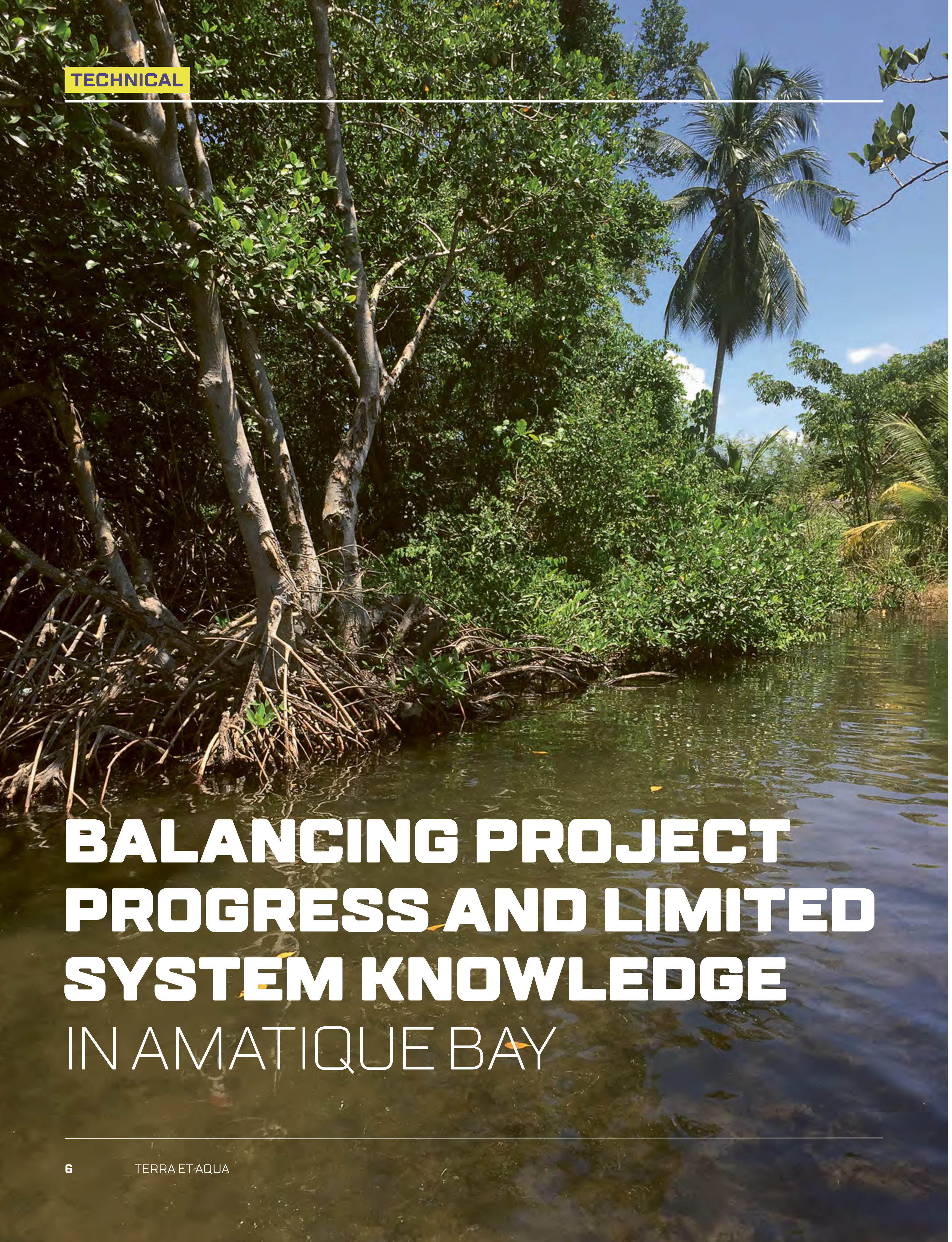
TECHNICAL



BALANCING PROJECT PROGRESS AND LIMITED SYSTEM KNOWLEDGE IN AMATIQUE BAY

The development of a new marine project demands a system approach in which all aspects, including technical, economic, environmental and social, are considered and integrated equally and at an early stage. While insufficient information may be available to make informed decisions, choices need to be made to progress a project, assess impacts and risks, and engage stakeholders. This article explores the case of a new port terminal in Amatique Bay, Guatemala. A method was developed to assess, at an early stage, the potential negative impacts on seagrass habitats from the disposal of dredged material at different locations, while having limited real-time and location-specific information at hand.

> **The challenge is determining the optimal disposal site in relation to dredging method, seagrass beds to be protected and potentially large disposal plumes.**

The development

Amatique terminal is a new port in a greenfield location along the Caribbean coast in the bay of Amatique, north of Puerto Barrios, in Guatemala (Figure 1). The terminal is designed for handling containers, general cargo and liquid bulk. The development consists of a port basin (dig-in), storage and handling areas. A new navigation channel will be dredged over a length of 4.3 kilometres (km) and will connect the existing navigation channel to the ports of Santo Tomás and Puerto Barrios with the Amatique terminal.

Amatique Bay is locally rich in biodiversity, especially in the shallow coastal areas where there are habitats of mangrove and seagrass, important for various marine wildlife including the manatee. These coastal areas are, for a large part, protected by Guatemalan Law (Decreto 4-89). Just north of the proposed terminal is the Punta de Manabique Wildlife Refuge, which is also recognised as a 'Wetland of International Importance' under the Ramsar Convention (www.ramsar.org). Information on habitats and species is scarce.

The bay is no longer a pristine natural system, as human activities have a negative effect on the habitat. The towns of Puerto Barrios and Santo Tomás, with their ports (and access channel), industrial activities and urban population concentrations generate wastewater that drains into the bay. There are cargo and passenger sea vessel movements, as well as commercial and artisanal fishing activities ongoing in the bay. In addition, mangrove habitats are often affected by recreational and agricultural practices. Hence the fact that the bay is only locally rich in biodiversity.

Port location and design

Different locations and designs were considered to develop the best alternative matching the requirements for the port and the value of the environment. Amatique terminal is proposed to be located north of Puerto Barrios (Figure 1). Here, the terminal will be protected from waves, with a good connection to hinterland infrastructure and away from various protected areas as much as possible.

A choice was made for a compact inland (dig-in) port, which reduces the visual impact of the port and integrates the terminal in the natural land- and seascape. The effect on the wildlife refuge would be reduced by limiting the permanent intrusion of the protected area and providing an opportunity to dig a large part of the port in a contained area, reducing plume extension and risks of spills. The downside of this choice is that the volume of earthworks is relatively large.

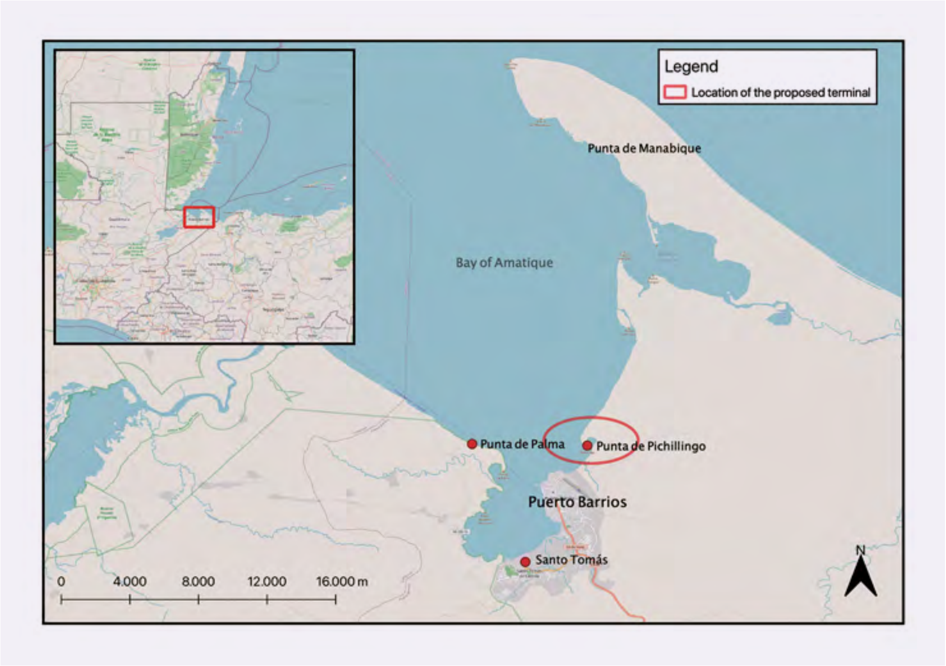


FIGURE 1

Location of the proposed terminal.

Dredging works

By dredging the navigation channel and the inner basin, a total volume of around 10 million m³ of dredged material will be generated. It is expected that the dredging operation will last between 12–15 months.

Reuse of the dredged material has been considered for fill material and the creation of an artificial island. Disposal on land was also considered. However, the dredged material appeared not suitable for reuse and no land was available for disposal purposes. Bringing the spoil to a marine disposal site appeared to be the only feasible option.

The proposed dredging equipment is largely determined by the minimum water depth required by the dredgers. At a water depth of less than 7 metres, a Backhoe Dredger (BHD) or Cutter Suction Dredger (CSD) can be used. In deeper sections of the access channel, a Trailing Suction Hopper Dredger (TSHD) is preferred. The different types of dredgers are shown in Figure 2.

The challenge

The map in Figure 3 shows the different aspects related to the dredging and disposal activities for Amatique terminal in its environment, showing the challenge of this project. Alternative dredge spoil disposal sites have been identified which have to be analysed for the environmental effects, resulting from the use of each site. Navigational charts of the bay showed two designated disposal sites (C and D) relatively close to the dredging location. The actual regulations regarding these disposal sites could not be confirmed with the authorities in Guatemala. Next to these designated sites, a potential disposal site E has been proposed, outside the protected area and large enough to accommodate all dredge spoil. The map also shows the location of the seagrass meadows and the ecologically sensitive areas in Amatique Bay. The relevant ecological conditions are elaborated on later in this article.

The challenge is to determine the most optimal disposal site in relation to the dredging equipment and method, seagrass beds to be protected and the fine soil, potentially resulting in large dredging and disposal plumes of high turbidity. All this in an environment with little data available and low (and therefore difficult to predict) dynamics in the bay. On the other hand, the project developers wanted to understand the feasibility of the project, inform relevant stakeholders and start the approval process with the local authorities.

FIGURE 2

Different types of dredging equipment (source Boskalis, 2018). (A) Backhoe Dredger (BHD). (B) Cutter Suction Dredger (CSD). (C) Trailing Suction Hopper Dredger (TSHD).

FIGURE 3

Overview of the Amatique terminal development and its environment.

> **Extensive survey campaigns were not opportune at this stage, forcing us to develop a practical and effective approach to select the optimal disposal site.**

Extensive survey campaigns were not opportune at this stage, forcing us to develop a practical, integrated and effective approach for selecting the disposal site.

Approach

Our approach is presented in Figure 4 and follows a number of steps. We began by obtaining an in-depth insight into the baseline situation, both for physical and ecological parameters. Most relevant for the physical environment are the hydrodynamic and soil conditions in Amatique Bay. The ecological baseline consists of the presence and extent of seagrass, and its sensitivity to increased sedimentation and turbidity levels due to the dredging and disposal activities.

Physical parameters were derived from analysis of vibrocores and basic flow and turbidity measurements. The seagrass extent was determined by a drone survey and scuba diving for verification at specific locations.

The sensitivity of the observed seagrass species to increased sedimentation and turbidity levels was based on literature review.

To predict the suspended sediment concentrations (SSC), which will affect the overall turbidity levels and the sedimentation of the released dredge spoil, a schematised numerical plume model was set up. As input to the model, a source term (elaborated on later in this article) is required. By combining soil conditions, the proposed dredge and disposal locations and the type of dredging equipment to be deployed, source terms were determined.

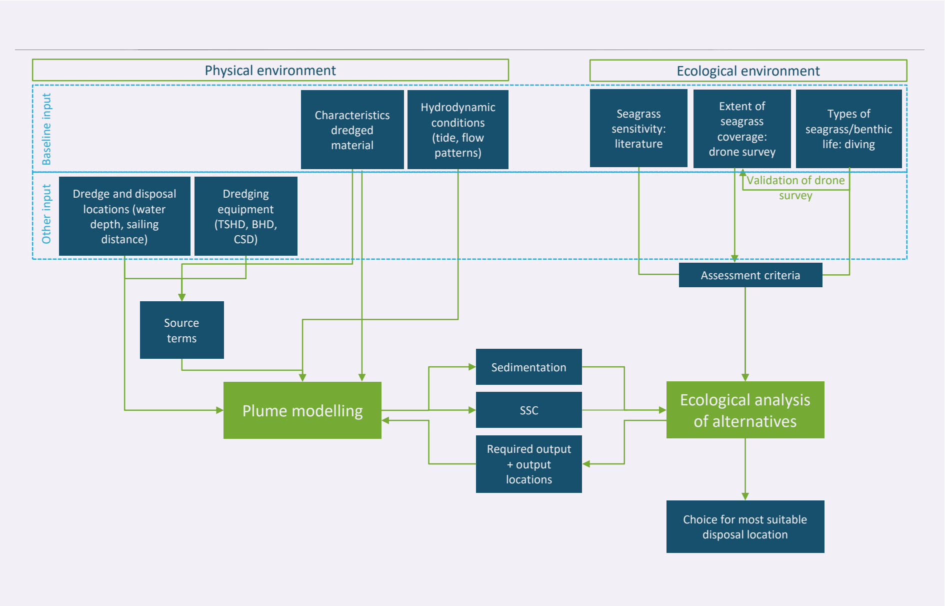


FIGURE 4

Steps of the approach.

Drone surveys for the extent of the seagrass beds were confirmed by diving surveys to determine species and their condition.

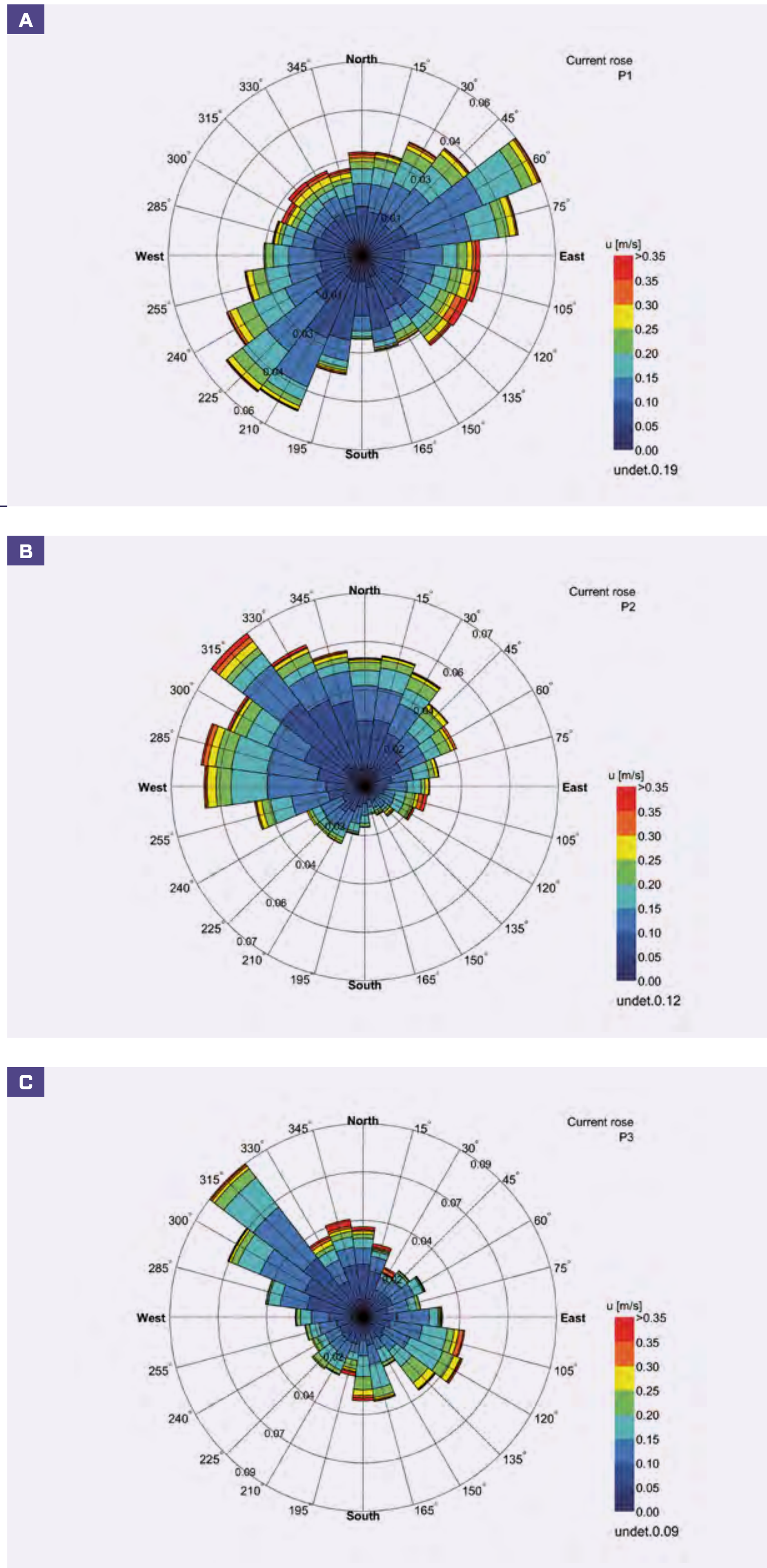


FIGURE 5

Current roses of the three survey locations P1 (A), P2 (B) and P3 (C), collected in the period April to June 2018. Current directions defined relative to north.

FIGURE 6

Schematisation of the measured current conditions as used in the plume dispersion study.

In this article, we will focus on the impact of disposal of dredge spoil at the different proposed disposal sites and the selection of the optimal disposal site. The impact of the dredging itself was added to the disposal impact when applicable. With the sensitivity criteria of the seagrass and the outcomes of the plume modelling, the effects of using the alternative disposal sites were compared to select the preferred one.

Baseline

Physical conditions

The bay is characterised by limited tidal difference and weak currents. At the dredging location, the soil material is very fine. Limited data on tidal currents, turbidity and soil characteristics in the bay were readily available.

According to the Admiralty Tide Tables, the tidal variation is limited: MLLW–MHHW range at Livingstone (about 20 km northwest of the project location), is only 0.5 m and the MLHW–MHLW range is 0.3 m.

The project location, in the south-western area of the bay, is sheltered against waves from the Caribbean Sea. The waves are locally generated and therefore low and short. Waves have therefore been ignored in the plume model.

As knowledge of the local currents is essential for a plume dispersion assessment, basic current measurements were conducted with a hand-held instrument in three, regularly alternating locations near the project area. The measurements were conducted in the period April–June 2018, just before the start of the wet season. The results are shown as current roses in Figure 5. For 95% of the time the velocities were smaller than 0.3 m/s.

Current directions measured with a hand-held instrument in a low-velocity environment are usually inherently inaccurate. Nonetheless, the measured current directions in the three survey locations do show evidence of a circulation pattern along the western shore of Amatique Bay, although variation in the direction is large. Figure 6 shows the measurement locations and our interpretation of the measured current conditions as used in the schematised plume model.

The current in Amatique Bay is likely a combination of tidal filling and emptying, large-scale wind-induced circulation patterns and small-scale disturbances due to bathymetry, topography and local wind variation. The currents are the sum of several subtle processes, whilst the relevant importance of each process will vary in both time and space. Such low-dynamic, complex systems are extremely difficult to simulate accurately with a numerical flow model.

Together with the current measurements, turbidity levels were also measured. Except for occasional peak values of up to 50 NTU (Nephelometric Turbidity Unit), the turbidity levels were generally low resulting in average turbidity levels of around 1 NTU. The turbidity measurements were conducted in the same period as the current measurements. The few rain showers that occurred did not result in increased turbidity levels. Turbidity levels during the wet season may be higher than measured in the dry season, due to more sediments entering the bay with the run-off.

Water samples were collected to establish a correlation between NTU and actual suspended sediment concentrations (SSC) under natural conditions, but unfortunately, no useful correlation could be derived: although NTU values varied substantially, SSC values remained in a very narrow range. An explanation could be locally occurring tannins dissolved in the waters of the bay. These tannins cause strong water discoloration and can significantly influence turbidity without appreciably altering SSC values (Czuba et al., 2011; Fink, 2005). The drone survey images confirmed the dense mangrove forests and associated channels to be the sources of tannins in the system (Figure 7A). The extent of tannins in the system varied along the coastline and occasionally made the observation of seagrass difficult (see following section and Figure 7B).

In March 2018, several vibrocores in the bay were taken of which a selection was analysed on physical characteristics. The percentage of fines (<63 μm) ranged between 70–99% with an average value of 82%. The median grain size d50 was correspondingly small with values between 1.6–22.0 μm, being in the range of clay and medium silt. The in-situ wet density was estimated to be 1,400 kg/m³.

Distribution of seagrass beds

Seagrass beds are highly productive ecosystems, which play an important role in preventing coastal erosion, siltation of coral reefs and enhancing fish productivity. In Amatique Bay, the seagrass beds are an important food source for manatees. Based on local observations, manatees were known to gather in the area north of Punta de Pichillingo. However, no manatees were observed during the drone surveys. Sightings are rare, as the animals are elusive by nature and difficult to see. However, local fishermen indicated that they see the manatees regularly.

A first drone survey was executed in August 2018 to determine the extent of seagrass beds. With the Map Plus application (iOS), the targeted sections/areas of investigation were preloaded into the base-map. These sections consisted of tracks parallel and perpendicular to the coast using georeferenced waypoints for the drone flights (Figure 8). The planned drone tracks and actual flight coordinates were merged with the recorded videos. These drone surveys were augmented with dive surveys in specific locations to verify assessed species, maximum extent of seagrass beds and local conditions. The drone survey footage was analysed by detailed viewing and notes taken for each transect flown. From these notes, an overall summary assessment was made on the extent of seagrass beds and patterns identified.

FIGURE 7

(A) Tannins (plant extracts dissolved in water) released by mangroves and channels result in strong water discoloration along the coast.
(B) Tannin-rich waters make assessing seagrass bed presence at depth difficult. In the shallows however, the distribution of tannins visualise the effect of seagrass on water movements.

Based on the drone and dive surveys, two species of seagrass were identified. These are *Thalassia testudinum*, also known as turtle grass, and *Syringodium filiforme*, known as manatee grass. *Thalassia testudinum* is most abundant. Both species of seagrass are classified as of 'least concern' on the IUCN Red List of Threatened Species (www.iucnredlist.org). Other species were not observed during the surveys, but if they do occur in the bay, they exist in much lower abundance. Green algae and possibly *Halimeda* species were observed during the drone surveys.

The surveys show that the seagrass grows close to the coastline and extends approximately 200 m into the bay. The seagrass is found up to an approximate water depth of 6 m. On the south-western coastline near Punta de Palma, patches of seagrass have also been observed (Figure 3).

A second drone survey was executed in September 2018 to determine the extent of the seagrass along the western coastline near Punta de Palma. During this survey, only parts of the coastline were surveyed. The footage shows that the seagrass beds have a patchy distribution along all coastlines. The drone survey showed that seagrass was present all along the surveyed coast, with highest densities observed in very shallow waters (Figure 9). When seagrass was not visible, it was assessed that this was most likely due to local turbidity and/or discoloration of the water due to plant extracts (tannins) coming from the mangrove coast.

Plume modelling

Source terms

One of the most important parameters to be considered when assessing environmental impact of dredging is the generated turbidity. Source terms, being the mass of fines released per second, are needed as input for turbidity modelling. Source terms can be calculated as peak source terms or cycle average source terms. Peak source terms are calculated for the duration of the activity that is causing the turbidity, e.g. dredging or overflowing. Cycle average source terms average the mobilised mass of fines over the entire dredging cycle, consisting of dredging, sailing to disposal location, disposing and sailing back to dredge location. Such a dredge cycle is typically related to dredging with a TSHD. CSD or BHD dredging is more or less a continuous process for which there is no distinction between the peak and cycle average source term, whilst disposing by means of barges is intermittent, just like TSHD dredging.

FIGURE 8

Drone flights along the coast, launched from a small boat, aided in surveying the presence and extent of seagrass beds and patches.

FIGURE 9

Seagrass was present all long the surveyed coast, with highest densities observed in very shallow waters.

The source terms are calculated with the method put forward in CEDA/IADC (2018). The magnitude of the source terms of dredging operations depends on the type of dredger, the dredger's production rate, percentage of fines in the bed, in-situ density and the far-field factor, being the fraction of the dredged fines that will form the sediment plume.
In this study, the source terms have been calculated deterministically, although the input parameters involved are variable and uncertain.

As various disposal locations are reviewed with different water depths, as well as different types of equipment, multiple situations have been considered in the source term determination (see Table 1). Four types of equipment have been examined. Disposal takes place at locations C, D or E and dredge spoil will be disposed by either of the equipment types. As the CSD is deployed in combination with non-overflowing barges, the CSD disposal source term is relatively small due to the large volumes of process water in the barges. The TSHD can be loaded most efficiently, hence the relatively large disposal source term. Note that the peak source terms of the two BHDs are equal but the cycle time differs with a factor of approximately two, because of which the two BDHs will have different impacts.

TABLE 1

Source terms for various work methods and disposal locations.

Equipment	Location	Depth [m]	Source term [kg/s]	Cycle
CSD	C	6	25.6	Intermittent
BHD A	C	6	95.3	Intermittent
BHD B	C	6	95.3	Intermittent
TSHD	D	10	131.1	Intermittent
	E	9	131.1	Intermittent

Plume spreading

Following the determination of the source terms, the spreading and associated sedimentation of fines is determined. The current pattern in Amatique Bay is complex and difficult to reproduce with a numerical model, especially due to the absence of accurate bathymetric data, spatially and temporally varying wind fields and more accurate current and water level measurements. We therefore chose an approach using a schematised Delft3D model rather than a model of the actual bay.

The schematised numerical model was based on uniform representative depths and schematised flow patterns (Figure 6). This enabled us to isolate the influence of parameters and processes and provide valuable insight into the model sensitivities.

In the schematised model, the tidal flow is strictly bi-directional, ensured by imposing water levels at one end and flow velocities at the other end of the domain. Boundary conditions are imposed in such a way that the average current velocity represents the measured current velocities of approximately 0.2 m/s. Wind-driven currents are neglected. The model domain has a length of 20 km in the direction of the flow and a width of 5 km perpendicular to the tidal axis, with a grid resolution of 50 m in both directions.
A 3D modelling approach was adopted to accurately simulate the slowly settling fines, resulting in a variation in concentration over the water column. Ten vertical layers were used over the water column, each containing 10% of the water depth. The seabed level is uniform but may vary for the considered locations, resulting in water depths ranging between 5–10 m.

The release of fines during the different disposal activities was simulated by adding the source terms in the middle of the model domain. A far-field situation was considered so the sediment source term was divided equally over the ten vertical layers. The discharged spoil typically has a particle size (d_{50}) of 10 µm, with an associated settling velocity of 0.08 mm/s. For each location, a schematised model was set up and the appropriate source term was imposed representing the different dredging methods and cycle times.

The numerical model predicts the variation of suspended sediment concentrations and sedimentation layer thickness, both in time and space. Due to the recurring tidal flow pattern, the released fines flow back and forth while slowly settling to the seabed. This symmetric pattern in the sediment plume can clearly be seen in the maximum (or average) concentration of suspended fines over a period of 4 days (Figure 10) for disposal at site E with the TSHD. It should be noted that the maximum (or average) values shown here do not occur simultaneously. The concentrations and sedimentation thickness are highest close to the dredging location and quickly decrease in the flow direction (Figures 10A and 10B). At a distance of 2 km, the maximum concentration has decreased to 66 mg/l.

Table 2 summarises the results of the sediment plume dispersion model. For all simulations, the maximum and mean suspended sediment concentration (SSC_{max} and SSC_{mean}) in 4 days is given for locations at 2 km and 3.5 km away from the disposal location. These distances have been chosen to provide a general overview of the results of the different simulations and to support the ecological assessment. In addition, the mean and maximum lengths (Lp) and the widths (Wp) of the SSC plume have been listed, where the edge of the plume is assumed to be at a suspended sediment concentration of 1 mg/l. Furthermore, the average sedimentation thickness (over the entire area where sedimentation occurs) was calculated (D_{mean}). Only the average sedimentation thickness

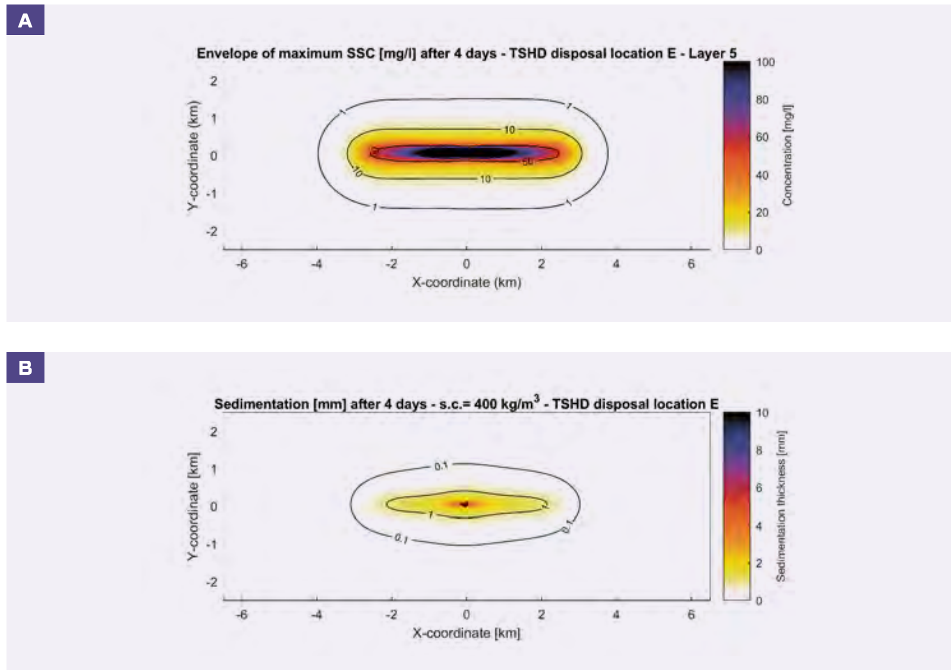


FIGURE 10

(A) Maximum suspended sediment concentrations half-way the water column following disposal activities with the TSHD. (B) Sedimentation on the seabed from disposal activities with the TSHD.

is presented, because this fine material, once on the bottom, spreads out easily and becomes an almost flat area. Note that the SSC are excess SSC and that for the total SSC the ambient SSC should be added.

In this way, the effects of the different disposal methods and locations are compared (Table 2). The suspended sediment concentration at 2 km is highest for the BHD A. At 3.5 km it is highest for the TSHD. The sedimentation is also larger for the TSHD and BHD A. For the disposal activities, there is some variation in the length of the plume. It should be noted that not only does the magnitude of the source term play a role in the SSC and sedimentation patterns, but also the dredging operation cycle time and depth.

In this assessment, the sensitivity of the plume dispersion and deposition to flow velocity, sediment particle size, dry density of deposited sediment and assumptions in the source term determination were assessed, in order to account for natural variations in the system. For example, the maximum measured flow velocity of 0.3 m/s results in a longer but more diluted sediment plume. When the disposed sediment is finer, the sediment plume is significantly larger in extent, both due to advective and diffusive processes. When determining the source term, the percentage of fines reaching the far field (i.e. the far-field factor) needs to be estimated, but this estimate can have a large effect on the plume extent.

The schematised model results were transformed into impact maps (Figure 10 and 11) using the interpretation of the measured current conditions (Figure 6). These maps show the 1, 10 and 50 mg/l contour line of the mean suspended sediment concentration, based on disposal either in the centre or at the edge of the disposal location.

In these maps, the general flow direction is considered as well: the plume extent was rotated in such a way aligning it with the dominant flow direction, following the circulation pattern in the bay as shown in Figure 6. As disposal can in principle take place anywhere within the boundaries of the disposal site, an impact area around the edges of the disposal site was indicated, covering the area of the disposal site and the maximum extent of the plume around it.

TABLE 2

Suspended sediment concentrations and sedimentation at different distances from the source location.

Equipment	Location	SSC_{max} (mg/l) in layer 5		$W_{p,max}$ (km)	$L_{p,max}$ (km)	SSC_{mean} (mg/l) in layer 5		$W_{p,mean}$ (km)	$L_{p,mean}$ (km)	D_{mean} (mm)
		2 km	3.5 km			2 km	3.5 km			
CSD	C	45	1.4	2.4	3.5	13	0.3	2.3	3.0	0.5
BHD A	C	80	1.9	2.5	3.6	18	0.4	2.3	3.0	0.6
BHD B	C	56	0.8	2.0	3.4	3.2	0.1	1.9	2.7	0.4
TSHD	D	61	3.6	3.0	3.9	17	0.7	2.9	3.3	0.6
TSHD	E	66	3.7	2.9	3.9	18	0.7	2.8	3.3	0.6

Impact on seagrass beds

Methodology

The tolerance of seagrass to increased turbidity and additional sedimentation is species and location specific. Larger, slow-growing species with substantial carbohydrate reserves show greater resilience to such events than smaller opportunistic species of seagrass. However, the latter display much faster post-dredging recovery when water quality conditions return to their original state (Erftemijer and Lewis, 2006). The species present in Amatique Bay, *Thalassia testudinum* and *Syringodium filiforme*, belong to the larger, slow-growing species. Literature, for example Erftemeijer and Lewis (2006), was reviewed to determine the tolerance of these species to dredging activities.

The actual impact of dredging and disposal activities on seagrass depends on multiple factors, such as ambient levels and changes to light availability, turbidity levels and sedimentation rate. Not only are the levels of these different parameters important but also the duration at which the seagrass species is exposed to increased levels of turbidity and sedimentation. Temporary exposure to high turbidity levels may not be fatal while long-term exposure can cause degradation of seagrass beds. Seagrass can tolerate sediment plumes (and therefore elevated turbidity levels) for relatively long periods. Tolerance levels vary between species based on their growth strategy and morphology (i.e. amount of starch reserves in the roots). However, most species are less tolerant to increased sedimentation, with only the fastest-growing species capable of outpacing sedimentation rates for a limited period before eventually exhausting their resources. Based on the literature reviewed, the tolerance of the species to increased levels of turbidity and sedimentation showed a large range and differed per location. No studies were found specifically on the tolerance of seagrass in Amatique Bay.

The exact requirements for the seagrass species in Amatique Bay and the water quality parameters (including seasonal changes) within which the species occur were unclear as there was only limited data on natural turbidity levels and light availability. Ideally, critical thresholds should be determined in terms of light availability close to the seabed (% SI) and suspended sediment concentrations (SSC).

TABLE 3

Table showing the overlap of the plume with the seagrass areas in km² for different disposal scenarios.

Disposal site	Equipment	Flow velocity	Settling velocity	Overlap maximum extent plume with seagrass
C	CSD	0.2 m/s	0.08 mm/s	3.4 km²
D	TSHD	0.2 m/s	0.08 mm/s	2.0 km²
E	TSHD	0.2 m/s	0.08 mm/s	1.3 km²

Without robust survey data, a critical threshold could not be determined to assist in the selection of the disposal locations. Therefore, to enable an assessment, the impact of disposal activities on the seagrass was based on the total area of seagrass exposed to both the maximum extent of the sediment plume and the extent of the sediment plume with an average increase of SSC levels of 1, 10 and 50 mg/l over a period of 4 days. These levels were chosen based on a practical basis, with 1 mg/l dictating the 'maximum plume extent', 10 mg/l indicating an 'area of influence' and 50 mg/l indicating an 'area with potential for impacts'.

Selection of the optimal disposal site

At first, disposal sites were compared based on the total area exposed to the maximum extent of the sediment plume. The maximum extent is the maximum area that could have raised SSC levels (of at least 1 mg/l) at one point in time during the dredging and/or disposal activities. The extent of the plume was based on the equipment that was most likely to be used at the disposal site. For disposal site E and D, the TSHD is proposed, while for disposal site C, the CSD is suitable due to the location's shallower water depth.

Figure 11 shows an example map of the maximum extent of the sediment plume at disposal site E with different concentration levels.

Table 3 shows the maximum area of seagrass, which could have SSC levels of at least 1 mg/l at one point in time during disposal activities.

Site E was selected as the most favourable disposal site for the following reasons:

Site C:
- Shows the highest potential overlap (3.4 km²) of the sediment plume with the seagrass area;
- Suspended sediment concentrations and sedimentation from disposal accumulate with those from dredging in the navigation channel (NC); and
- Effort of maintenance dredging increases as the navigation channel crosses this disposal site.

Site D:
- Generates a substantial area (2.0 km²) of seagrass to be exposed to the sediment plume;
- Is located within the Punta de Manabique Wildlife Refuge; and
- May create exposure of known feeding areas of manatees to the sediment plume.

Site E:
- Shows the smallest area of seagrass exposed to the sediment plume (1.3 km²);
- Is located outside Punta de Manabique Wildlife Refuge and further away from Ox Tongue (a known manatee area); and
- This site is further away from the dredging site than the other sites.

Sensitivity analysis

The imposed source terms that were used in the model were based on multiple assumptions, such as the amount of material reaching the far field and the settling velocity of the spoil. A sensitivity analysis was performed to show the effects of the choices in (input) parameters on the suspended sediment concentrations and the amount of sedimentation.

In addition, the location where the dredge spoil is disposed within the area of the disposal site

FIGURE 11

Extent plume disposal site E using TSHD.

FIGURE 12

Extent of the sediment plume when disposing at the corner of disposal site E, based on the assumption that 5% of fines reach the far field, a current velocity of 0.2 m/s and a settling velocity of 0.08 mm/s.

(either in the centre or at the edge of the disposal site) can have a significant effect on the extent of the dredging plume.

Table 4 shows the difference in maximum extent of the sediment plumes with a variety in source terms, settling velocity and disposal in the centre or at the edge of site E. The maximum extent of the sediment plume increases slightly if the current is increased from 0.2 m/s to 0.3 m/s and if the percentage of fines in the far field increases from 5% to 25%. When applying the 5% source term, after 4 days, the disposal plume does not overlap with the seagrass beds when disposing in the centre of the site. However, when disposal near the edge is modelled, a small area of seagrass is potentially affected.

TABLE 4

Overlap of the plume with seagrass areas in km² at disposal site E for TSHD with different input parameters.

Flow velocity	Far-field factor (for source term determination)	Settling velocity	Maximum extent
0.2 m/s	5%	0.08 mm/s	1.3 km²
0.2 m/s	10%	0.08 mm/s	1.9 km²
0.2 m/s	25%	0.08 mm/s	2.6 km²
0.2 m/s	5%	0.2 mm/s	0.6 km²
0.3 m/s	5%	0.08 mm/s	4.4 km²

Based on the plume modelling results, we cannot rule out the possibility that during the 12–15 months of disposal, some areas of the seagrass might be exposed to increased SSC levels of more than 1 mg/l when the disposal would be undertaken near the edge of the disposal site (Table 4). Based on our analysis, a maximum area of 0.1 km² of seagrass will be exposed to these increased levels of SSC. However, the seagrass will not be exposed for a significant amount of time because the actual disposal location will vary over the dredging period. It can be concluded that the seagrass will experience minimal exposure to any appreciable elevated turbidity and sedimentation levels for longer periods.

Lessons learned

By sharing some lessons learned from this case of the Amatique terminal, we hope to provide insight to all stakeholders involved in similar projects around the world.

Multi-disciplinary team involved at an early stage

One of the most important lessons learned was the need for a multi-disciplinary team in a very early stage of the assessment. Experts in port design, dredging methods, ecology, coastal hydrodynamics and morphology need to be involved at the same time. An integrated system approach should be developed together.

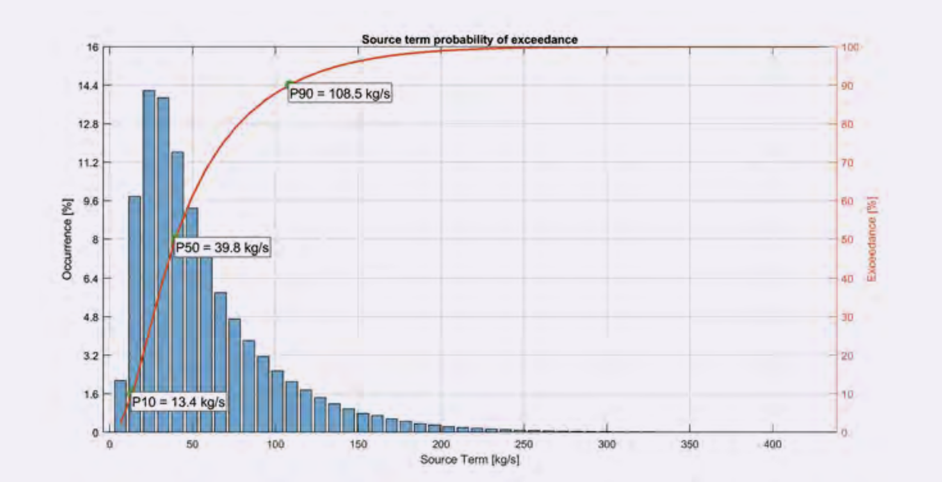


FIGURE 13

Example of a source term probability of exceedance curve.

Source term determination using a Monte Carlo approach

The source terms as input in the plume dispersion model were, in this case, calculated in a deterministic manner, which is one source term for each unique combination of dredger type, production and soil conditions. However, the parameters determining the source term are uncertain, vary in time and space and/or have limited accuracy. A probabilistic source term calculation does more justice to the uncertainty in these parameters.

A way to do this is to apply a Monte Carlo simulation, in which a large number of random samples are drawn from a pre-defined range of parameter values with an associated distribution (e.g. uniform or triangular). The result is a source term probability of exceedance curve. A typical example of which is shown in Figure 13.

With symmetrical distributions around the mean values of each parameter, the median (P50) source term is equal to the mean source term and to the deterministic source term. The added value arises from a quantification of the spreading in the source term, typically expressed in P10 and P90 values (values exceeded 90% and 10% of the time respectively). Depending on, among others, the purpose of the study and the need for a cautionary principle, the user can select one or more appropriate values for the source term.

Key considerations of the drone survey method

The drone survey provides some important opportunities. Drones can cover large areas in a relatively short timeframe with minimal interference in the natural environment. The results include a valuable ecological and morphological database, useful for the whole project cycle.

However, there are also some important considerations and limitations to make. Drone flights require in-situ validation of observed or assumed species, densities and other metrics. Satellite images can also support the outcomes of the drone survey. The principle of lateral continuation can help to interpolate the seagrass presence/absence, even if it appears to be absent due to low visibility for example.

Optical factors, such as weather, air quality, water depth, water quality and coloration, optics, sunlight reflection and waves, influence the quality of the video footage considerably. This demands careful planning and preparation.

Application of the plume model

The advantage of a schematised model approach as used here is the efficient testing of model sensitivities, providing valuable insight in possible bandwidths of results. Furthermore, setting up a realistic model in a data-poor environment such as Amatique Bay is complex and requires an enormous effort. Improvements to the schematised model can be made if more detailed field data, such as flow velocity, water level and turbidity, at locations of interest is available, enabling verification of the model results.

The set up of a realistic model of Amatique Bay is only feasible and of added value when extensive data sets are collected for model set up, calibration and validation. At minimum, detailed bathymetric data of the entire bay, spatial wind fields, water levels, water depth, flow data and turbidity data at various locations are required. Gathering this data would entail an extensive survey campaign, which was not feasible in this stage of project development.

Seagrass sensitivities in baseline conditions

There is a lack of information on the current levels of exposure and sensitivity of seagrass to turbidity and sedimentation levels within the bay. A key question remains whether the seagrass is naturally adapted to the already high turbidity levels, making them resilient to transitory plumes from the operations or if they are already near or at their maximum ecological threshold, in which case any added perturbation may trigger visible impacts. This made it difficult to determine the added impact of the dredging operation for the Amatique terminal. To determine thresholds values, above which measures are required to protect the seagrass, data of (the variation in) current ambient levels are required. To provide a robust assessment, a precautionary approach had to be adopted. When more information would have been available, a more realistic scenario could have been assessed.

Moving forward

The results of this study have been included in the Environmental Impact Assessment and when the dredging operation starts on the Amatique terminal, an adaptive management approach will be applied. Adaptive management ensures that the effects of the dredging activities will remain within environmental boundary conditions with the aim to limit, if not prevent, any negative impacts to the seagrass beds. This is done by adapting the operation based upon the monitored ecosystem's actual health, particularly of sensitive receivers such as the seagrass beds.

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Summary

In present times, the development of a new marine project demands a system approach, in which all aspects from technical, economic, environmental and social are considered and integrated equally and at an early stage. The process from a first project idea to actual implementation is complex, iterative and time-consuming with many (unknown) variables. For some aspects, there may not be sufficient information available (yet) to make a fully informed decision to feed the project development process. However, choices need to be made to progress the project, assess impacts and risks, and engage stakeholders. This is a dilemma common to those working in marine project development.

This article explores the case of the greenfield development of a new port terminal in Amatique Bay, Guatemala. We developed a method to assess, at an early stage, the potential negative impacts on seagrass habitats from the disposal of dredged material at different locations, while having limited real-time and location-specific information at hand. This method relied on basic surveying and the application of a schematised numerical plume dispersion model. We hope to inspire readers to think about similar cases and share these, so we can learn from each other and enhance our projects, contributing to sustainable development locally and globally.

REFERENCES

Admiralty Tide Tables, Volume 2 (2017)
No 2422 Rio Dulce Entrance (15°50'N 88°45'W near Livingstone, approximately 20 km NW of project area).

CEDA/IADC (2018)
Dredging for sustainable infrastructure. CEDA/IADC, The Hague, the Netherlands.

Czuba J. A., Magirl C. S., Czuba C. R., Grossman E. E., Curran C. A., Gendaszek A. S. and Dinicola R. S. (2011)
Comparability of suspended-sediment concentration and total suspended solids data sediment load from major rivers into Puget Sound and its adjacent waters. USGS fact sheet 2011–3083. Tacoma, WA: U.S. Geological Survey.

Erftemeijer P. L. and Lewis III R. R. R. (2006)
Environmental impacts of dredging on seagrasses: A review. *Marine pollution bulletin*, *52*(12):1553–1572.

Fink J. C. (2005)
'Establishing a relationship between sediment concentrations and turbidity' in The effects of urbanization on Baird Creek, Green Bay, WI (Thesis). http://www.uwgb.edu/watershed/fink/Fink_Thesis_Chap4.pdf