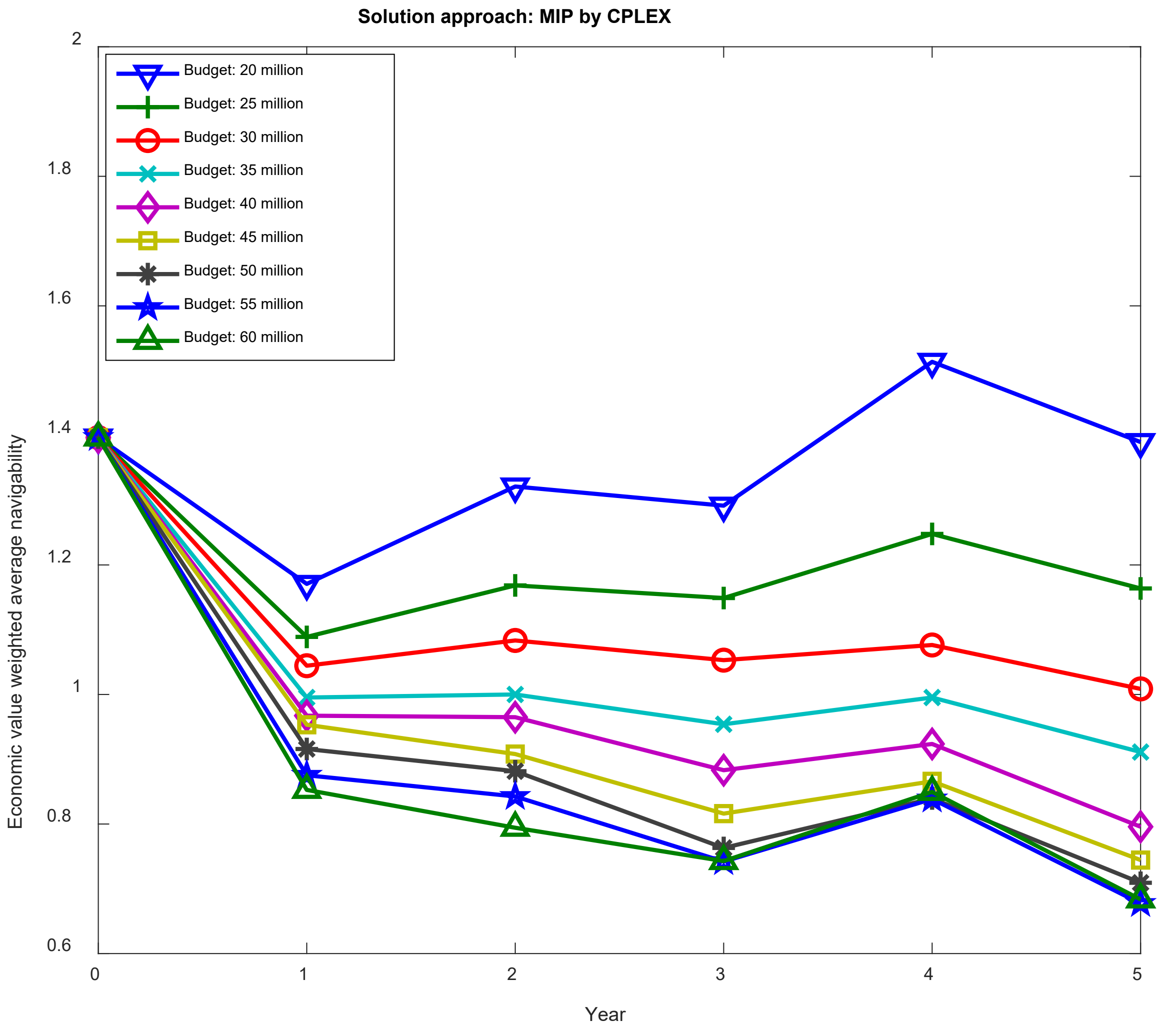


Figure 2 The change of the objective value - economic value weighted average navigability index over time given different annual budgets (5 years planning, exact optimization)

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% to 55.49% of the total cost, fixed cost accounts for 29.31% to 36.69% of the total cost, and the additional disposal cost account for 13.97% to 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 5 Breakdown of costs

	Variable cost	Fixed cost	Additional disposal cost

Annual budget	Total cost (dollars)	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

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.

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

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

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

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.

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	52700	54320	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

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) Our second priority hierarchy includes the channels whose navigability index will reach to "4" in the next year (i.e., beyond the 0-3 scale, which is not allowed in the system) 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 third priority hierarchy (here we refer to as the second highest priority), 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 fourth priority hierarchy (here we refer to as the third highest priority), 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.

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 199)	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

4.3 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.

Single-year optimization (separate planning for each year)

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 9. The single year optimization model is presented in Appendix B.

Static planning prioritization (SPP)

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 8, 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 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 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 to 12 seconds 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 less than 0.06 second for all cases.

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

5 MAMS Software

The aforementioned model and algorithm have been embedded in a software application named MAMS as a decision tool for NJDOT. Below is a figure showing the structural components of the software.

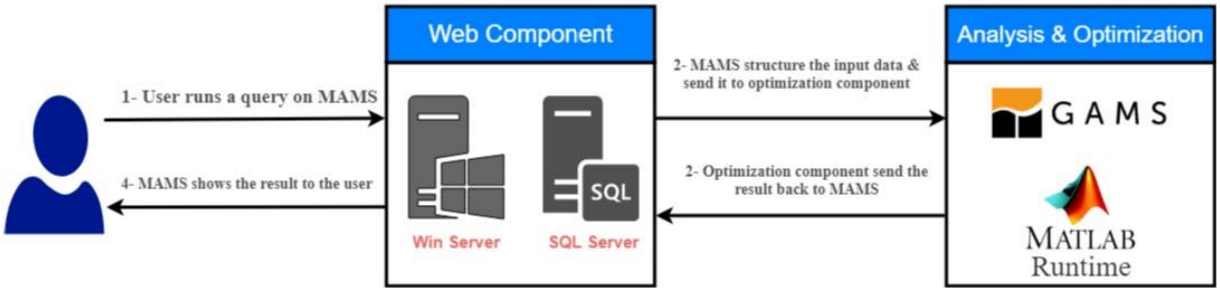


Figure 3 Structural components of the MAMS software

The input includes channel and disposal facility data as well as user input/selection/specification (e.g., performance objective, budget level). The output includes the optimal dredging plan for different years including channel bundle plan, yearly project selection, project priority list, material disposal plan to facilities, maintenance plan for disposal facilities, as well as condition forecast for channels and disposal facilities. In addition, the tool can output a number of performance results, including group fixed cost, variable cost, disposal cost, system navigability index, economic value, state of good repair status, budget needed, reimbursable cost, in total and annual average values. The tool also enables scenario analysis and comparison and outputs formatted asset management reports with charts, tables and summaries of the maritime system, as needed by agencies to fulfill the asset management requirements.

5.1 Dashboard Tab

Dashboard is the default home page of the application. It shows an overview of the asset inventory, i.e., channels and CDF facilities.

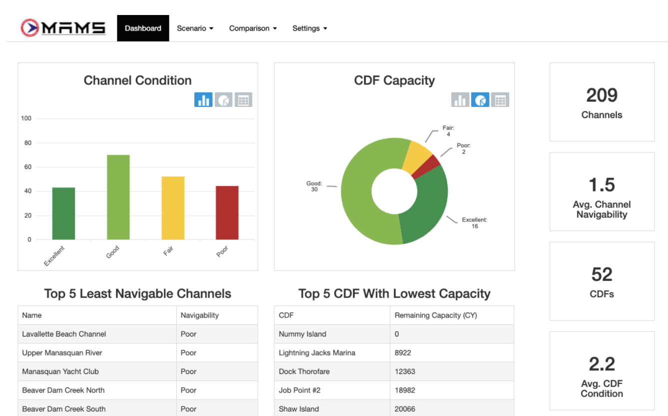


Figure 4 Snapshot of the MAMS software - dashboard tab

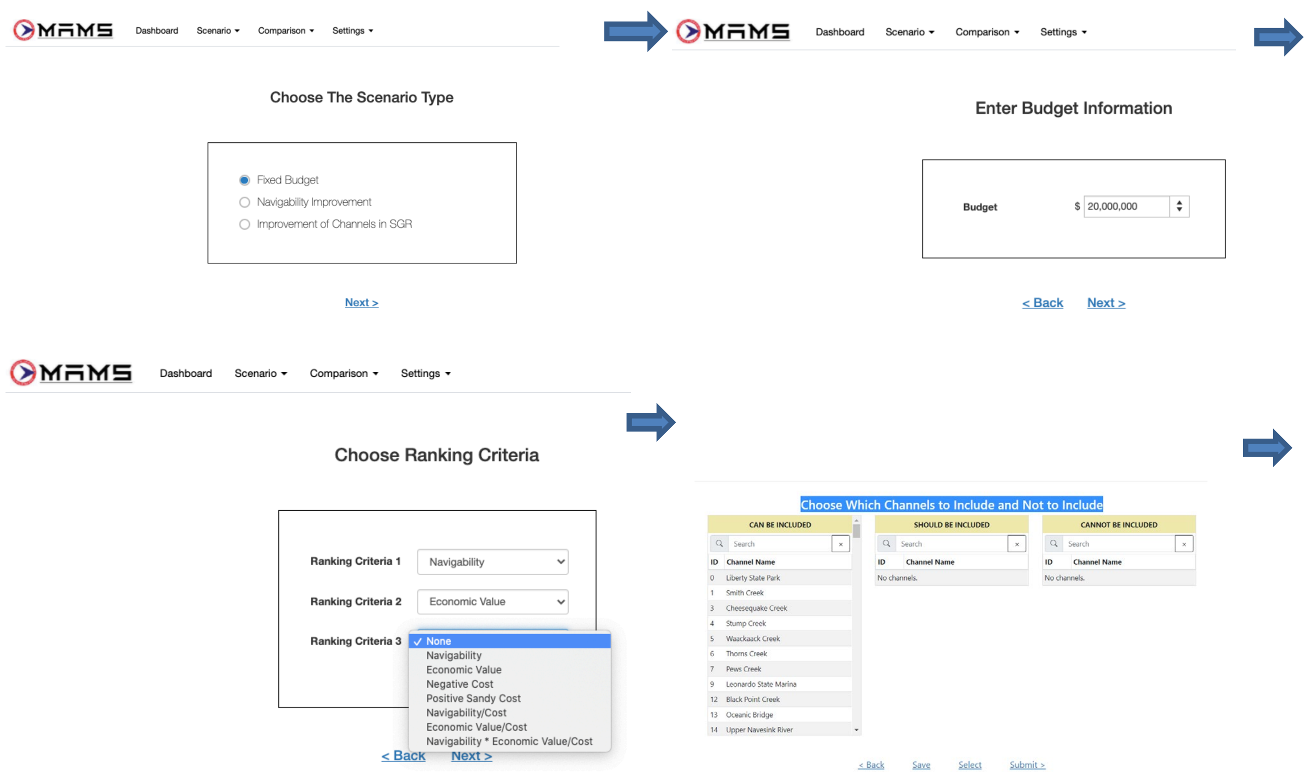
5.2 Scenario Tab

There are two major options when clicking on the Scenario Tab: Single Year and Multi Year. For single year, users can choose either prioritization or optimization algorithm.

Single Year Prioritization

Single Year Prioritization is based on a heuristic algorithm which ranks channels based on user specified criteria and outputs a list of channels to be dredged in priority order for the immediate decision year. Users will need to choose scenario type -> type in budget or performance improvement target -> choose ranking criteria in tiers -> choose channels that should be and cannot be included for dredging (by dragging them into the corresponding lists one by one or loading from a previously saved selection input). Screen shots of one example is shown as follows for a fixed budget scenario.

Example: A Fixed Budget Scenario



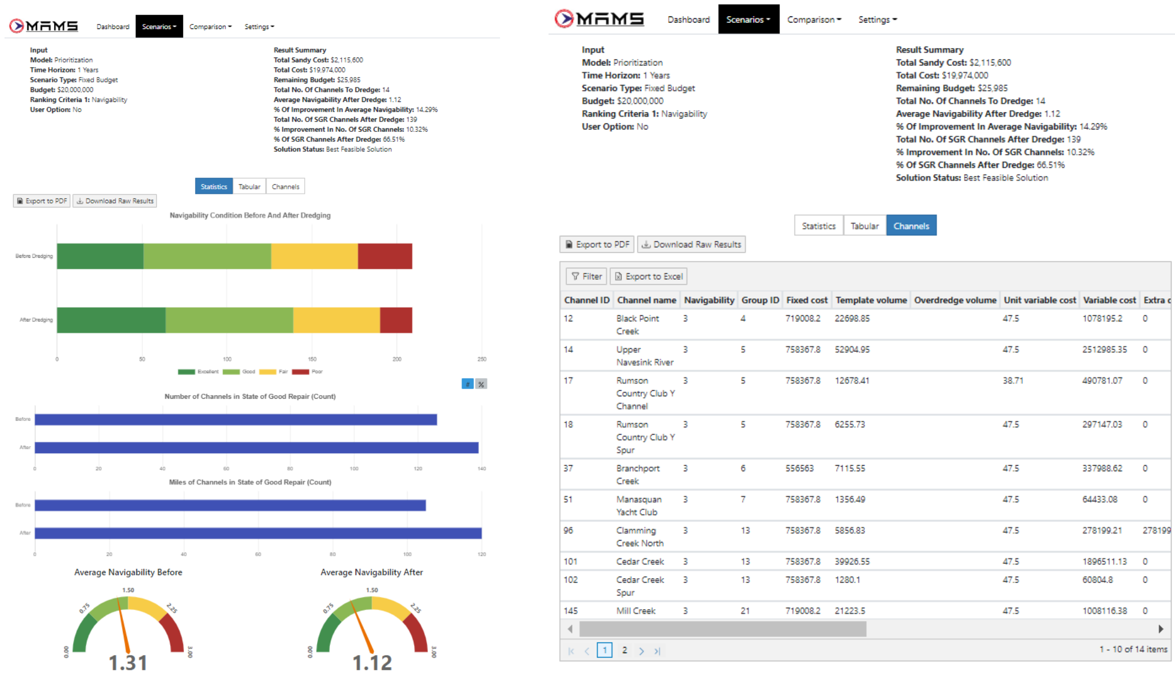


Figure 5 Snapshot of the MAMS software – an example run case of the single year prioritization scenario

In the "Choose Which Channels to Include and Not to Include" step, the user can save the manually inputted list of channels by clicking the "Save" button on the bottom of the page, or if there are previously saved inputs, the user can quickly load one by clicking the "Select" button.

In a few seconds after clicking on the "Submit" button, a result page should appear. **Note that there will be a Matlab command window activated showing the computation status. This Matlab command window will automatically close once the backend computation is completed, and should NOT be closed by users; otherwise, the computation will be interrupted and return an error message.** The overall performance metrics will be shown in charts under the "Statistics" tab and in a table under the "Tabular" tab. The priority list of channels along with channel characteristics and cost breakdown are shown under the "Channels" tab.

The tables and charts can be directly exported into a PDF format file by clicking on the "Export to PDF" button. The settings and results of each run case will be **automatically saved** as a scenario for direct access in future and scenario comparison, which can be pulled via the "Comparison" tab in the main menu, as shown below. You will find the scenario by referencing its name, description, and execution time, and pull out the saved results by clicking on the "View" button.

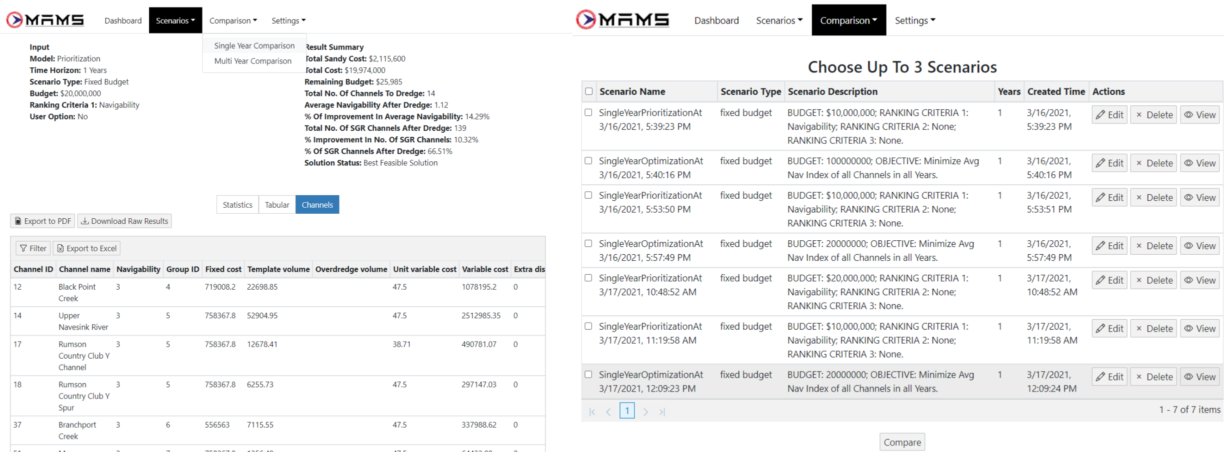


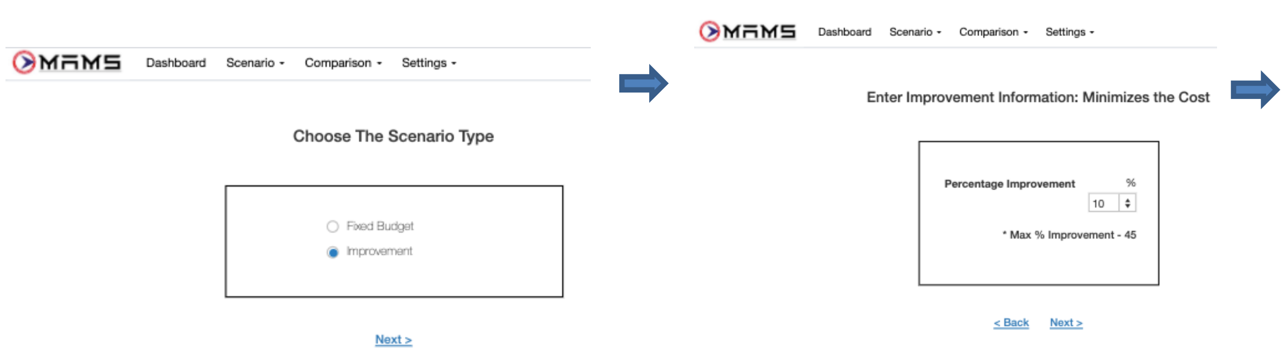
Figure 6 Snapshot of the MAMS software – output pages of the single year prioritization scenario

Single Year Optimization

Single Year Optimization is based on an optimization algorithm which maximizes one of the seven performance objectives (for fixed budget scenario) or minimizes the budget needed for achieving a certain performance target out of the seven metrics (for performance improvement scenario). It selects a subset of channels to be dredged for the immediate decision year. Users will need to choose scenario type -> type in budget or performance improvement target -> choose optimization objective or performance improvement constraint -> choose channels that should be and cannot be included for dredging (by dragging them into the lists one by one or loading from a previously saved selection input).

Screen shots of one example is shown as follows for a performance improvement scenario. Note that the inputted 10% value for "percentage improvement" enforces a constraint in the model that the specified performance metric (e.g., Econ Value Weighted Navigability in the following example) should improve by 10%.

Example: Performance Improvement Scenario



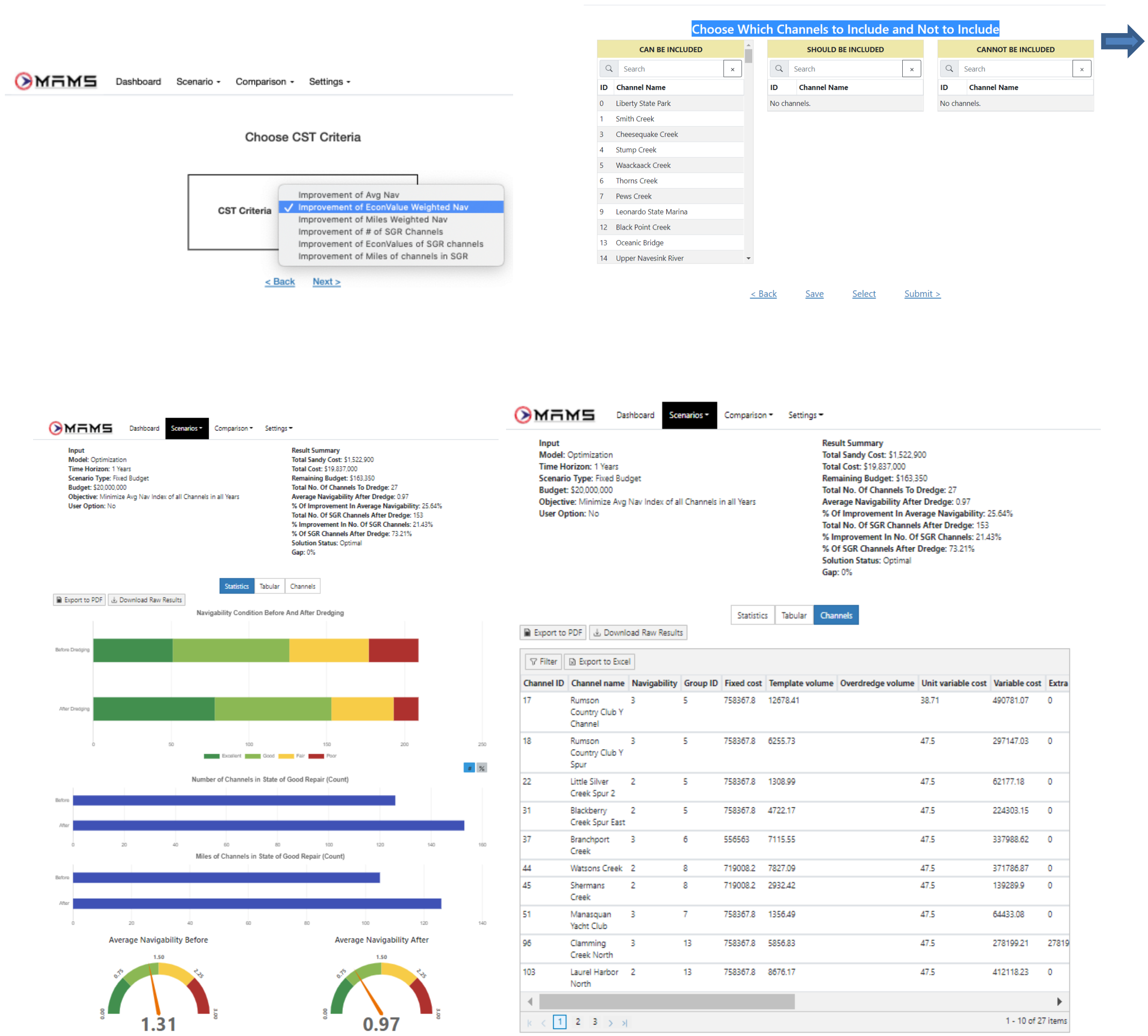


Figure 7 Snapshot of the MAMS software – an example run case of the single year optimization scenario

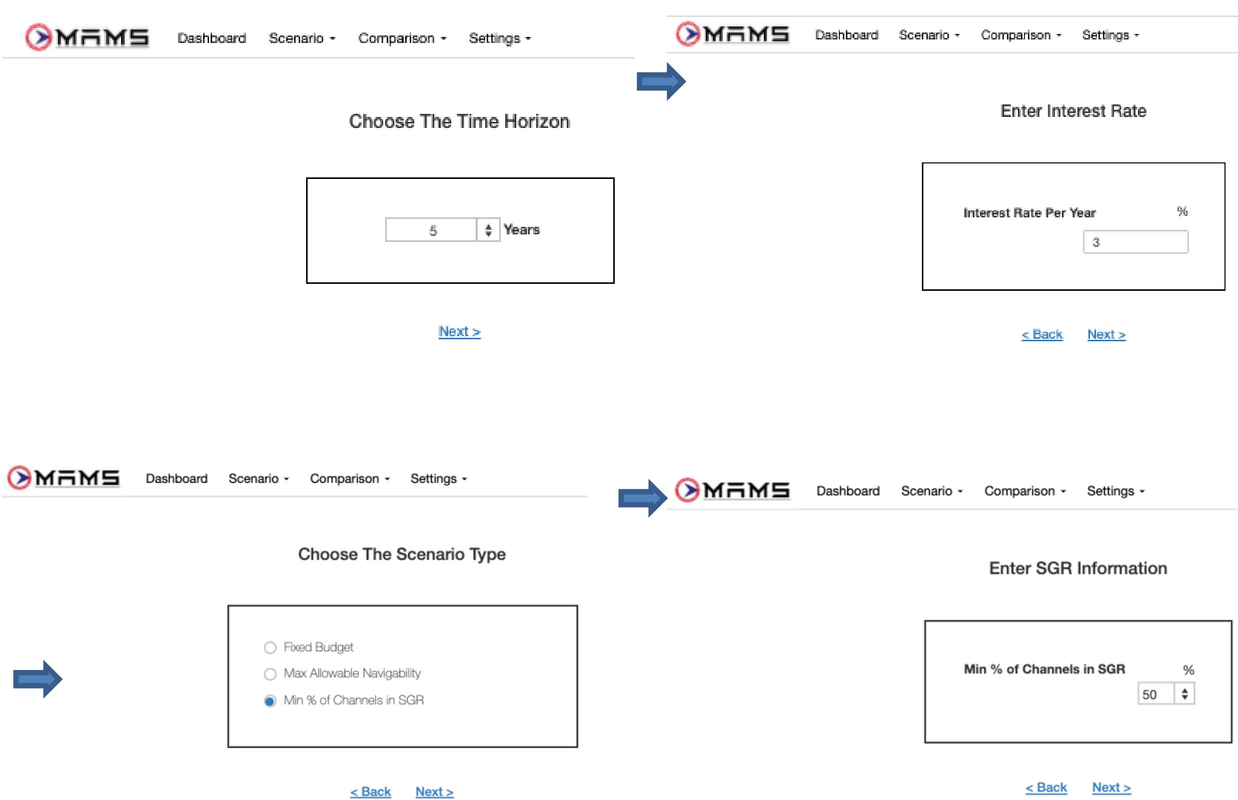
Multi Year Optimization

Multi Year Optimization is based on an optimization algorithm which either maximizes one of the seven performance objectives across all years (for fixed budget scenario) or minimizes the total budget needed for achieving a performance requirement (for two fixed performance scenarios). It selects a subset of channels to dredge for each year in the planning horizon. Users will need to input "number of years" -> input "interest rate" -> choose scenario type -> type in annual budget or annual performance target % -> choose optimization objective (for fixed budget scenario only) -> choose channels that should be and cannot be included for dredging (by dragging them into the lists one by one or loading from a previously saved selection).

Screen shots of one example is shown as follows for a fixed performance scenario to maintain a minimum 50% of SGR channels (over the total number of channels) for a 5 year planning period.

Notes for multi-year scenario input:

1. Input of performance requirement for multi-year optimization is the absolute value of minimum Average Navigability or % of SGR channels (over all channels), while for the single year optimization the input of performance requirement is % improvement of the chosen performance metric.
2. The selected "should be included" and "cannot be included" channels for dredging will be enforced for all years ("should be included" channels will be guaranteed to dredge in at least one of the years during the planning horizon, and may be selected multiple times if they deteriorate fast). The more advanced feature that allows variations in different years may be developed in future versions of MAMS.
3. Similarly, the yearly budget (for the fixed budget scenario) and performance requirement (for the two fixed performance scenarios) are taken as a single value input, same for all years. The more advanced feature that allows variation in different years may be developed in future versions of MAMS.



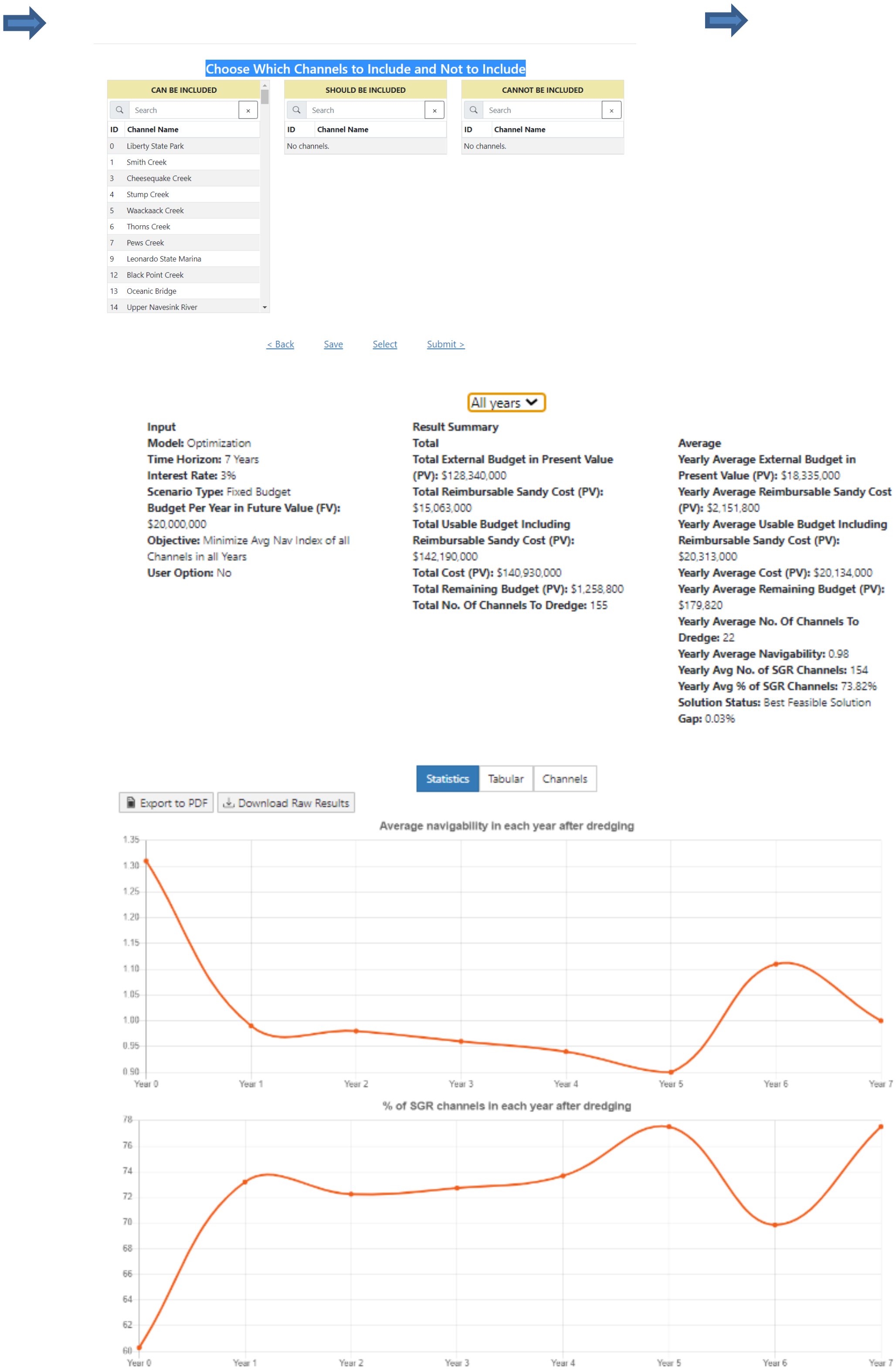


Figure 8 Snapshot of the MAMS software – an example run case of the multi-year optimization scenario

The performance result for individual years will be shown by clicking on a specific year in the drop-down list.

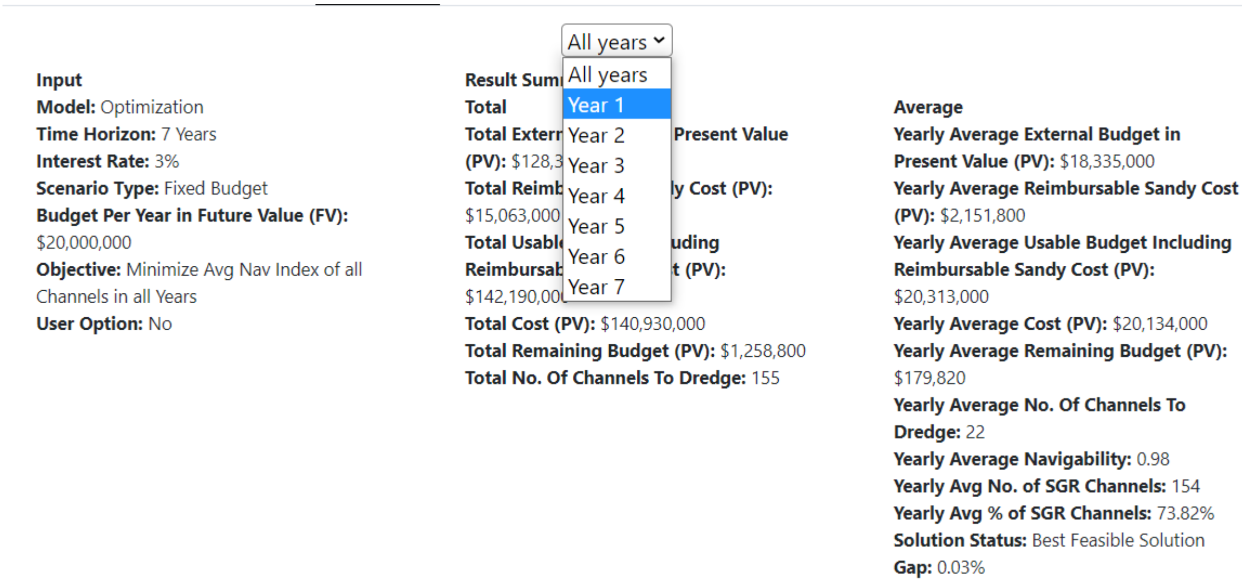


Figure 9 Snapshot of the MAMS software – output pages of the multi-year optimization scenario

By choosing the "All Years" option, average navigability indices and % of SGR channels of each year will be shown in a line chart. If needed, more charts can be developed in future versions of MAMS.

By choosing "Year X" option, detailed charts, tables comparing the selected year with its previous year will be shown under the "Statistics" and "Tabular" tabs, and list of selected channels in that specific year will be shown under the "Channels" tab.

5.3 Comparison Tab

There are two options when clicking on the Comparison Tab: Single Year Comparison and Multi Year Comparison. For the Multi Year option, there have to be at least two saved scenarios with the same number of years for comparison. The user can edit, delete or view the results of a saved scenario case. Up to 3 scenarios can be chosen in one comparison. The name and description of the saved scenarios can be edited. Below is an example illustrating a multi-year scenario comparison as follows:

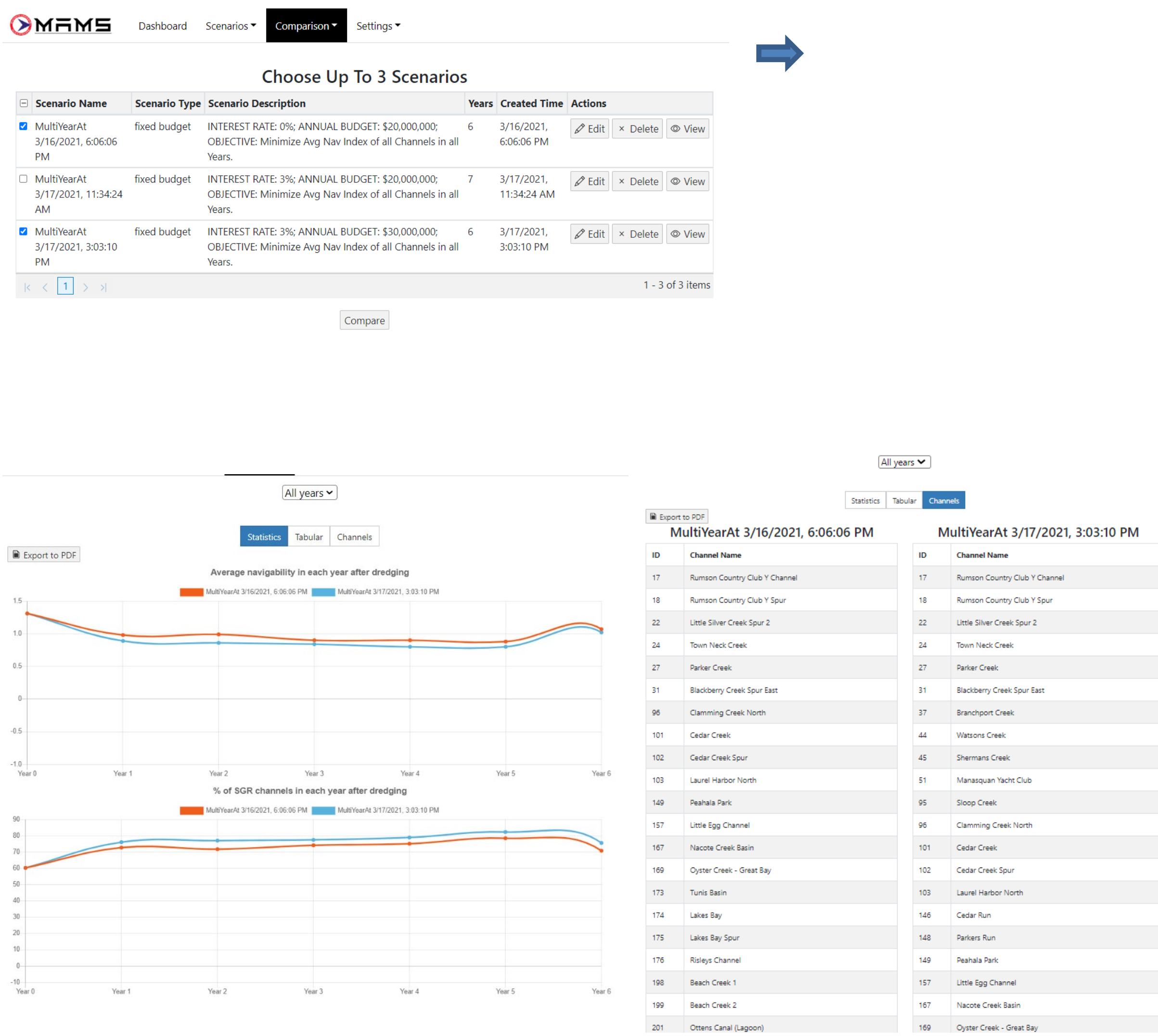


Figure 10 Snapshot of the MAMS software – scenario comparison

The user can compare both "All Year" results and each individual year's results of the selected scenarios by selecting year from the drop-down list.

6 Conclusions

This report summarizes the development of the first-of-its-kind Maritime Asset Management System (MAMS) which includes a methodological framework and a decision support software tool. A dredging planning optimization model (DPOM) is developed 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 a reasonable amount of time (the maximum computing time is 15,092 seconds). The developed DPP algorithm can solve the same set of problems instantly (within 0.06 second) with less than 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 this study 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 study 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.

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