MARITIME SOLUTIONS FOR A CHANGING WORLD

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TERRA ET AQUA

FLOOD RISK REDUCTION STRATEGIES

Economic evaluation of adaptation pathways

ACOUSTIC SENSORS

Optimisation of real-time monitoring systems

DYKE REINFORCEMENT

NEW CALCULATION METHODS IN ASSESSING FLOOD DEFENCES

ADAPTATION PATHWAYS

Reports by the International Panel of Climate Change (IPCC) highlight the unequivocal evidence of climate warming, emphasising the urgent need for both mitigation and adaptation measures. Adaptive pathway planning is considered as a promising approach to develop flood risk reduction strategies that can adapt to changing circumstances. Read the full article on page 6.

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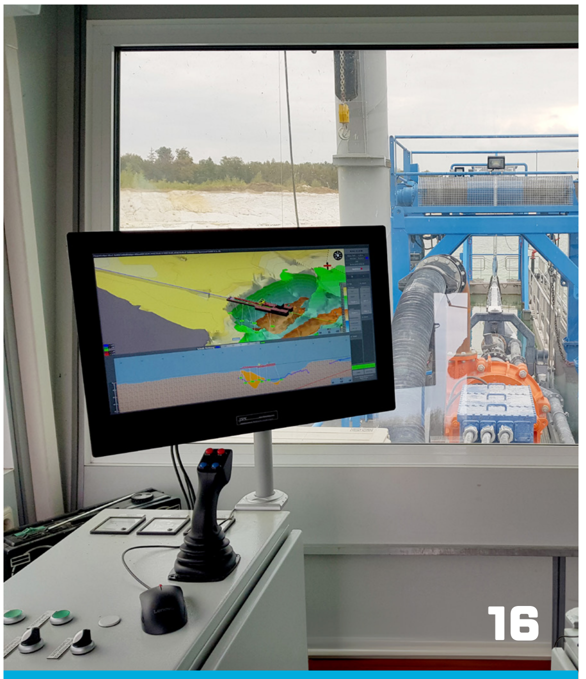


KNOWLEDGE IS KING

Last year was officially the hottest year on record. A fact that reinforces the importance of preparing communities for the impacts of climate change and finding climate-adaptive solutions. In this first issue of 2024, our continuing drive for sustainability is showcased throughout the pages of the spring edition, with particular focus on the research undertaken by young people.

Back in the summer of 2023, two students were awarded the National Hydraulic Engineering Prize for the most innovative and valuable thesis. Maria Montijn won the award for her master's thesis on "The economic evaluation of adaptive pathways for flood risk reduction strategies". Sea level rise is one of the largest climate change-related threats to coastal areas. However, the uncertainty surrounding the expected sea level rise makes it difficult to choose the right safety level and take the associated coastal defence measures.

An adaptive safety strategy based on the observed sea level rise can be advantageous.

Maria used the adaptive pathways method to investigate the influence of uncertainty and time on adaptability, based on, among other things, economic indicators. Conducted as a conceptual case study, the results show that time is an important factor and that, given the uncertainties, an adaptive safety strategy based on the observed sea level rise can be advantageous compared to a strategy that is based on a fixed view of the future.

It is expected that the method used will play a major role in developing a climate-adaptive coastal policy in the Netherlands and internationally.

Joppe Vugts, won the award for his bachelor's thesis, "Dealing with calculation innovation at dyke reinforcement projects". Since 2023, water board organisations have had to determine how to calculate the probability of flooding. New calculation methods have been developed in recent years but only validated to a limited extent, which makes water boards reluctant to apply them. Joppe's research investigated the added value of the new methods for the two most common specific failure mechanisms in dyke reinforcement: the strength of the initially unsaturated zone during macro stability and cracking during piping.

With regard to championing research and development in our industry, IADC and PIANC are organising a 1-day conference on 18 October in Vietnam on integrating dredging in sustainable development. The format will be interactive to engage participants and C-level and senior management of all IADC members will be present, providing invaluable knowledge to discussions.

Hearing from young professionals in our industry is also vital. That's why IADC has set up the Young Sounding Board to find out what young people think of IADC's activities and in what ways things can be improved. On the topic of sound, that brings us to our last article in this issue that discusses the optimisation of real-time dredge monitoring systems using acoustic sensors. There are many benefits to such tools including lower hydrographic-survey costs, increased production, safer operation, improved fleet-asset utilisation and most importantly, reduced greenhouse gas emissions.

Frank Verhoeven
President, IADC

A NEW METHOD TO ECONOMICALLY EVALUATE ADAPTATION PATHWAYS

The consequences of climate change are becoming more apparent and mitigation measures alone are no longer sufficient to prevent its impact. Investing in adaptation measures has become inevitable. However, the uncertain future conditions and the high associated investment costs puts pressure on making the best choice. Adaptive pathway planning is considered as a promising approach to develop flood risk reduction strategies that can adapt to changing circumstances. However, limitations in the existing evaluation methods pose challenges in the choice for the best strategy.

Over the past decade, scientific understanding of climate change and its consequences has advanced. The increase in knowledge has led to significant upward adjustments in future damage expectations. Reports by the International Panel of Climate Change (IPCC) highlight the unequivocal evidence of climate warming, emphasizing the urgent need for both mitigation and adaptation measures. The focus has shifted beyond merely reducing greenhouse gas emissions to substantial investments in adapting to the ongoing impacts of global warming.

The financial requirements for adaptation, particularly in developing countries, have surged. Estimates for the annual adaptation financing gap in 2050 have quadrupled in the last decade, from USD 70-100 billion to USD 315-565 billion. This underscores the growing financial burden of climate adaptation. As evidenced by the strong increase in expected costs over the last decade, adapting to climate change is an increasingly pressing issue. As a result, governments and organisations are seeking to implement effective flood risk reduction strategies. However, compounding this challenge is the uncertain nature of climate change. The connected uncertainties lead subsequently to uncertainties into the planning and decision-making processes.

The consequence of climate change uncertainty is that there is a likelihood that in case the climate scenario turns out to be milder than expected, unnecessary investments will be made. Contrarily, if the climate change impacts turn out to be more severe than expected, there are chances of extensive damages.

Flood risk reduction strategies and uncertainty

One of the consequences of climate change is

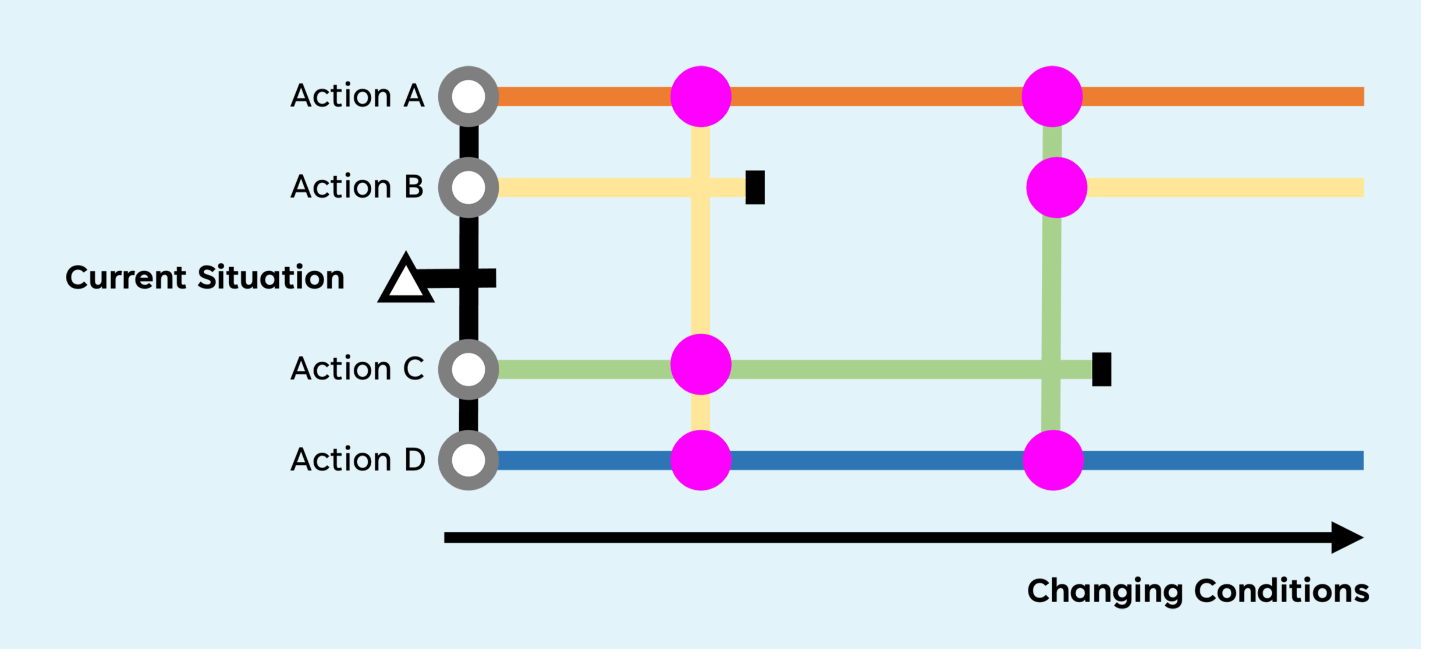


FIGURE 1

Schematic overview of adaption pathways.

the increase in flood risk. Traditionally, flood risk is defined as the exceedance probability of events of a certain magnitude and given loss. As a result, flood risk is determined by two aspects: hazard and vulnerability. Flood hazard is the likelihood of harmful water levels, while vulnerability considers exposure and susceptibility to damage during a flood event. Flood risk is influenced not only by flood characteristics but also by factors like population growth and economic development.

In the past decade, the population of some coastal cities doubled and multiplied their gross domestic product (GDP), which resulted in a significant increase in their flood risk. In 2022, the IPCC reported that by 2050 around one billion people will be living in low-lying coastal areas, compared to the 680,00 million who live there today. These demographic and economic elements and their future developments are also subject to uncertainties.

Next to these uncertain variables concerning environmental conditions, societal perspectives and preferences may also alter over time. Therefore, it can be concluded that long-term flood-risk planning are subject to different sources of uncertainty.

Adaptation pathways

To develop effective flood risk reduction strategies that can adapt to changing circumstances, planning approaches that incorporate adaptability and flexibility are essential. To accommodate flexibility into decision-making and account for the evolving nature of flood risk, the application of "adaptation pathways" has been identified as a promising approach. Adaptive pathway planning enables decision-making over time, in response to how the future unfolds.
The dynamic adaptive policy pathways (DAPP) method is a method in which adaptive pathways are used to develop plans that are subject to uncertainty (Haasnoot et al., 2013).

Figure 1 shows a schematic overview of a pathway map, a feature of the DAPP approach. It shows the available actions and the different pathways that can be chosen. The methodology is based on the idea that investment choices (or actions) have a finite lifespan and may no longer meet goals if circumstances change, i.e., when a threshold is crossed, known as the adaptation tipping point (ATP) (Kwadijk et al., 2010).

In a flood risk reduction strategy, for example, sea level rise can result in a minimum safety level no longer being met. When an action no longer fulfils the objective, new actions are required to meet the standards again, leading to a variety of alternate pathways. The trade-offs between their costs and benefits will determine which pathways are preferred over others. If there is only one initial decision moment, the strategy is considered static. However, if there are opportunities to make decisions based on available knowledge at different points in the design process, the strategy is flexible or adaptive.

While adaptive planning offers advantages, it also presents challenges and weaknesses compared to static approaches. Some challenges include uncertainty in future developments, potential trade-offs between short-term and long-term objectives, and the need for continuous monitoring and adjustment. In contrast, static approaches provide a more straightforward and predictable framework but may lack the ability to respond effectively to changing circumstances. To discover which strategy is optimal for a project location, adequate and thorough evaluation is necessary.

Economic evaluation

Various methods exist for economically

evaluating adaptive strategies, including cost-benefit analysis (CBA), real option analysis (ROA) and robust decision making (RDM). Multiple flood risk evaluation methods have been evaluated and it was found that each method comes with its own strengths and limitations. The premise of adaptive pathway planning is the ability to re-evaluate and reassess taken or possible new actions. Currently, no method is found to evaluate strategies under uncertain conditions and include the premise adaptation pathways.

Research objective

This research focussed on filling these identified gaps and contributing to enhancing the economic evaluation of adaptive pathways. Without an adequate evaluation method, validating positive expectations about adaptive pathway planning remains challenging. The study was divided into three subtopics:

1. Evaluation of current evaluation methods.
2. Investigate the value of time.
3. Test new evaluation method.

Creating a new method

Analysis of evaluation methods

Multiple approaches exit to develop and evaluate flood risk reduction strategies. Certain methods focus on the uncertainty, other focus more on incorporating flexibility. For this study, the most used techniques were evaluated to derive its strengths and weaknesses. Based on the found results a new method could be formulated.

Robust decision making (RDM)

RDM aims to create decision strategies that are robust and perform well under diverse future scenarios. It emphasises evaluating various options, including worst-case scenarios, to identify robust strategies. Robust refers to the ability to perform well even under conditions of high uncertainty or ambiguity. Identifying strategies that are robust helps decision-makers minimise the risk of negative outcomes and increase the resilience of their systems. Additionally, RDM aims to increase transparency by taking into account various objectives and criteria in the decision-making process.

RDM has the ability to facilitate so called “deliberation with analysis” (Groves et al., 2019). This term describes the process of decision-making where people or groups carefully and methodically consider options and potential outcomes before reaching a final conclusion. It involves careful consideration of relevant information, weighing of alternative options and evaluation of the potential consequences of each decision. This approach is often used in complex situations where there are multiple factors to be considered and where the stakes are high.

Real option analysis (ROA)

ROA, rooted in financial option theory, captures and values flexibility in decision-making. It introduces the concept of real options, allowing for changes in investments based on new information. ROA categorises options as “on” or “in” a system, offering valuable insights for climate adaptation plans. An example of a real option “on” a system is the option to defer or abandon a project. On the other hand, real options “in” a system are options that are incorporated into the design of the system. For example, making allowance for future expansion of a levee by over designing the foundations.

Both options “in” as options “on" a system are valuable for climate adaptation plans. So, in contrast with the traditional planning approach in which only one-off investment options are recognised, the real option’s concept is able to take management flexibility and volatility into account by enabling changes to an investment, in case new information becomes available in the future (Buurman and Babovic, 2016).

In a traditional CBA, uncertainty is included by expected values depending on probability distributions. The downside of this approach is that it connects a “now or never” quality to the decision moment. This quality is only suitable in case there is no flexibility. However, when the possibility exists to modify the decision, a traditional CBA tend to undervalue. With ROA, at every moment, the option to invest or not to invest is evaluated. The value of options of taking measures later or now is valued.

The ability to choose a different course of action or to decide to postpone an action until more information is available, results in the opportunity to limit the negative effects of making a poor choice while also maximising the positive effects of the newly available information. This aspect is the main premise of the adaptive planning concept. However, the downside of ROA is that it is complex to perform as many uncertainties need to be quantified, integrated and discretised in scenarios, as showed by Kind et al. (2018).

Extended cost-benefit analysis (CBA)

The study of de Ruig (2020) and Haasnoot et al. (2020) extended the traditional CBA framework to evaluate adaptation pathways. They both extended the time horizon of the traditional CBA and included evaluation of sequential measures. De Ruig’s method (2020) incorporates both the temporal and spatial dimensions of climate change impacts and evaluates a range of adaptation measures and their timing to identify the most cost-effective and efficient pathway. Similarly, Haasnoot et al. (2020) extended the traditional CBA framework by incorporating multiple scenarios and an extended time horizon to evaluate sequences of investments or adaptation options. The most effective pathway is determined by the climate and socio-economic scenario that is considered. Transfer costs are included that quantify the path-dependency of options.

> **Adaptive pathway planning enables decision-making over time, in response to how the future unfolds.**

Both methods build on the traditional CBA framework and provide a more thorough analysis by taking into account a range of factors and considering the long-term effects of climate change. The recommendation that followed from this research is to incorporate the flexibility in the economic assessment that would enable alterations in the type and/or height of subsequent measures for conditions different from assumed.

Reduced uncertainty: the value of time

A flood risk reduction strategy is subject to various uncertainties which makes it difficult to design the optimal strategy. The performance of the strategy could be increased in case there is a possibility to base decisions on new and more accurate information. The “updated” knowledge which could lead to reduced uncertainty is one of the possible drivers of the added value of adaptive pathway planning.

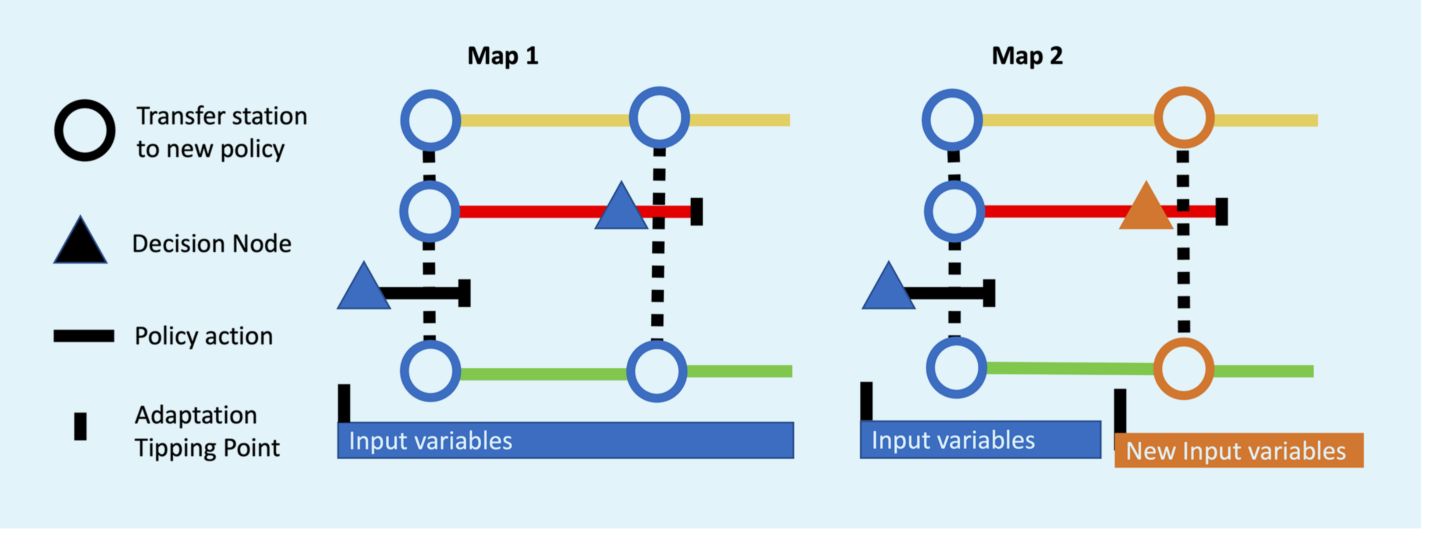


FIGURE 2

Altered Adaptation Pathway map to illustrate the asset of new knowledge.

Figure 2 illustrates this principle of "updated knowledge" and is also referred to as the value of time. The schematisation depicts two pathway maps. Map 1 illustrates the scenario in which no updated knowledge is used. In Map 2, new input variables, based on knowledge retrieved over the past time span, are included at the decision node and transfer station, marked in orange. To describe it more simply, do we learn over time about relevant future conditions? However, although time passes, not all input variables will experience a reduced uncertainty. In this article, the analysis of the three most dominant factors are included: the sea level rise (SLR), economic growth and damages.

Sea level rise projections

For this research, a study was conducted to find a trend in the uncertainty ranges of the past SLR projections. Over the past 200 years, observations of sea levels have mainly been based on tide gauge measurements. Technological advancements, such as satellite altimetry in 1992 and high precision gravity measurements in 2002, have enhanced our knowledge of global SLR and our understanding of the magnitude and relative contributions of the different processes causing sea level change.

Various factors contribute to projection uncertainty, including glacier and ice sheet mass loss, thermal expansion and changes in non-glacial water storage. There is not a universally accepted best estimation technique or a single agreed-upon probability distribution. To refrain from choosing a particular projection, decision makers often use the IPCC projections, which are an ensemble mean or consensus estimate.

A study by Garner et al. (2018) compared 70 SLR projections, published over a time span of 35 years. It revealed a slow reduction in the range of projections from 1983 till 2000, however the uncertainty bands remained relatively great. The projections between 1983 and 1989 contain the greatest range from all other periods across the 35 years. The projections included many assumptions, which resulted in higher uncertainty factors, and future research should overcome these shortcomings.

The third assessment report (TAR) of the IPCC in 2001 and the studies after assumed no major contributions to SLR due to loss of founded ice from the West Atlantic ice sheet could be expected before 2100. Which resulted in a reduction in the uncertainty bands of the projections in the years between 2000 and 2007. In 2007 this trend reversed and greater ranges were projected, experts argue that this reflects the uncertainty about the maximum contribution of the Greenland and Antarctic ice sheets.

It is sensible to say that the increase of understanding has also resulted in an increased of understanding of the elements that are not understood yet. The latest IPCC report emphasises the critical next decade for gaining insights into future projections and their implications. This underscores the importance of ongoing research in the coming years. Figure 3 shows the evolution of SLR projections divided by the publications of the IPPC assessment reports. Initially, a reducing uncertainty is clearly visible, which changes with the fourth assessment report (AR4) in 2007.

Economic damages

For the economic evaluation in this study, only direct physical damages are included in the risk assessment. This procedure consists of three elements: 1) determination of flood characteristics; 2) assembling data on land use and maximum damage amounts; and 3) application of stage-damage functions (Jonkman et al., 2008). These three elements were evaluated in order to determine whether they are subject to reduced uncertainty when time passes.

The first element involves determination of flood characteristics, which are prone to model uncertainties and will therefore not benefit from more time. For the second element, the uncertainty in captured in the future developments of the land (use). The land use of the project area can change over time due to, for example, development projects. Besides, in case of land use change or not, the value of the

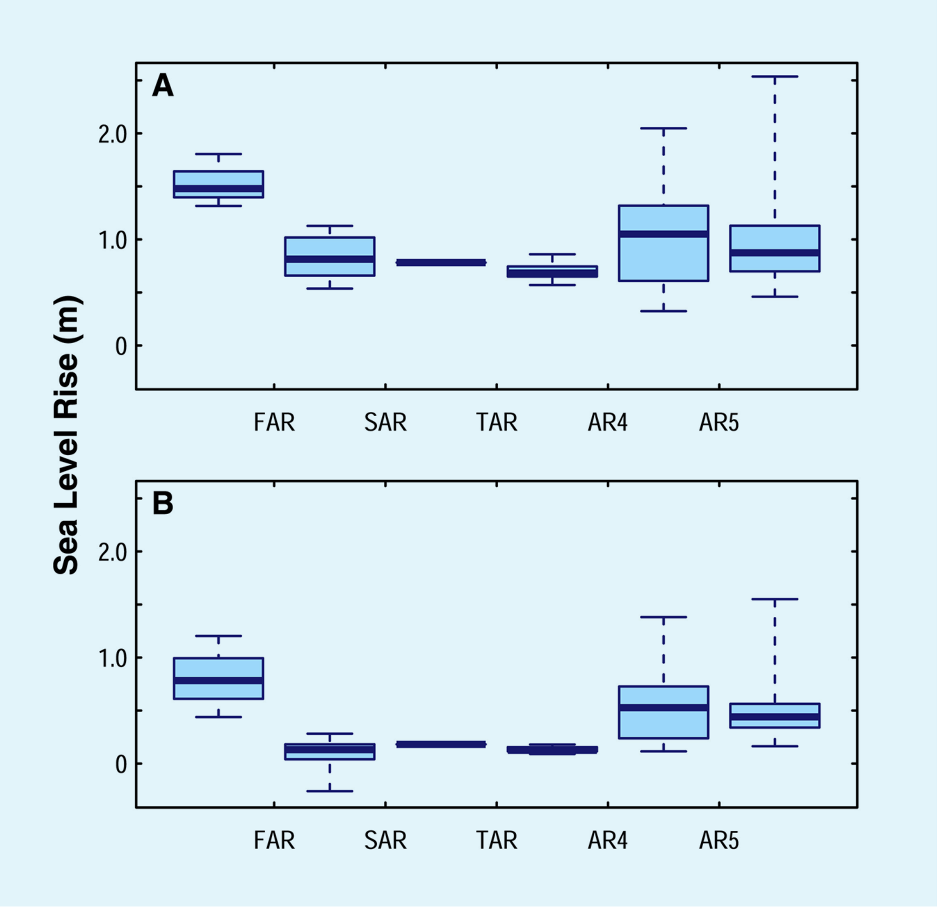


FIGURE 3

Evolution of bandwidth of the SLR projections.

land can also change over time. These are local uncertainties, so no generic conclusions about a reduction over time can be drawn. The third element concerns the damage curves. There are methods to increase the accuracy but is not assumable to expect a reduction over time achieved by more data.

Socio-economic growth in flood risk context

Socio-economic growth, describing the future value evolution of a project area, is influenced by various factors. Economic growth indicators like gross domestic product, coupled with development plans, impact this growth rate. Six key drivers of economic growth, including natural resources, infrastructure, population, human capital, technology and law, contribute to uncertainties. The growth rate's uncertainty is dependent on the initial GDP per capita and the current level of development in the project area. The specific characteristics of a project area determine whether the uncertainty range changes over time.

Impact on the framework

The performed study into the strengths and limitations of existing methods and the premise of adaptive pathways lead to a focus on incorporating flexibility and evaluation metrics of a new framework.

Flexibility

To enhance flexibility and therefore create adaptability in a strategy, it's crucial to consider two key factors: sea level rise (SLR) rate and the timescale of adaptation measures. The timescale involves the functional lifetime of a measure and the time needed for its completion. Adaptive pathways planning emphasises flexibility and shorter timescales enhance the ability to make informed, low-regret decisions. The framework evaluates flexibility by alternating between measures with different functional lifetimes and required timescales. The envisioned lifetime of a measure depends on the protection level, which is influenced by which SLR scenario is considered. Secondly, shorter lead time (time needed from planning till completion) contribute to increased strategy flexibility. The considered SLR scenario determine the expected timing of the adaptation tipping point (ATP).

While low SLR measures have more predictable ATP timing, extreme scenarios introduce uncertainty, emphasising the need for adaptable strategies. Creating decision moments in the strategy is essential to achieve different levels of adaptability and find the right balance between flexibility and costs. When smaller measures, for shorter expected lifetimes with short lead times, more flexibility is implemented in the strategy. However, more flexibility is not directly better and the right balance should be found.

Evaluation metrics

From the performed study into the existing evaluation methods, it was evident that incorporation of uncertainty is crucial. Utilising simulation techniques like Monte Carlo analysis, where uncertain variables are expressed through probability density distributions, enhances the analysis.
To provide a more comprehensive evaluation and increase understanding, three additional metrics next to the commonly used net present value (NPV) and benefit cost ratio (BCR) have been identified. The search for more metrics came forward after the assessment of existing evaluation methods.

Equivalent annual costs (EAC)

EAC introduces a valuable indicator, particularly when dealing with strategies of different lifetimes. EAC facilitates the fair comparison of cost-effectiveness for assets with unequal lifespans, ensuring a more nuanced financial assessment. Important to note that as the NPV is used, a positive EAC

> **The latest IPCC report emphasises the critical next decade for gaining insights into future projections and their implications.**

value implies benefits. In this formulation, the higher the EAC, the better. The following formulas are involved in this concept:

$$EAC = \frac{NPV}{A_{t^*,i}}$$

$$A_{t^*,t} = \sum_{t=1}^{t^*} \frac{1}{(1+i)^t} = \frac{1-(1+i)^{-r^*}}{i}$$

with A = annuity factor, r = discount rate and t = numer of years of entire lifespan.

Coefficient of variation (CV)

The spread of results in flood risk reduction strategies is influenced by stochastic variables. While variance is a commonly used metric to describe spread, the coefficient of variation (CV) provides a unique perspective. Unlike variance, CV offers a relative measure of variability, showcasing the standard deviation as a percentage of the mean. This dimensionless metric allows for meaningful comparisons across datasets with varying scales or units. This ensures decision-makers can effectively assess and compare the variability of outcomes, irrespective of differences in scales or units.

$$\sigma^2 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{N-1}$$

In which:
X = variance; X = each value in the data set; X = Mean of all values in the data set; and X = number of value in the data set.

$$Coefficient\ of\ Variation\ (CV) = \frac{\sigma}{\mu} * 100\%$$

In which: X = standard deviation and X = mean.

Probability of loss (PoL)

While metrics such as (NPV) offer insights into economic performance, relying solely on the highest mean NPV can be misleading. The probability of loss (PoL) can turn out to be crucial in evaluating the potential financial impact of a flood risk reduction investment. It represents the probability that the NPV will be negative. By considering the PoL, decision-makers can gain a more nuanced understanding of strategy performance, avoiding a distorted view based solely on mean NPV. As the example in Figure 4 shows, when only considering the highest mean NPV, Strategy A would be preferred. However, the high chance of a negative outcome would have been missed.

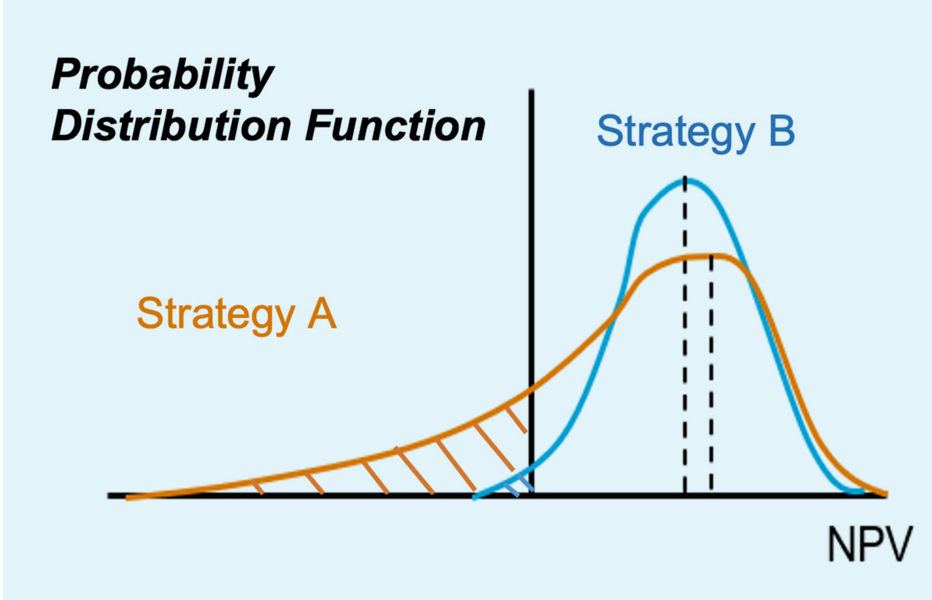


FIGURE 4
Schematic overview of the PoL illustrating its potential relevance.

Formula for probability of loss:

$$\text{Probability of Loss} = \frac{\text{Number of outcomes of NPV} < 0}{\text{Total number of samples}} \times 100\%$$

In summary, these evaluation metrics collectively provide a robust framework for assessing flood risk reduction strategies, considering uncertainty, variability and potential financial impacts.

Conceptual case study

The analysis of existing methods showed that to capture the value of adaptive pathways, it is important to consider uncertainty, include sufficient and relevant evaluation metrics, and acknowledge the value of time. Uncertainty needs to be incorporated in the evaluation of a strategy, either through a scenario-based approach or a sampling technique. Multiple evaluation metrics should be used to obtain a deeper understanding of the performance of a strategy which supports decision-making. The value of time lies in the ability to reassess and reevaluate with newly obtained data that becomes available over time, which connects with the premise of adaptive planning. Overall, by considering these focus points, a new framework for evaluating flood risk strategies was established.

Incorporation of value of time

Earlier was explained that, multiple stochastic variables play a role in a flood risk reduction strategy and if and how extra time would impact its uncertainty. For this conceptual case study, it was assumed that only the amount of SLR is influenced by the value of time. As discussed, it was concluded that no evidence was found that the uncertainty of SLR will reduce over time. However, the coming years will tell whether we are heading for an extreme or moderate climate change scenario. Therefore, to include this prospect, in this research it is assumed that the absolute uncertainty band would remain stable with respect to the time horizon.

For clarity, this assumption is schematised in Figure 5. In this example, the horizon of the first measure is 65 years (2020-2085) and expected horizon for the second measure is also 65 years (2085-2150). Since the projected time is equal, so should be the absolute variance. In other words, when an ATP is reached in 2085, a narrower uncertainty band can be used to find the optimal measure for the next action. This extra knowledge is used to optimise the decision of the new investment at the decision moment and leverages the newly retrieved data, and therefore the value of time. The moment of the ATP is a stochastic variable as it is influenced by the rate of SLR. The pink dot expresses the ATP for a single simulation.

Results

The framework was tested on a conceptual coastal case study. Seven different strategies were formulated that differed in the level of flexibility.

By varying in envisioned lifetimes of measures, and measures with different lead times, different levels of adaptability can be accomplished. Furthermore, from real option analysis, the concept of formulating and creating extra flexibility in terms of options was retrieved. This was formulated in one of the strategies, in which a flexibility premium was included. It entails higher costs upfront to achieve lower costs for possible future investments.

In Figure 6, the results of two different strategies are plotted. In Figure 6A, a static strategy was followed in which a levee was built for an envisioned lifetime of 100 years, based on a low SLR scenario. In Figure 6B, a more adaptive strategy was followed in which initially dry-flood proofing was applied and when the ATP was reached, a levee was built. For the adaptive strategies, the second action was optimised based on the retrieved knowledge over time. When the strategies were tested for a situation in which the knowledge was not used, it was found that these strategies showed a reduced performance of 6% in terms of NPV. This indicates that when the value of time was not acknowledged, the adaptive strategies were undervalued. Subsequently, the evaluation method was able to show the difference in performance in case of a fully deterministic situation (using no uncertainties) and in case the more SLR scenarios were used. Finally, the performance for the strategies that included a flexibility premium increased when the probability on a high SLR scenario increased.

Discussion

SLR knowledge

In the framework, the assumption was made that the absolute variance of SLR projections remains stable over time. However, recent findings from the IPCC Synthesis Report (March 2023) emphasise the urgency to curb temperature rise. This raises questions about the stability of SLR projections. The currently used assumption is arguable to be conservative and might underestimate the potential impact of future insights. However, this assumption can be easily altered in the evaluation procedures.

Economic appreciation

The CBA used a deterministic discount rate to value future cash flows. The discount rate, considered as a political decision, holds ethical and political implications. Ethically, it shapes the distribution of costs and benefits across generations, with higher rates potentially favouring the present. Politically, divergent

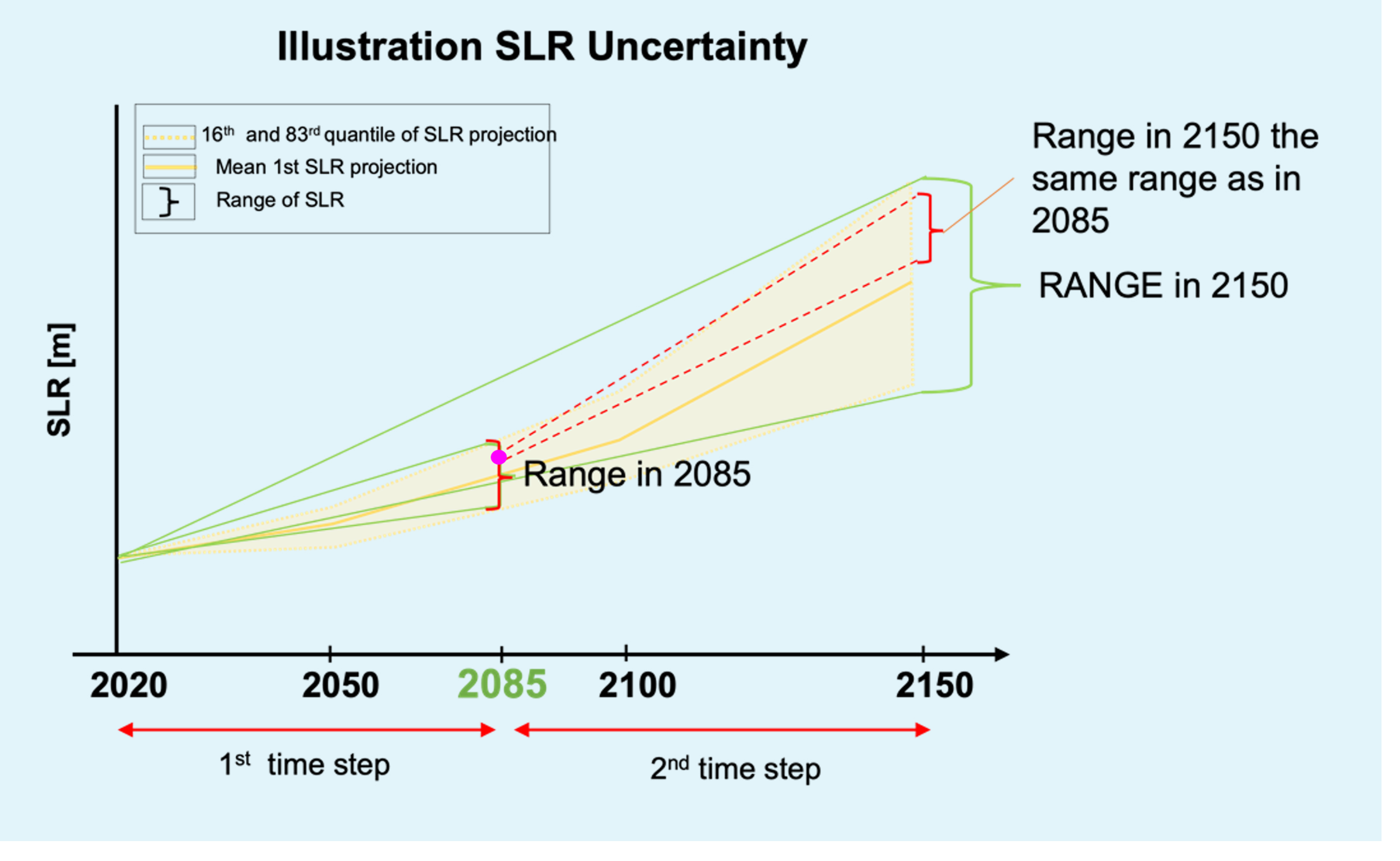


FIGURE 5

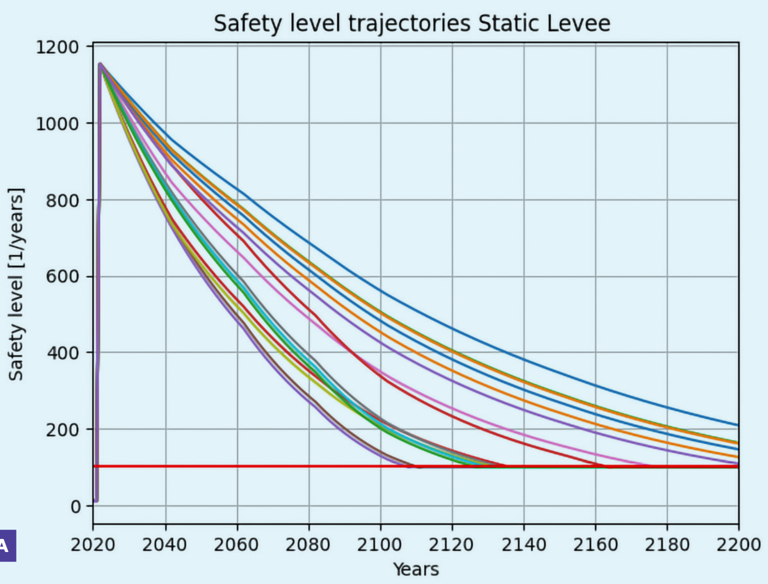
Schematisation of how the value of time influences the SLR uncertainty.

stakeholder views on discount rates reflect varied interests and priorities. An analysis with a 2% discount rate instead of 4%, highlights the significant impact on the performance of adaptive strategies, emphasising the need for thoughtful consideration in aligning discount rates with societal values and long-term goals.

Real case study

While the framework demonstrated functionality in a conceptual case study and sensitivity tests, its true validation lies in application to a real case study. Currently, a relatively simple project area with straight forward measures were evaluated.

Besides, the framework used only direct damages in the CBA. Questions can be raised about the framework's completeness in capturing non-economic factors and potential limitations when applied to more complex case studies.



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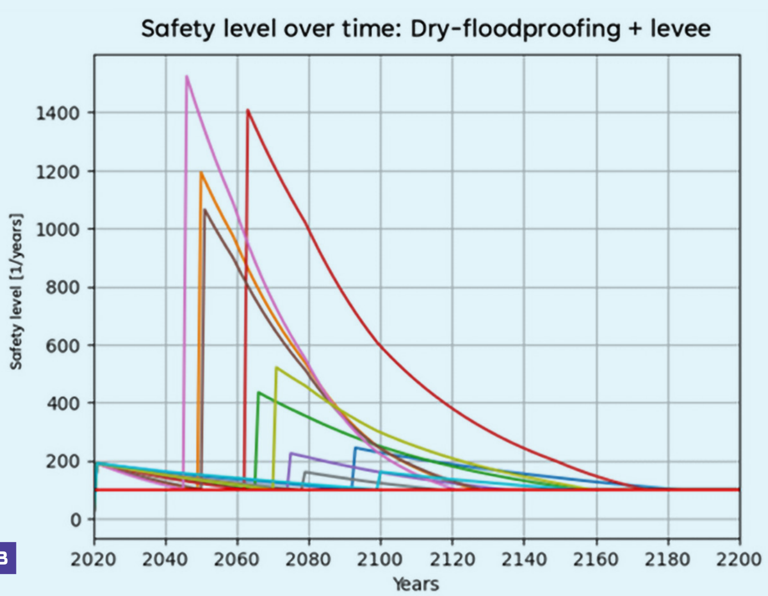

6B

FIGURE 6A & B

Safety level overtime for two strategies. Note only 15 simulations shown.

Conclusions

In this research it was investigated how to incorporate the value of adaptive pathway planning. It was found that an adequate evaluation method should include uncertainties, use diverse evaluation metrics and finally acknowledge the value of time.

The study examined variables in adaptive planning with potential reduced uncertainty over time. Notably, there's no scientific basis for expecting a reduction in uncertainty regarding future sea level rise (SLR) projections. The next two decades are crucial for gaining clarity on potential scenarios, assuming the stability of SLR uncertainty. Economic growth rate and related factors show no conclusive evidence of decreasing uncertainty over time and are highly influenced by local conditions.

The framework incorporates uncertainty by using a Monte Carlo to include all stochastic variables. While certain metrics like the PoL and CV did not provide meaningful insights for the conceptual case study, the value of time was confirmed. Strategies adapting to observed sea level rise performed approximately 6% better. Additionally, the framework succeeded to show the difference in performances between static and adaptive strategies when conditions were altered. Secondly, within the adaptive strategies, the evaluation method also showed the difference in performance for the strategies with a flexibility premium, inspired on the ROA concept.

The developed framework is able to capture the impact of uncertainty and the value of time successfully. Although these features did not yield a significant impact on the results, the framework provides a proper foundation for further studies. When the framework is refined and validated through real case studies, it has the potential to serve as a valuable tool for decision-making. It enables the evaluation of adaptive pathways' performance and supports the justification for either a static and robust strategy or a more flexible adaptive strategy.

Summary

Climate change and its impacts have necessitated a shift from relying solely on mitigation measures to implementing adaptation strategies. The financial requirements for adaptation have increased substantially. The annual projected needs have nearly quadrupled over the past decade and are anticipated to reach significant amounts by 2030 and 2050. Sea level rise is considered a critical threat and allocating financial resources efficiently becomes challenging due to the uncertain nature of SLR. Adaptive pathway planning, which allows for flexible decision-making over time, offers a promising approach to develop flood risk reduction strategies that can adapt to changing circumstances. However, evaluating the effectiveness of adaptive pathways requires accounting for uncertainty, using multiple evaluation metrics and considering the value of time.

To address these requirements, a new framework for evaluating flood risk strategies was established, incorporating Monte Carlo analysis to incorporate uncertainty and evaluation metrics including EAC and POL. A conceptual case study involving seven strategies was conducted to test the framework and sensitivity tests were performed to assess its robustness. The results demonstrated the framework's effectiveness in capturing uncertainty and the value of time, providing a solid foundation for further research.

Future research should focus on refining and validating the framework through real-world and more complex case studies, evaluating the performance of adaptive pathways and incorporating various stochastic variables. Once refined, the framework has the potential to serve as a valuable evaluation tool, enabling the comparison of static and robust strategies against more flexible adaptive strategies, and facilitating decision-making in flood risk management.

Maria Montijn

Maria gained a bachelor's degree in civil engineering from Delft University of Technology (TU Delft) in the Netherlands. She continued her academic journey at TU Delft studying for a master's degree in hydraulic engineering, specialising in flood risk and graduated in June 2023. Maria was honoured with the National Hydraulic Engineering Prize 2023 for the most innovative and valuable master's thesis, in recognition of her achievements.

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OPTIMISING REAL-TIME DREDGE MONITORING SYSTEMS WITH ACOUSTIC SENSORS

Driven by an increasing population, global maritime trade activity is at an all-time high. To keep up with demand, larger vessels and expanded port facilities are being built. Larger vessels, particularly container vessels, often require multiple expansion projects, such as expanding turning basins, widening shipping channels and digging deeper berths. These port expansion projects often require dredging to ensure the upgraded facilities can handle vessels of any size. However, dredging in the maritime industry is continuous, expensive and resource intensive. To meet evolving demands while remaining economically viable, tools that increase dredging efficiency need to be evaluated and incorporated into dredging operations.

Many older dredges are dredging blindly. There are significant costs to dredging without seeing the work area, including contract penalties for under-dredging. There are also costs due to lost production and increased fuel usage when a dredge must be repositioned back to a previous work area to remove material that was missed (or that slipped back into the dredged area).

Over-dredging is another unfortunate cost of dredging blindly. The client is not responsible for paying for excess material removed by the dredging contractor. The contractor pays for both labour hours and fuel – money which cannot be recovered from the client.

There can even be financial penalties if the dredge removes material placed as an environmental cap over contaminated sediments. Should the dredge cause a slope failure, the cost to fix it are borne by the dredge contractor, not the client. These costs are mitigated or even eliminated when using optimised dredging methods such as real-time dredge monitoring.

Optimised dredging methods

Most dredging contractors conduct periodic surveys to confirm performance to the design horizon. Typically, these surveys are performed by hydrographers using a manned survey vessel. But hydrographic surveys require moving the dredge away from the worked site. If the survey reveals under-dredging or missed material, the dredge must be repositioned and put back to work. This inefficiency results in schedule delays, excess fuel use and emissions, and more labour time.

With the advent of positioning sensors and three-dimensional engineering software, vendors have begun to market predictive visualisation software to dredge contractors. In addition, some larger contractors have realised the negative impact on their operating profits from dredging blindly. They have subsequently developed their own in-house software or are even using old dredge-monitoring software.

These visualisation software programmes generally use algorithms to determine the correct position of the loosening tool. They then calculate the theoretical amount of material removed during operations and show the removed material on a digital terrain map derived from a baseline survey.

However, in many cases, these assumptions are not accurate in the real world. Clamshell or backhoe buckets are not 100% full each load. Up to 20% of material loosened by cutter-suction dredges can settle back into the worked area (Ramsdell, 2022). Therefore, an inclinometer on the ladder will not provide an accurate picture of material removed from the digital terrain map. These software packages are an improvement over dredging blindly but are still suboptimal.

Real-time monitoring method

Real-time monitoring, using acoustic sensors installed on the dredge, provides the dredge operator with actual sonar soundings of the work site. These soundings are obtained either during the operation or during brief halts in the operation – without having to reposition the dredge.

> **Real-time monitoring can establish the baseline conditions, then continuously record sediment loading in the water column during dredging.**

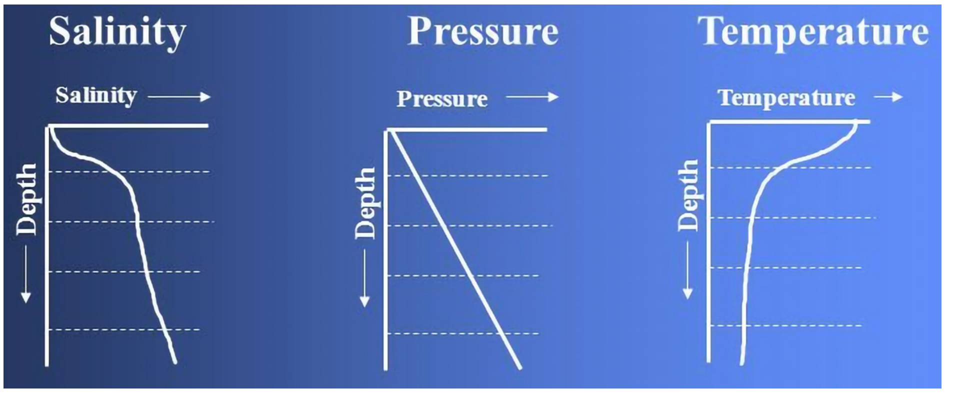

FIGURE 1

Variable effects of salinity, pressure and temperature on sound speed in water.

Typically, the sonar systems used for real-time monitoring use sound-velocity sensors to increase the accuracy of the sonar soundings. These sensors correct for variations in speed of sound in water. These corrections are important because several localised environmental factors affect the accuracy of acoustic soundings. These factors include surface temperature variations during the day, temperature variations in the water column and salinity variations due to salt water/ freshwater mixing, particularly in estuaries with tidal mixing and substantial rainfall.

Real-time Kinematic (RTK) positioning equipment also ensures the accuracy of the sonar soundings, which are then used to modify the digital terrain map. Motion reference units correct for pitch, heave, roll, and yaw of the dredge, as vessel movement can impact the accuracy of soundings.

Perhaps the most significant impact on acoustic instruments during dredging is turbidity, both background turbidity and turbidity caused by the dredging operation itself. The type of sediment on the bottom is related to turbidity. Fluid mud (also referred to as cohesive sediment) can obscure the true seabed.

When operating on the seabed with fluid mud, higher sonar frequencies give better acoustic accuracy, while lower frequencies allow better penetration of fluid mud. High turbidity or fluid mud attenuate sonar energy and the reflected sound wave of higher frequencies may not indicate the true seabed. Lower-frequency sonars will penetrate fluid mud, but the data will be coarser with less resolution.

Mitigating turbidity impacts during dredging requires managing suspended solids released at site or stopping solids from entering sensitive areas. At present, monitoring of resuspended solids in the water column arising from dredging operations is performed by spot sampling over time. However, real-time monitoring can establish the baseline conditions prior to start of dredging, then continuously record sediment loading in the water column during dredging.

For turbidity, the key parameters to track are the size of sediment plume in the water column, the density and, if possible, the fractions of particles in the sediment plume. The direction and rate of dissipation of the sediment plume should also be tracked. Real-time monitoring of turbidity can be used to track these key parameters and enable timely management of suspended solids before resettlement sets the dredging operation back, or worse causes damage to sensitive environments.

Operator skill levels also impact efficiency. All industries, including dredge contractors, face a declining pool of candidates entering the workforce. There are more technical job vacancies than people to fill them. Any tool that increases efficiency for new employees who do not have years of practical experience is an asset.

Thus, effective training and tools increase production. It is possible for young unexperienced employees to learn faster with a real-time monitoring system, because they see what they are doing and how much progress they are making. They can literally

Real-time monitoring also results in safer operation by reducing risk of slip-back and slope failure.

see their efficiency with one view in the dredge-monitoring software (see Figure 2 for an example).

In addition, with fewer workers, contractors struggle to perform the same (or more) work to the expected quality standards. As a result, innovators are looking to reduce the number of workers required to do the job. By automating some dredging functions, such as vessel repositioning and anchor management, workers can instead focus on tasks requiring human judgement and intervention.

In the future, autonomous dredging may become practical, akin to autonomous ferry operation and container-vessel trials currently under way. Autonomous dredging would require skilled operators who are comfortable with the technology involved in offsite remote real-time dredge monitoring.

Benefits of real-time dredge monitoring

There are several benefits to monitoring dredges in real-time. These benefits include increased operator confidence, lower hydrographic-survey costs, accurate records of work performed, increased production, safer operation, reduced greenhouse gas emissions and improved fleet-asset utilisation. Operators gain increased confidence through the use of the visualisation software as they can see, based on actual soundings, what work has been completed.

If the dredge is outfitted with accurate sonars, sound-velocity and motion sensors, as well as accurate positioning equipment to fix and orient the dredge, daily surveys can be eliminated. Not only are project costs lowered, but the project manager also has accurate records of work performed. This record may prove useful for verifying performance to the client, even if local currents carry sediments back into the dredging area later.

Real-time dredge monitoring reduces the frequency of repositioning the dredge for rework. If the operator knows the area has been dredged to design by actual soundings, the operator can advance the dredge to the next area. This avoids having to stand by for a survey and if the survey results are not good, having to rework the previous position.

Real-time monitoring also results in safer operation by reducing risk of slip-back and slope failure (North, 2022). Safety is of particular concern at port-deepening projects where the slope under existing berth decks was designed for shallower depths, or when shipping channels are being widened (Stainer et al., 2019).

Efficient dredging produces lower greenhouse gas emissions from optimised diesel engine run-time. For the foreseeable future, until alternative fuels become commonplace, dredges will operate on diesel. Efficient dredging without rework reduces both excess emissions and fuel costs.

When a dredging contract is executed on time and on budget, without extended time on site for rework, the contractor can commit that dredge to follow-on contracts. Knowing the asset can be deployed to a new project on time is vital when contractors have their reputation on the line.

Acoustic sensor options

A key piece of equipment in real-time dredge monitoring is the acoustic sensor. Four types of acoustic sensors can be used to obtain soundings: single-beam echo sounders, split-beam echo sounders, dual-axis sonars and multibeam echo sounders. Each have their own advantages and disadvantages.

Single-beam echo sounders

Single-beam echo sounders are low-cost sonars, available in wide-beam or narrow-beam versions. However, they produce downward soundings only. They do not provide area coverage, merely point soundings. To be of value to the operator, multiple sensors must be installed on a dredge to get sufficient data points of the seabed. Thus, system cost scales with the number of sensors employed.

In addition, single-beam echo sounders do not cover the worked area until the dredge has moved forward to the worked area. As one operator commented, they only know what they dredged four hours later and then they must still reposition the dredge and do the rework.

Split-beam echo sounders

Whereas single-beam echo sounders provide no information on target location, split-beam echo sounders use multiple transducers to cover a larger area and calculate target location in three dimensions. Split-beam echo sounders can therefore detect solids throughout the water column, quantify the amount and density of solids, and quantify what the material is.

With this functionality, the potential for split-beam echo sounders in real-time turbidity monitoring is promising. Split-beam echo sounders have already been successfully used to identify targets in the water column in other similar applications. For example, by ocean scientists to study biomass and in the Gulf of Mexico to quantify hydrocarbon seeps.

The use of split-beam echo sounders for sediment detection is still being studied, but proof of concept is not far behind. Kongsberg's Frank Reier Knudsen conducted a preliminary feasibility study to determine whether split-beam echo sounders can detect sediments in the water column, with good results.

Furthermore, preliminary controlled environment studies in an outdoor tank by Deltares and Ifremer indicate that split-beam echo sounders have potential to show sediment plume density, shape and rate of dispersion. Preliminary field work by Boskalis shows that a split-beam echo sounder can track and quantify resuspended sediments in an open water column, even in the presence of background sediments (Mech, 2023).

As mentioned above, the type of bottom and amount of turbidity may determine whether you pick a high- or low-frequency sonar. Split-beam echo sounders sweep through the broad band transmit frequency and by using different bands, the back-scatter amplitude of the returned signal allows users to quantify the amount and density of solids, and to quantify what the material is.

If mitigating turbidity is a major concern, split-beam echo sounders may be worth considering when putting together a real-time monitoring system. Understanding how much (and where) sediment is being transported and

The benefit of all these acoustic-sensor options is that they reduce the amount of rework required.

resettled is important, especially if there is concern of industrial pollutants or contaminants being transported downstream.

Dual-axis sonars

A dual-axis sonar is comprised of a single narrow-beam transducer mounted on a precise two-axis rotator. The transducer is safely housed inside an oil-filled acoustically transparent dome, which isolates the transducer from the environment. A dual-axis sonar produces point-cloud data similar to a multibeam sonar. These soundings can be integrated into post-processing software, such as QPS Qinsy, Hypack, EIVA or Sonarwiz. The operator can select the best area coverage for a particular dredging site by adjusting the step pitch between pings to gain a fast, coarse measurement or a fine measurement over more time.

For example, a pitch of 7 degrees between pings provides 26 soundings in a 180-degree arc, while a pitch of 0.2 degrees provides 900 soundings in that same arc. Crucially, these soundings cover the area around the loosening tool, allowing for rework before the dredge is moved forward to advance the operation.

It is pertinent that the ASCE Manual of Practice 156 (Navigation Channel Sedimentation Solutions) speaks to the importance of field observations when developing models of sediment behaviour in shipping channels. Dual-axis sonars are emerging as a useful tool for collecting these field observations. Of particular importance is slope stability during and after deepening dredging for acceptance of larger vessels at existing berths.

Dual-axis sonars are steadily replacing single-beam echo sounders as the acoustic sensor of choice in real-time monitoring solutions. This fact is reflected in the fact that several of the case studies presented here use a dual-axis sonar.

Multibeam sonars

Multibeam sonars are available in imaging and point-cloud versions. Some multibeam sonars perform both functions in same sonar head. For dredge monitoring and visualisation, users should select point-cloud function sonars.

The main advantage of multibeam technology is speed. Multibeam sonars can provide soundings rapidly in a single sweep of the work site. Similar to dual-axis sonars, the soundings can be integrated into post-processing software, such as QPS Qinsy, Hypack, EIVA or Sonarwiz. However, processing the soundings causes a delay to visualising work progress.

Multibeam systems require a single or dual-axis rotator to sweep the beams over the work area. However, more moving parts means more potential points of failure and maintenance to address seal wear. They can be more susceptible to damage depending on the dredge type. Therefore, extra precautions must be taken to protect these systems from transducer damage due to solids in the water column.

Good-better-best

One framework to consider when deciding what level of instrumentation is appropriate for dredge operations is Good-Better-Best. These acoustic sensors run on a price-performance continuum where single-beam echo sounders are most economical, split-beam and dual-axis sonars are more expensive, and multibeam systems are most expensive. As the systems increase in performance and capability, the cost of ownership also increases due to maintenance and spares.

Regardless of which system is used, the benefit of all these acoustic-sensor options is that they reduce the amount of rework required by providing the operator with actual dredging performance, rather than imputed performance derived from inaccurate assumptions.

Case study 1: Cutter-suction dredge for maintenance dredging

In this case study, the sonar is mounted on the front of the dredge, so the beam pattern covers the area swept by the dredge as it pivots on its spud. The operator has a touchscreen in the cabin, which is used to run the sonar and see progress of the removed material to the design horizon.

Operators have found that relying only on the inclinometer readings to show dredging progress almost always showed more material dredged than was actually removed. As mentioned above, up to 20% of solids disturbed by the loosening tool resettle back onto the seabed. This resettlement can be clearly seen in the side elevation view shown in Figure 2.

In Figure 2, the 3D view at the top and 2D-elevation view at the bottom show the dredge and material removed from the

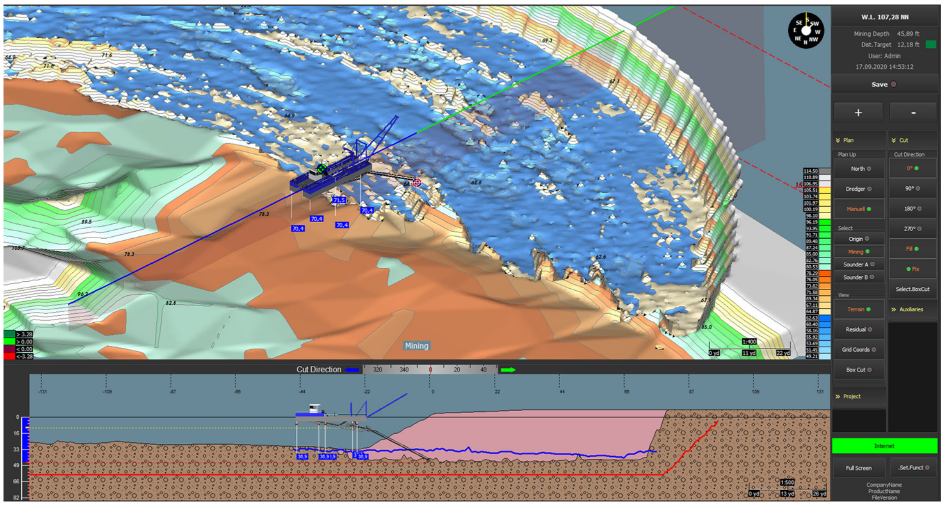

FIGURE 2

Operator's view of a touchscreen monitor installed on a cutter-suction dredge.

This elimination of redundant work contributes directly to the dredge contractor's profitability and schedule performance.

FIGURE 3

Backhoe dredge operating off a pontoon on a German canal construction project.

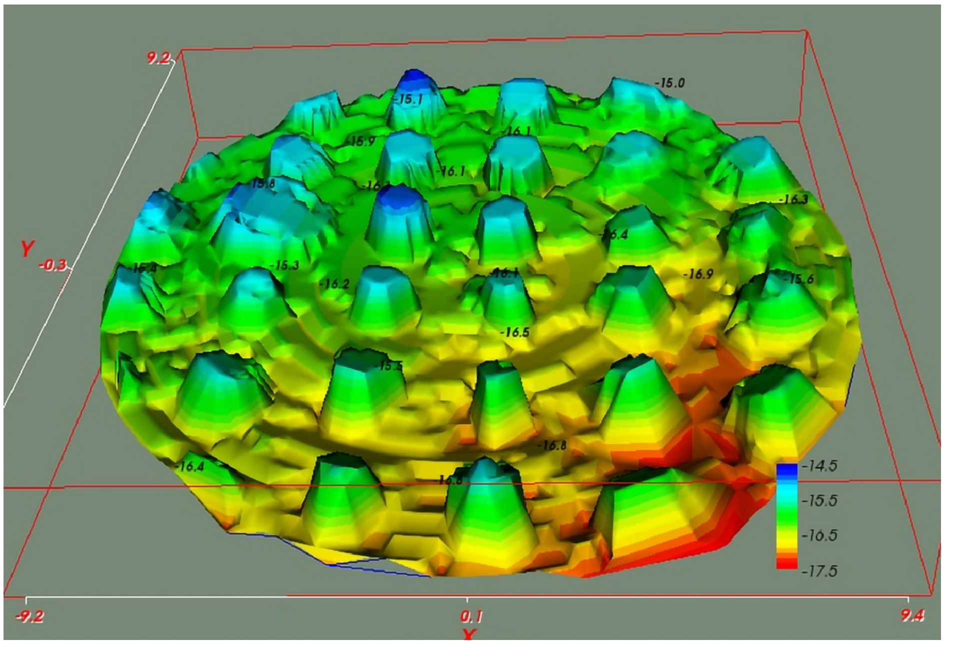

FIGURE 4

Screenshot of operator's view.

baseline digital terrain map. The 2D-elevation view at the bottom shows the design horizon as a red line and the theoretical removed material based on ladder inclinometer in pink. The blue line shows the resettled sediments disturbed by the cutting tool from soundings.

Soundings can be taken during the dredging process, either when the dredging operation is stopped for anchor repositioning or at shift change. Each dredging operator needs to determine what method best suits their workflow. However, when the dredge is stationary, turbidity in the work area reduces as disturbed solids settle back to the seabed or are carried away by the current.

The sonar is set to work and the sonar soundings are processed in the visualisation software, showing dredged material removed from the baseline digital terrain map. This rapid validation of dredging progress, performed before the dredge is moved, eliminates the legacy method of moving the dredge, standing by for a survey vessel to map the worked area, processing the data and then repositioning the dredge for rework. This elimination of redundant work contributes directly to the dredge contractor's profitability and schedule performance.

Case study 2: Backhoe dredge for precision/surgical dredging on a capital project

As in case study 1, the sonar is mounted on the front of the dredge platform (Figure 3) where the sonar beam pattern can cover the work area.

The dredge-monitoring system in this case is comprised of a dual-axis sonar (mounted on a pole on the pontoon – see front left of photo in Figure 3), and a monitor inside the operator's console. The dual-axis sonar covers the work area dredged by the backhoe.

Some dredge-visualisation software uses inputs from position sensors located on the backhoe. The software assumes that each bucket scoop is 100% full. The visualisation software then removes material from the baseline digital terrain map per the position sensor data.

However, just as disturbed material in rotating cutter-suction dredges is not removed from the site, but resettles on the seabed, these assumptions mean that physical survey often shows the area is under-dredged and rework is required. Real-time dredge monitoring allows for surgical dredging when used in conjunction with positioning sensors, as shown by the example in Figure 4.

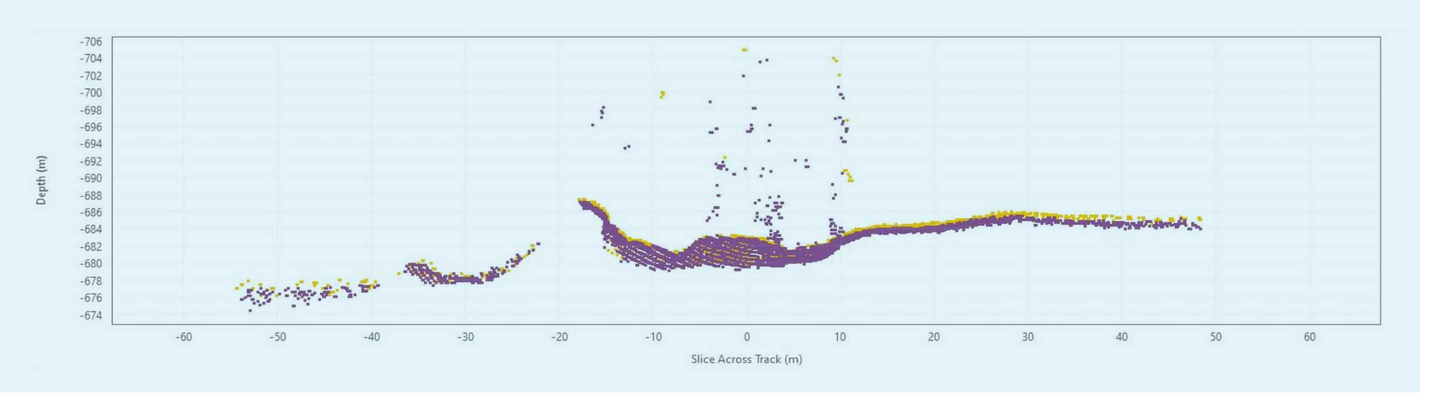

FIGURE 5

Side elevation of clamshell dredge operation.

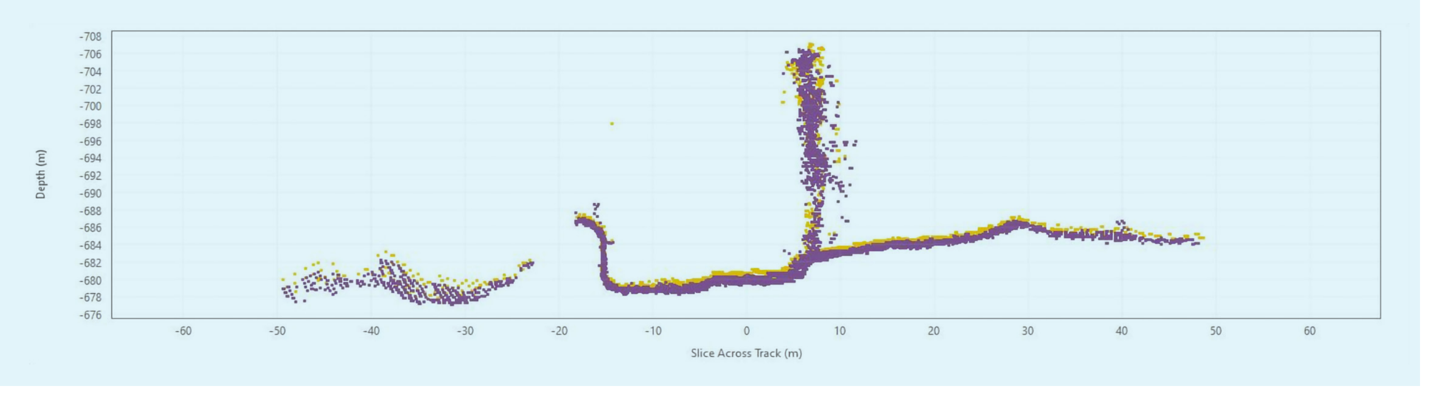

FIGURE 6

Side elevation of clamshell dredge after work progress.

The point-cloud data provided by the dual-axis sonar provides the operator with the ability to surgically remove material where desired and leave material undisturbed when required for project construction to be successful. The operator can then touch up areas requiring removal before the pontoon is advanced further up the canal.

This dredging operation in a German canal required undisturbed areas to remain as anchor points to secure a concrete lining. The dredge operator was able to accurately position and remove material, leaving each pillar of approximately three metres on the canal bed. Efficiencies and accuracy combine to ensure quality work while performing on schedule and to budget.

Case study 3: Clamshell dredge during maintenance dredging

In this case study, silt was dredged from a dam reservoir. However, the dredging operation had to be conducted without causing damage to a concrete wall in the bottom of the reservoir. Precise operation by the dredge operator was required. The operator benefitted from being able to see progress via the dredge-visualisation software using actual soundings. Figures 4 and 5 show two elevations of dredging progress.

In Figure 5, the operation is in its beginning stage. Note the silt sloped along the concrete wall, which is the high point to left of work area. Suspended solids are seen in the water column (caused by the clamshell lifting to the surface) and disturbed solids are shown as a purple pile in the centre of the work area.

In Figure 6, material removal in the reservoir has progressed and the face of the concrete wall is now clearly visible. Note the heavy quantity of suspended solids in the water column (from sediment falling out of the clamshell as it lifts). If not using sonar, a theoretical assumption of 100% fill of the clamshell would have incorrect.

Note that the sonar soundings reflect off suspended solids at various points in the water column from the seabed to the surface. This noise can be filtered out so that the operator is presented with data only in the dredged area, as seen in Figure 7.

Figure 7 shows a screenshot of dual-axis sonar data on the operator's monitor in the dredge. The software applies filters to remove backscatter from suspended solids in the water column. The face of the concrete wall is clearly visible, giving the operator confidence in dredging with minimal damage to this structure or the dredge.

Again, as noted previously, if the dredge-visualisation software relies on positioning data only and assumes 100% material removed per bucket load, performance must be proved by moving the dredge, running a survey vessel over the work site and repositioning the dredge to perform rework clean-up.

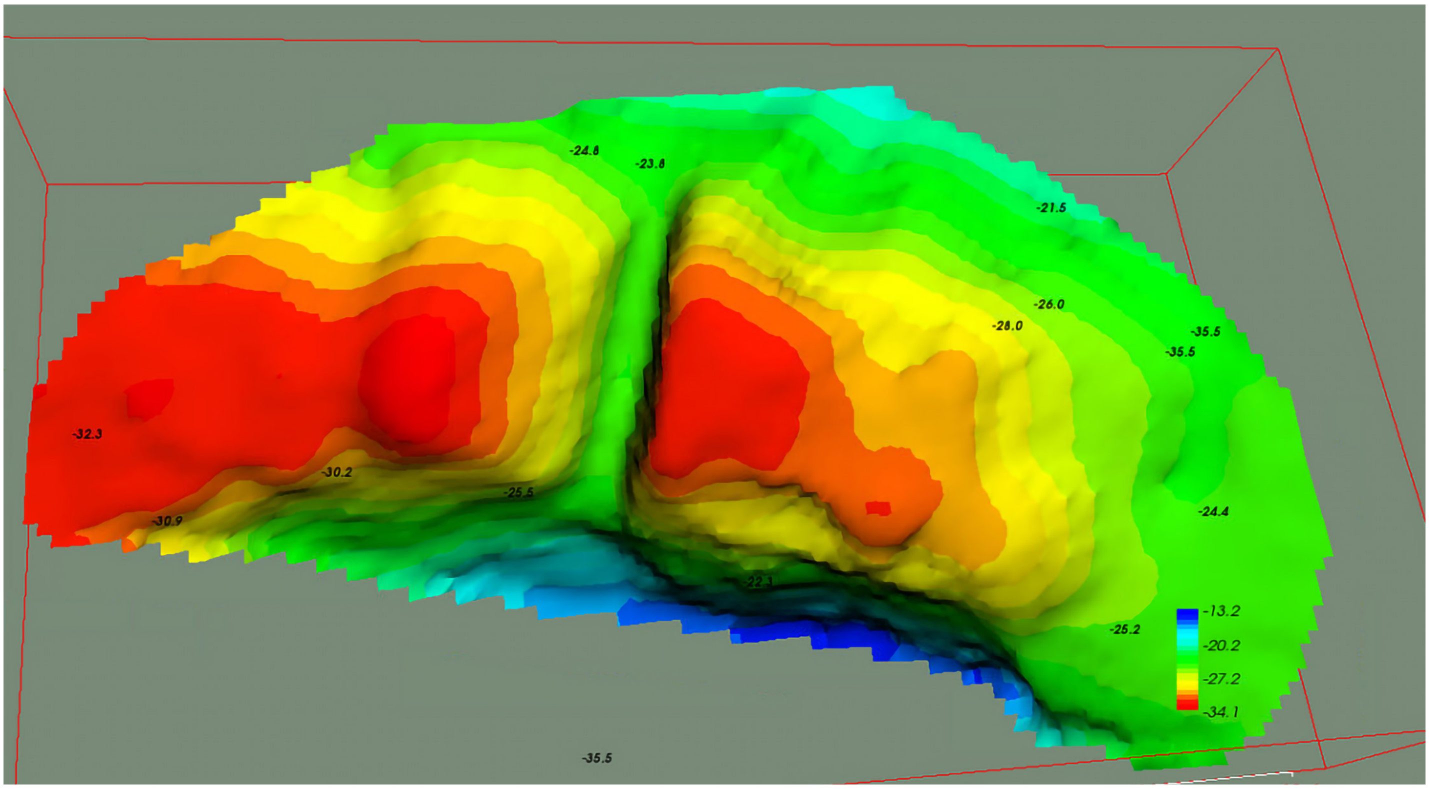

FIGURE 7

Plan view of reservoir dredging project.

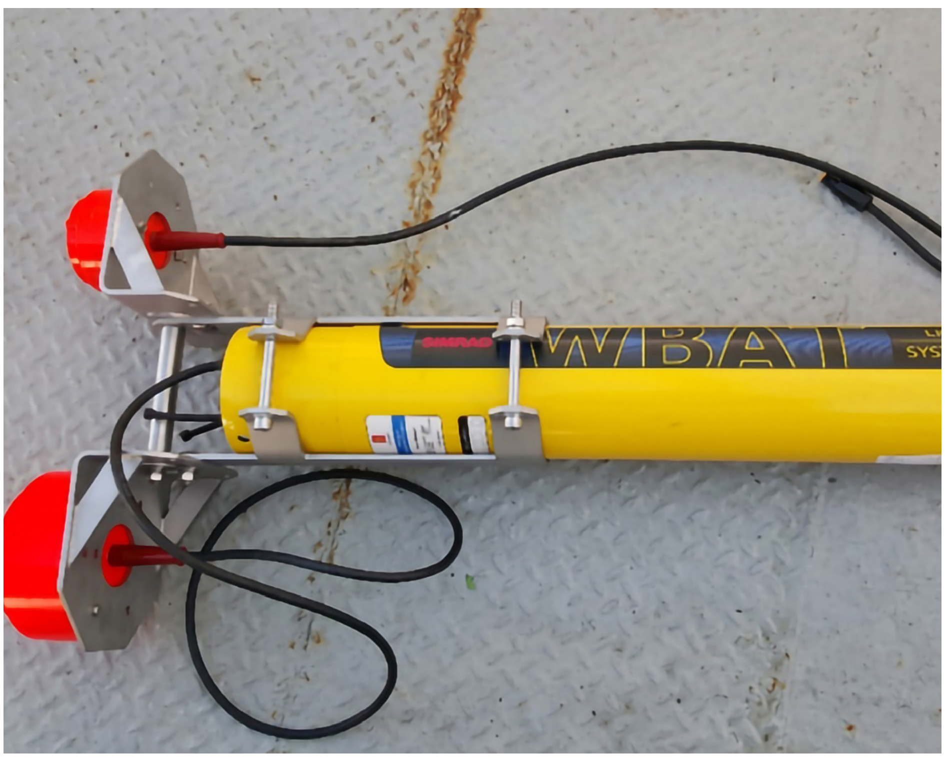

FIGURE 8

Wide-band transducer.

Case study 4: Visualising solids in the water column with a split-beam echo sounder

Boskalis has done preliminary field work using a split-beam echo sounder in open water. The purpose of their study was to visualise solids in the water column and to collect data for further analysis. The set-up consisted of a wide-band transducer pole mounted over the side of a small survey vessel (Figure 8).

This vessel then ran multiple passes crossways, behind the path of a water-injection dredge operating at the Port of Rotterdam. Rotterdam has significant amounts of fluid mud. This has the potential to cause significant background sediment noise due to the number of large super container vessels (18,000 TEU and up) and large tugs to manoeuvre them in the port.

Figure 9 shows the survey vessel track behind the water-injection dredge. The range of the echo sounder was set to 30 metres. You can see the heat map of the resuspended sediment at the lower edge where the survey vessel was just behind the dredge. You can also see how the resuspended sediment drifts left of the dredge's track over time due to local currents.

Figure 10 shows the water column data as the survey vessel crosses from side to side of the channel, across the dredge's track. You can see how each time it crosses the track the resuspended solids occur through the entire depth of the water column. The data shows density and thickness of the plume.

It should be noted that while this field work is promising, more detailed study needs to be done before this can be considered proof of concept. It is important to emphasise that this solution generates real-time remote measurements and makes 3D visualisations possible.

Conclusions

Installing acoustic sensors on a dredge provides the operator with a real-time monitoring method that is far more efficient than dredging blindly. Real-time dredge monitoring brings tangible benefits to operators of cutter-suction dredges, clamshell dredges and mechanical backhoe dredges.

Although single-beam, split-beam, dual-axis and multibeam sonar systems have both advantages and disadvantages, the benefits of integrating it into dredge operations is clear. Real-time dredge monitoring improves operator economics and safety by giving the dredge operator situational awareness, including missed material, slip-back and potential slope failure.

Investment options range from the lowest cost option – single-beam echo sounders – to the most expensive multibeam systems. Before making an informed investment decision, contractors need to trade off the costs and benefits of each system, while considering maintenance and replacement costs for damaged equipment.

Operators should be mindful of local conditions that may impact the accuracy of soundings, such as variations in water temperature and salinity during operations. For the best results, they may need to adjust sonar software parameters and make sure that sound-velocity sensors, motion reference units, and Real-time Kinematic positioning (RTK) are being properly used. Operators must also consider the trade-offs between sonar frequency and data accuracy from soundings, which are impacted by turbidity and fluid mud (cohesive sediment) in the water column.

Dredging operations can potentially impact water quality and affect ecosystems, due to increased turbidity caused by sediment resuspension or contaminant mobilisation and transport. Sediment can also enter the water column when the dredge does not fully capture the dredged material. The dredge itself can disturb sediment, causing it to resuspend in the water column. For these reasons, real-time monitoring of resuspended sediment is also of particular concern.

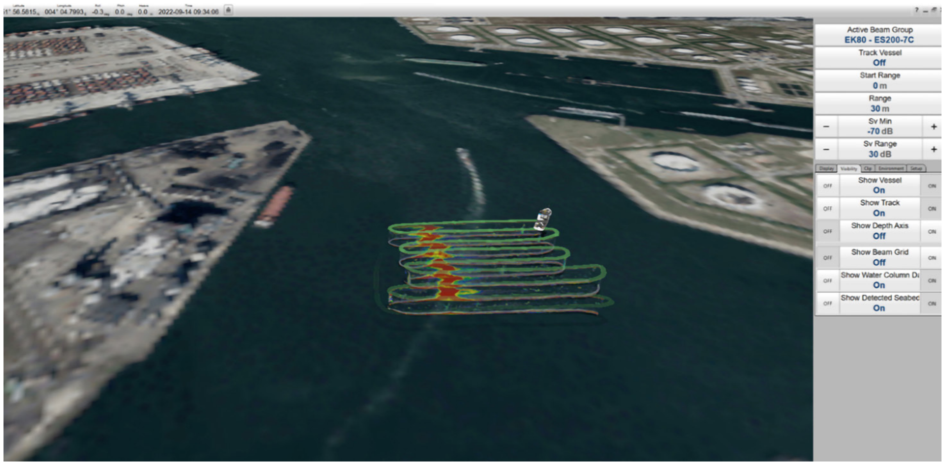

FIGURE 9

Drift of resuspended sediment to port of track behind a water injection dredge.

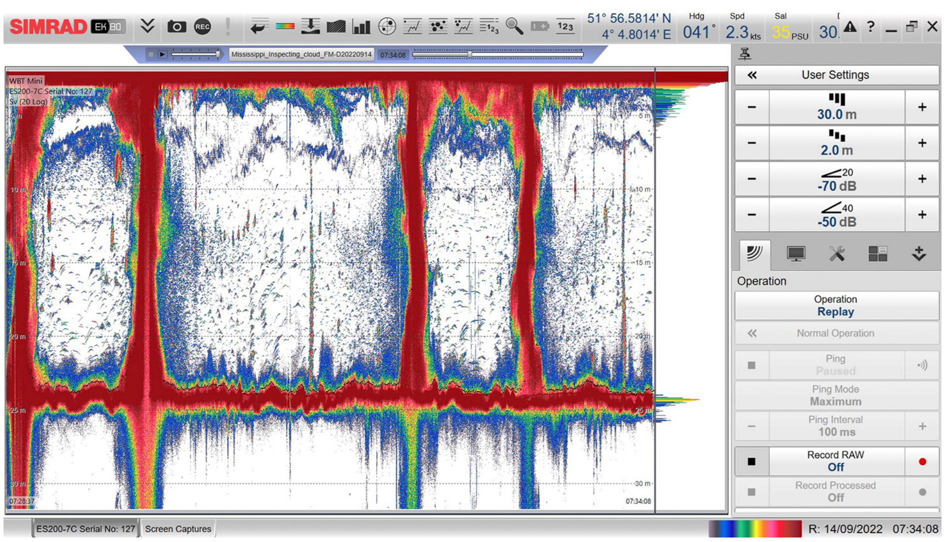

FIGURE 10

Resuspended solids in water column as sensor crosses track of water injection dredge.

Summary

This article discusses the optimisation of real-time dredge monitoring systems using acoustic sensors in response to the growing demand for maritime trade and the expansion of port facilities. Larger vessels necessitate dredging to accommodate their size, making the process continuous, expensive, and resource intensive. Blind dredging, without real-time feedback, incurs costs such as contract penalties, lost production and increased fuel usage.

The traditional method involves periodic surveys performed by hydrographers using manned survey vessels, causing inefficiencies and delays. This article advocates for the adoption of real-time monitoring methods, specifically using acoustic sensors installed on dredges. These sensors provide actual sonar soundings of the worksite without repositioning the dredge, allowing for immediate adjustments.

The benefits of real-time dredge monitoring include increased operator confidence, lower survey costs, accurate records of work performed, enhanced production, safer operations, reduced emissions and improved fleet asset utilisation. This article presents case studies highlighting the application of acoustic sensors on cutter-suction dredges, backhoe dredges, and clamshell dredges, demonstrating their effectiveness in improving efficiency, accuracy and safety.

Different types of acoustic sensors, such as single-beam echo sounders, split-beam echo sounders, dual-axis sonars and multibeam sonars, are discussed, each with its advantages and disadvantages. The choice depends on factors like cost, performance and maintenance considerations. This article concludes by emphasising the importance of real-time monitoring in mitigating the environmental impact of dredging operations and enhancing overall operational efficiency.

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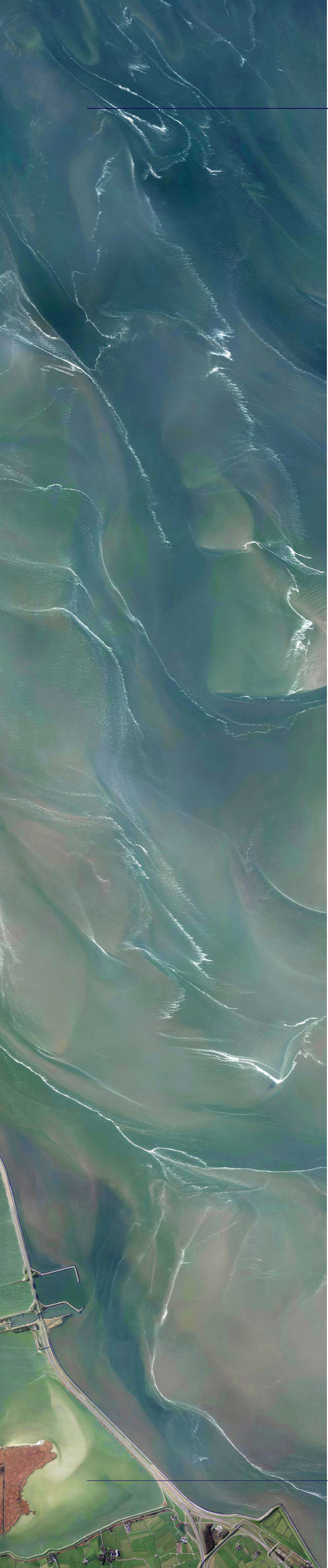


DEALING WITH COMPUTATIONAL INNOVATION IN DYKE REINFORCEMENT PROJECTS

Since 2023, the Dutch government no longer prescribes which calculation models must be used in the assessment of dykes. The water boards themselves must determine which method they use to calculate the probability of flooding. This enables the development of calculation innovations. Following various dyke assessments, the largest safety risk is caused by the failure modes of slope stability and piping, therefore substantial investment is being made to better understand these failure modes. In our research, we found a way to deal with computational innovation in dyke reinforcement projects by applying specific innovations and looking at their general implementation.

This study aims to investigate, for each project, the potential for application of two computational innovations still under development, namely shear strength of initially unsaturated soil for slope stability and bursting for piping. This investigation will show which components play a role in whether or not to include this computational innovation. The information is then incorporated into an assessment framework. The assessment framework aims to advise the water boards whether or not to apply these computational innovations in dyke reinforcement projects. Existing schematisations and semi-probabilistic analyses were used for the calculations. The main question for this study is, how can a trade-off be made for applying the computational innovations bursting and shear strength of initially unsaturated soil within dyke reinforcement projects?

Our study started with background research on the failure mode and computational innovations by reviewing the literature of research reports by the Dutch Water Board (Rijkswaterstaat), Deltares, the Flood Protection Programme (Hoogwaterbeschermingsprogramma

For the SAFE project, great returns were achieved at two of the ten locations.

(HWBP)), as well as interviews with experts in the field. Data was then obtained from contact with water boards about the specific projects, with which the application of the computational innovation to the project is calculated and a gap analysis is done. Based on these results and conversations with industry experts, an assessment framework was drawn up, substantiating the choice of whether or not to include the computational innovation. After the background research was completed, we started focussing on the computational innovations.

At first, we will take a look at the shear strength of initially unsaturated soil for slope stability. For the initial unsaturated zone, the computational innovation was applied to two projects in the Netherlands: Sprok-Sterreschans-Heteren (SSH) and Pannerdense Waard-Westervoort (Pan-Wes). From this application, it can be concluded that for both projects the computational innovation leads to a large reduction of the task by using a Su table, which determines the shear strength of soil with undrained behaviour. SSH went from 77% approved dyke sections to 91%, with three additional dyke sections. In Pan-Wes, the sections were rejected at first but after applying the computational innovations 90% were approved.

These results are considered significant but cannot yet be applied in practice because there are many uncertainties about the structure and behaviour of the dyke. Moreover, knowledge about the computational innovation is still developing in practice, which makes water boards cautious. A conservative assumption or more research is necessary, but the potential is visible.

For the computational innovation of bursting for piping, the computational innovation was applied to two projects, namely Mastenbroek-IJssel (MAIJ) and Streefkerk-Ameide-Fort Everdingen (SAFE). From this application, it can be concluded that for the MAIJ project, there is no difference between applying and not applying the computational innovation. No significant results were obtained here. However, for the SAFE project, great returns were achieved at two of the ten locations. At one of these two locations, there is certainly no more safety risk, at the other location there may be no safety risk. This means that the computational innovation produces significant results for the SAFE project because here parts of the task are dropped. These results cannot yet be applied in practice because knowledge about the computational innovation is not yet at a far enough stage.

Results

Our studies have produced results that address the probability of success for two specific computing innovations. From these results, discussions were held on what considerations should be made to substantiate the decision whether or not to include computational innovation within a project. From these conversations with experts, it can be concluded that the expected yield from the application of computational innovations is central to the choice of whether or not to include it.

On the other hand, the knowledge and information available about the innovation and the dyke are important. Little information results in high research costs and/or long waiting times, making the higher investment costs in the innovation. This assessment framework incorporates this acquired knowledge. Water boards must use the results of this assessment framework to enter into discussions (with the HWBP, for example) about which choice they will make for including the computational innovations. If, for example, the weighing framework shows that the computational innovation should be included, but they do not want to do so, they must be able to substantiate this and otherwise apply it.

By offering the weighting framework as an aid to water boards, they are provided with tools to support the choice of whether or not to include computational innovations in a project. This gives a water board or the HWBP guidelines for identifying promising projects. This reduces the chance of wrongly not including the computational innovations resulting in a chance of over-dimensioning the dyke. The social values associated with this, such as sustainability, cost savings (of tax money) and effective use of space, are in addition to this trade-off framework.

The levees are dimensioned strong enough through this flowchart because the amount of knowledge and information is included in the trade-off framework. This tests the certainty of the computational innovation tests so that the levee will meet the 2050 standard. Moreover, there is such climate action attached to the product, because over-dimensioning is prevented.

Explanation of weighting framework

The weighting framework (as shown in Figure 1) consists of four steps and is intended as an aid to the discussion about whether or not to include the computing innovation. This is often done during preliminary exploration but can also be done later in the process, because it

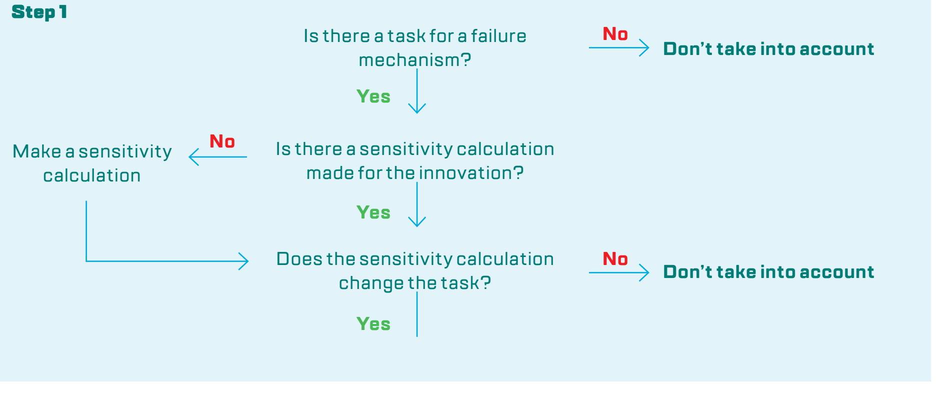
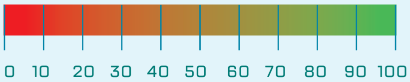


FIGURE 1

The weighting framework.

Potential

Cost and sustainability
Costs are saved by changing the task. Sustainability correlates with this change in the task, because sustainable options are predominantly cheaper but less robust.

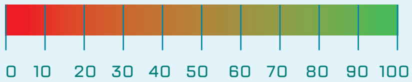


0 Task does not change
30 Optimisation measure
60 Change of measure
100 Task expired

Environment
Does the necessary measure damage the environment? If the computing innovation ensures that this is removed, there is greater motivation to include it.
Bonus score: 100

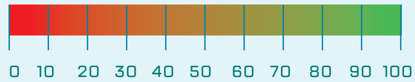
Knowledge and information

Subsurface and dyke material
Amount of information



0 Few
25 Moderate/ mediocre
50 reasonable
75 High
100 Complete

Innovation
Knowledge development stage



0 Just an idea - TRL 1
25 Hypothesis written - TRL 2
50 Laboratory and/or scale tests done and consistent with hypothesis - TRL 4
75 Practical test done and consistent with hypothesis - TRL 6
100 Innovation report delivered and validated - TRL 9

FIGURE 2

Grading scheme.

still seems promising due to possible changes in the project.

Step 1
The project determines whether it is possible to apply the computational innovation. This is done by first checking whether there is a task for the failure mechanism for which the computational innovation is intended. Then a sensitivity calculation is performed to see if the task changes when it is assumed that the computational innovation is fully functional.

Step 2
A score is given for the two components of potential and knowledge and information. This is done by filling in different part scores and based on that an average score is calculated.

For potency, there are two criteria. These are the criteria cost and sustainability, and environment. The criterion of cost and sustainability is based on the degree of change in the task. Cost and sustainability are linked here because they have a mutual correlation. When the project becomes cheaper due to the change in task, it is always also a more sustainable solution when it comes to levees. This is because cheaper often means less use of materials. The criterion environment is only included as a bonus criterion. This means that it can only raise the score and not lower it. This is done because this is about the extra motivation to apply computational innovations when the required measure damages the environment.

For knowledge and information, there are also two criteria. These are subsoil and dyke material, and computational innovation. The subsoil and dyke material criterion deals with the amount of information that the water board has about the dyke. The score for this criterion can be increased by the water board itself by doing more research on the dyke. The criterion of computational innovation is about the stage at which knowledge about computational innovation is now in. The stage is defined in Technology Readiness Levels (TRL). This is a widely accepted way of defining at what stage a computational innovation.

Using the results of Step 2, in which the total score of the potential and the knowledge and information are determined, a colour is assigned within a system of axes (see Figure 2). The table contains an explanation of how the line was determined.

Certainty: 0 Potency: 75 – From this limit, it becomes relevant to invest in more research, to wait for knowledge or to choose a conservative variant, because there is enough potential that can bear the risk of the large investment due to low certainty.

Certainty: 50 Potency: 30 – From this limit, it becomes relevant to invest in more research, to wait for knowledge or to choose a conservative variant, because there is a good indication by moderate certainty that the sensitivity calculation is correct and the potency covers the risk.

Certainty: 75 Potency: 100 – From this limit, it is stated that the computational innovation can be included because the potency is so high and the certainty is such that the remaining risk can be taken.

Certainty: 80 Potency: 50 – From this limit, it is stated that the computational innovation can be included because the certainty is so great and the remaining risk is carried by reasonable potential.

Certainty: 90 Potency: 15 – From this limit, it is stated that the computational innovation can be included because the certainty is so high that it can be assumed that it is correct.
Certainty: 100 Potency: 0 – At this point, it matters because you are completely certain but applying the computational innovation has no result.

Step 3

The advice was then developed for the different colours. For green, the computational innovation is promising and should be included. It is important to focus on risk management because it is still a computational innovation. For yellow, there are also opportunities for the computational innovation, but follow-up steps must still be taken to be able to implement the computational innovation, such as more research, waiting for more knowledge or making a conservative variant. Finally, for red, it is advised not to include the computational innovation, but at changes that might respond positively to the computing innovation, the flowchart should be used again from the beginning.

Conclusions

This research answers the question, how can a trade-off be made for including or excluding or not to include the computational innovations bursting and initial unsaturated zone within a dyke reinforcement project?

A decision can be made whether or not to include the calculation innovations by first looking at the dyke section at whether the sensitivity calculation changes the task, then giving a score on both the potential of the computational innovation and the knowledge and information. Based on a combination of these scores, an interim conclusion is given for the dyke section (green, yellow, orange) as shown in Figure 3.

Finally, based on the results of all dyke sections, the scope of the entire dyke section must be expanded. This involves looking at: what the outcomes mean for the complexity of the project; whether the results of other failure mechanisms play a role; and whether the effort required outweighs the benefits of the computational innovation. Using the assessment framework for the application of computational innovations helps water boards to decide whether or not to include the computational innovation. These dykes will be designed more soberly and efficiently, saving taxpayers' money and allowing more sustainable measures to be taken. Potentially more sustainable measures can be taken.

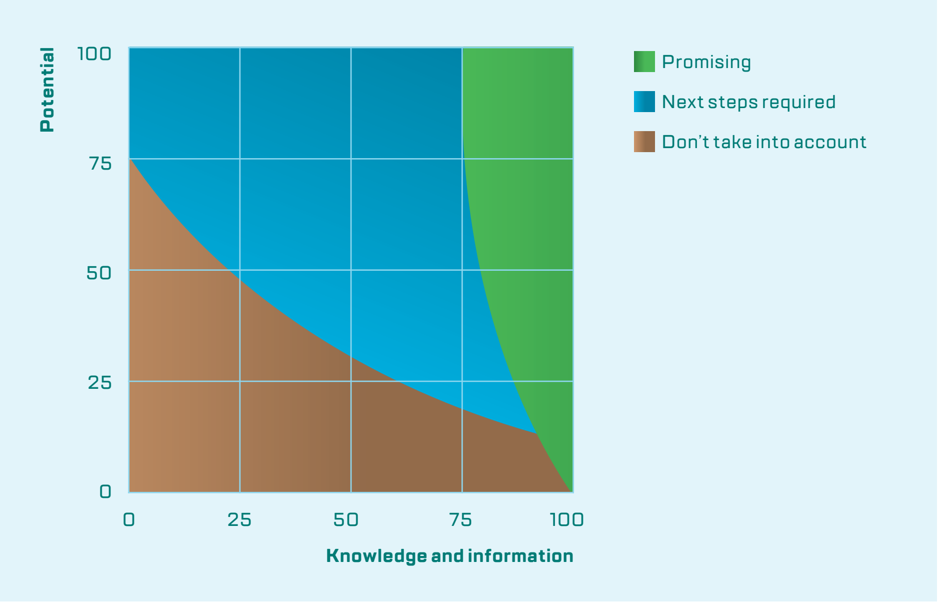


FIGURE 3

Recommendations.

Summary

This article describes our research of dealing with computational innovation in dyke reinforcement projects. Specifically, two computational innovations still under development – shear strength of initially unsaturated soil for slope stability and bursting for piping. It will describe which components play a role in whether or not to include this computational innovation. This information is incorporated into an assessment framework. The assessment framework aims to advise the water boards whether or not to apply these computational innovations in dyke reinforcement projects. The main question for our study was, how can a trade-off be made for applying the computational innovations bursting and shear strength of initially unsaturated soil within dyke reinforcement projects?

Dykes will be designed more soberly and efficiently, saving taxpayers' money and allowing more sustainable measures to be taken.

Joppe Vugts

Joppe has a bachelor's degree in civil engineering from Avans University of Applied Sciences in the Netherlands. In recognition of his achievements, he received the National Hydraulic Engineering Prize 2024 for the most innovative and valuable bachelor's thesis. Joppe is currently doing a bridging year at Delft University of Technology before starting a master's degree.

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UPCOMING COURSES AND CONFERENCES

Dredging and Reclamation Seminar

3-7 July 2024
IHE Delft Institute for Water Education
Delft, The Netherlands

18-22 November 2024
Venue to be confirmed
Abu Dhabi, United Arab Emirates

About the seminar

Since 1993, the IADC has regularly held a week-long seminar developed especially for professionals in dredging-related industries. These intensive courses have been successfully presented in the Netherlands, Singapore, Dubai, Argentina, Abu Dhabi, Bahrain and Brazil. With these seminars, IADC reflects its commitment to education, encouraging young people to enter the field of dredging and improving knowledge about dredging throughout the world.

For whom

The seminar has been developed for both technical and non-technical professionals in dredging-related industries. From students and newcomers in the field of dredging to higher-lever consultants, advisors at port and harbour authorities, offshore companies and other organisations that carry out dredging projects. Attendees will gain a wealth of knowledge and a better understanding of the fascinating and vital dredging industry.

In the classroom

There is no other dredging seminar that includes a workshop covering a complete tendering process from start to finish. The in-depth lectures are presented by experienced dredging professionals from IADC member companies. Their practical knowledge and professional expertise are invaluable for in the classroom-based lessons. Among the subjects covered are:

- the development of new ports and maintenance of existing ports;
- project development: from preparation to realisation;
- descriptions of types of dredging equipment;
- costing of projects;
- types of dredging projects; and
- environmental aspects of dredging.

Site visit: seeing is believing

Practical experience is priceless and it sets aside this seminar from all others. There will be a site visit to a dredging yard of an IADC member to allow participants to view and

Submissions for IADC Safety Award 2024

Conceived to encourage the development of safety skills on the job as well as heighten safety awareness, the award recognises the exceptional safety performance of a particular project, product, vessel, team or employee.

Two safety awards will be presented in 2024: one to a dredging organisation and a second to a supply chain organisation active in the dredging or offshore industry. This concerns subcontractors and suppliers of goods and services.

There is no limit to the number of submissions that can be entered and the awards are open to both IADC members and all other dredging contractors. All submissions must be received by 31 May 2024 via https://bit.ly/SafetyAward2024.

experience dredging equipment first-hand to gain better insights into the multi-faceted field of dredging operations.

Networking

Networking is invaluable. A mid-week dinner where participants, lecturers and other dredging employees can interact, network, and discuss the real, handson world of dredging provides another dimension to this stimulating week.

Certificate of achievement

Each participant will receive a set of comprehensive proceedings and at the end of the week, a certificate of achievement in recognition of the completion of the coursework. Full attendance is required to attain the certificate.

Costs

The seminar fee in Delft is EUR 3,100 (incl VAT) and for Abu Dhabi EUR 3,100 (out of scope EU VAT). The price includes all tuition, proceedings, workshops and a special participants' dinner, but excludes travel costs and accommodations. We can assist you in finding a hotel or accommodation. For more information and how to register visit https://bit.ly/SemDelft2024.

CEDA Dredging Days 2024

27-29 May 2024
WTC Rotterdam, Rotterdam,
The Netherlands

CEDA Dredging Days is the flagship conference of CEDA and is the main event on the dredging industry calendar in the CEDA (EMEA) region. A forum for leading researchers and industry experts, to share ideas, discuss challenges and consider potential solutions. The conference is well-attended by professionals representing the entire cross-section of the dredging field, from across the CEDA region and beyond.

The dredging community has proven its ability to adapt to a changing world. Rather than simply following new rules and regulations, the industry is leading, innovative and open to cooperation. To reflect the dredging community spirit even more, CEDA has decided to revamp its Dredging Days programme for the 2024 edition, where it will engage with the theme "Dredging in a changing world, leading science and business in the dredging industry". This revamped edition will take place from 27-29 May 2024 at the Postillion Hotel & Convention Centre WTC Rotterdam, situated in the centre of the city; a modern, central and invigorating location.

What can you expect from the new CEDA Dredging Days?

One of the main features of the revamp is the addition of the central clubhouse, which has a strong focus on networking in an intimate setting and serves as the central meeting place for coffee breaks, lunches and social events. The clubhouse will replace the formal exhibition set up with stands and create an informal networking area instead, with a mix of lounge furniture where attendees can relax and enjoy a moment to engage in informal conversations with their peers at any time during the conference.

Other key features:

- a 3-day event dedicated to the dredging industry;
- a "stand-alone" conference (no longer combined with Europort);
- a widely varied programme, interesting for a broad audience and promoting attendee interaction; and
- parallel sessions featuring the latest technical developments, learning from other industries, innovation pitches, panel discussions and much more.

https://www.cedaconferences.org/dredgingdays2024

Integrating Dredging in Sustainable Development Conference

18 October 2024
Sheraton Saigon Hotel & Towers
Ho Chi Minh City, Vietnam

INTEGRATING DREDGING IN SUSTAINABLE DEVELOPMENT

For those working in the fast changing world of dredging, waterborne transport infrastructure and related industries, IADC & PIANC's 1-day conference is dedicated to advancing industry knowledge in the arena of sustainable dredging and related topics.

Whether an individual or company aiming to deliver dredging projects with longevity that also maximise the benefits to society, nature and economy, this event will be of particular relevance. The 1-day conference "Integrating Dredging in Sustainable Development" will bring essential knowledge for planners, designers, decision makers, regulators, contractors, project owners and environmental advocates.

Joining this event also provides the unique opportunity to network with more than 60 CEOs and senior management of IADC member companies. And all participants are welcome to join the special pre-conference networking drinks and dinner on Thursday 17 October 2024. For more information and how to register visit https://bit.ly/VietnamConf24.

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