PORT & COASTAL SOLUTIONS

CLINTON VESSEL INTERACTION PROJECT

Fine-grained Sediment Validation Monitoring Plan

Final 1.0

Gladstone Ports Corporation
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Clinton Vessel Interaction Project

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Port and Coastal Solutions Pty Ltd (PCS) has been commissioned by Gladstone Ports Corporation (GPC) to develop a Monitoring Plan to allow the mass of fine-grained sediment (defined by the Department of Environment and Energy (DOEE) as sediment finer than 15.6 µm) predicted to be released by the Clinton Vessel Interaction Project (CVIP) to be validated through field measurements. DOEE requested that this Plan be prepared as part of the preliminary documentation for CVIP.

To prevent the interaction of vessels travelling to and from Wiggins Island Coal Terminal with those berthed at the RG Tanna Coal Terminal, GPC proposes to conduct approximately 800,000 m^3 of capital dredging to widen the Clinton Channel by approximately 100 m. It is proposed by GPC that the material that is dredged as part of the CVIP will be beneficially reused as fill in the Western Basin Reclamation Area (WBRA). The material to be dredged is predominantly sand and gravel sized sediment, with 55% being sand sized sediment, 25% gravel sized sediment, 8% silt and clay sized sediment and the remaining 12% is rock.

As part of a literature review it was found that despite the number of field monitoring campaigns which have been undertaken related to dredging, there have not been any studies which have required the mass of sediment finer than 15.6 µm released by the dredging to be measured. As such, this Monitoring Plan has been able to adopt the overarching monitoring approaches recommended in the literature, however, additional detailed measurements are also required to ensure sufficient data are available to determine the particle size distribution (PSD) of the sediment in the plumes and in the background suspended sediment concentration (SSC).

The Plan provides details of the monitoring required for the range of possible dredging approaches which could be adopted for the CVIP (Trailing Suction Hopper Dredger, Backhoe Dredger and Cutter Suction Dredger). The proposed monitoring includes the following:

- Dredge Activity: a mobile monitoring approach is proposed using a survey vessel to monitor the spatially and temporally varying plumes generated by the dredging. The survey vessel will undertake the monitoring to characterise the dredge plumes using multiple measurement techniques, including an ADCP, optical sensors to measure turbidity and PSD and water sampling (which will be analysed to determine SSC and PSD); and
- Tailwater Discharge: the release of fine-grained sediment from the WBRA will be monitored using a fixed position turbidity meter located within/adjacent to the discharge pipeline, as well as regular water sampling (which will be analysed to determine SSC and PSD) throughout the duration of the tailwater discharge.

The Plan also provides an overview of the data processing required following the monitoring to allow the mass of sediment released by the dredging activity and tailwater discharge to be calculated. Following this the results from the monitoring will be used to define the final best estimate of the mass of sediment finer than 15.6 µm released by the CVIP.

1. Introduction

Port and Coastal Solutions Pty Ltd (PCS) has been commissioned by Gladstone Ports Corporation (GPC) to develop a monitoring plan to allow the mass of fine-grained sediment (defined by the Department of Environment and Energy (DOEE) as sediment finer than 15.6 µm) predicted to be released by the Clinton Vessel Interaction Project (CVIP) to be validated through field measurements.

We understand that following referral of the project by GPC, DOEE determined that the project will be assessed by preliminary documentation. The preliminary documentation is required to provide the additional information requested by DOEE, which includes estimating the mass of fine-grained sediment (<15.6 µm) that will be produced by the CVIP. The mass of fine-grained sediment produced by the CVIP was estimated by PCS (2018a) and BMT (2019). Following completion of these, DOEE requested that a monitoring plan also be prepared, to detail how the estimated mass of fine-grained sediment would be validated during the dredging campaign. It is understood that this Monitoring Plan will subsequently be submitted to the DOEE as part of the preliminary documentation for CVIP.

1.1. Project Overview

Cape-sized vessels travelling to and from Wiggins Island Coal Terminal (WICT) currently pass within 80 m of vessels moored at the RG Tanna Coal Terminal (RGTCT). The passing of vessels in such close proximity to moored vessels results in vessel interactions, whereby forces are imposed on the two vessels due to the displacement of water. These forces may be sufficient to break mooring lines and, in the extreme, have the vessel fully break away from the berth, posing significant safety and economic risks. The CVIP is aimed at providing a permanent solution to this issue created by the interaction forces.

To prevent the interaction of vessels travelling to and from WICT with those berthed at the RGTCT, GPC proposes to conduct approximately 800,000 m^3 of capital dredging to widen the Clinton Channel by approximately 100 m, to a depth of -16 m LAT, with an over-dredging allowance of 0.3 m (Figure 1). In addition, GPC proposes to dredge a small wedge between the Clinton Bypass Channel and Clinton Channel to -13 m LAT, with an over-dredging allowance of 0.3 m (Figure 1). This wedge will enhance safe navigation for other outbound vessels departing Fisherman's Landing, Curtis Island and Wiggins Island, as they transition from Targinie Channel to the Clinton Bypass Channel. Of the 21 hectares of the dredge footprint, 14.1 hectares are located within a current approved channel. It is proposed by GPC that the material that is dredged as part of the CVIP will be beneficially reused as fill in the Western Basin Reclamation Area (WBRA).

1.1.1. Sediment Properties and Dredge Approach

Borehole and bathymetric data were used to develop a soil model for the CVIP dredge area (Figure 2). Based on this the material was found to be predominantly sand and gravel sized sediment, with 55% being sand sized sediment, 25% gravel sized sediment, 8% silt and clay sized sediment and the remaining 12% was rock (PCS, 2018a). Using all the available information it was estimated that 109,300 tonnes of sediment within the CVIP dredge area was finer than 15.6 µm (herein sediment finer than 15.6 µm will be referred to as fine-grained sediment in this report).

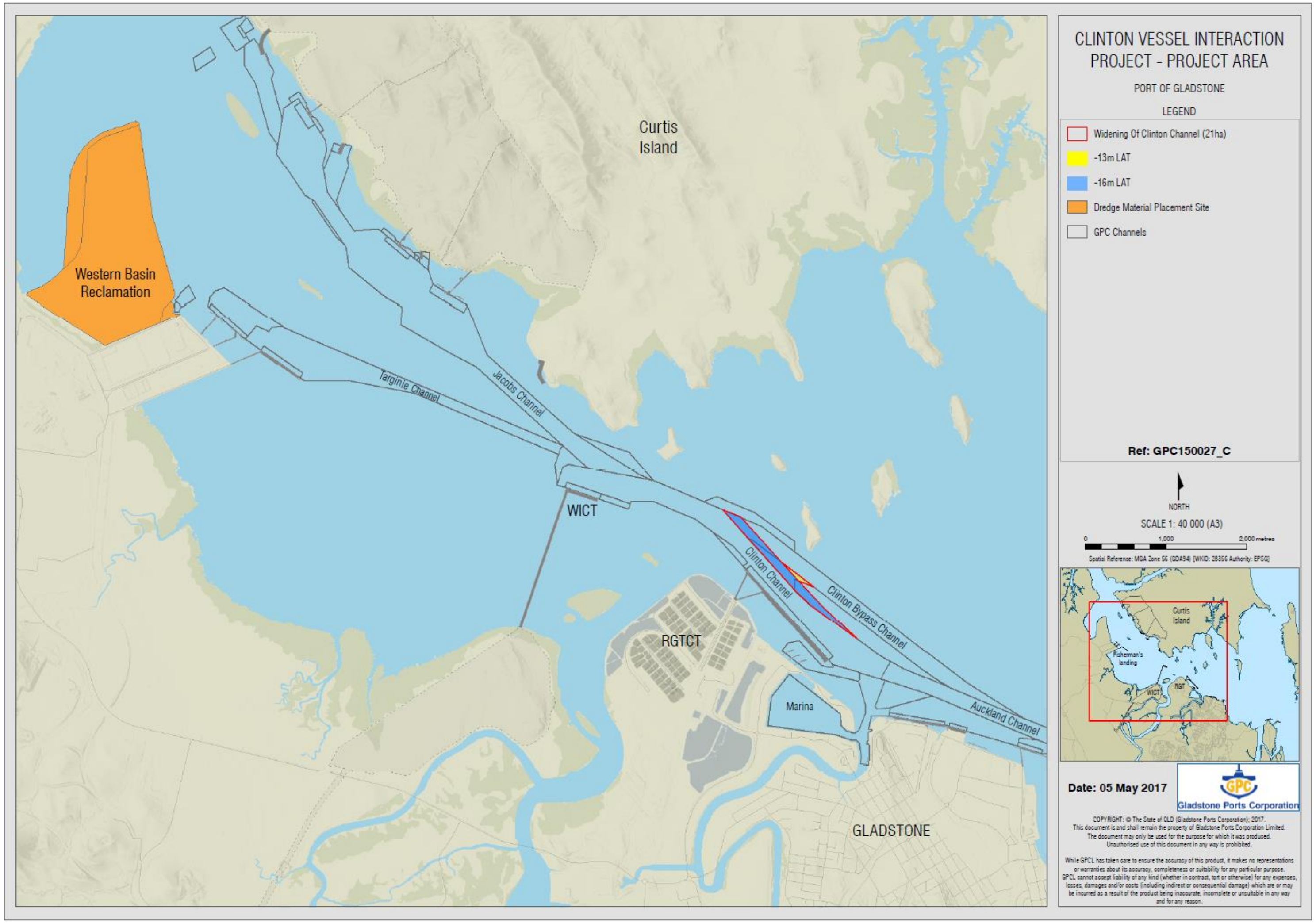

Figure 1. Map showing the proposed dredge area and placement site for the CVIP.

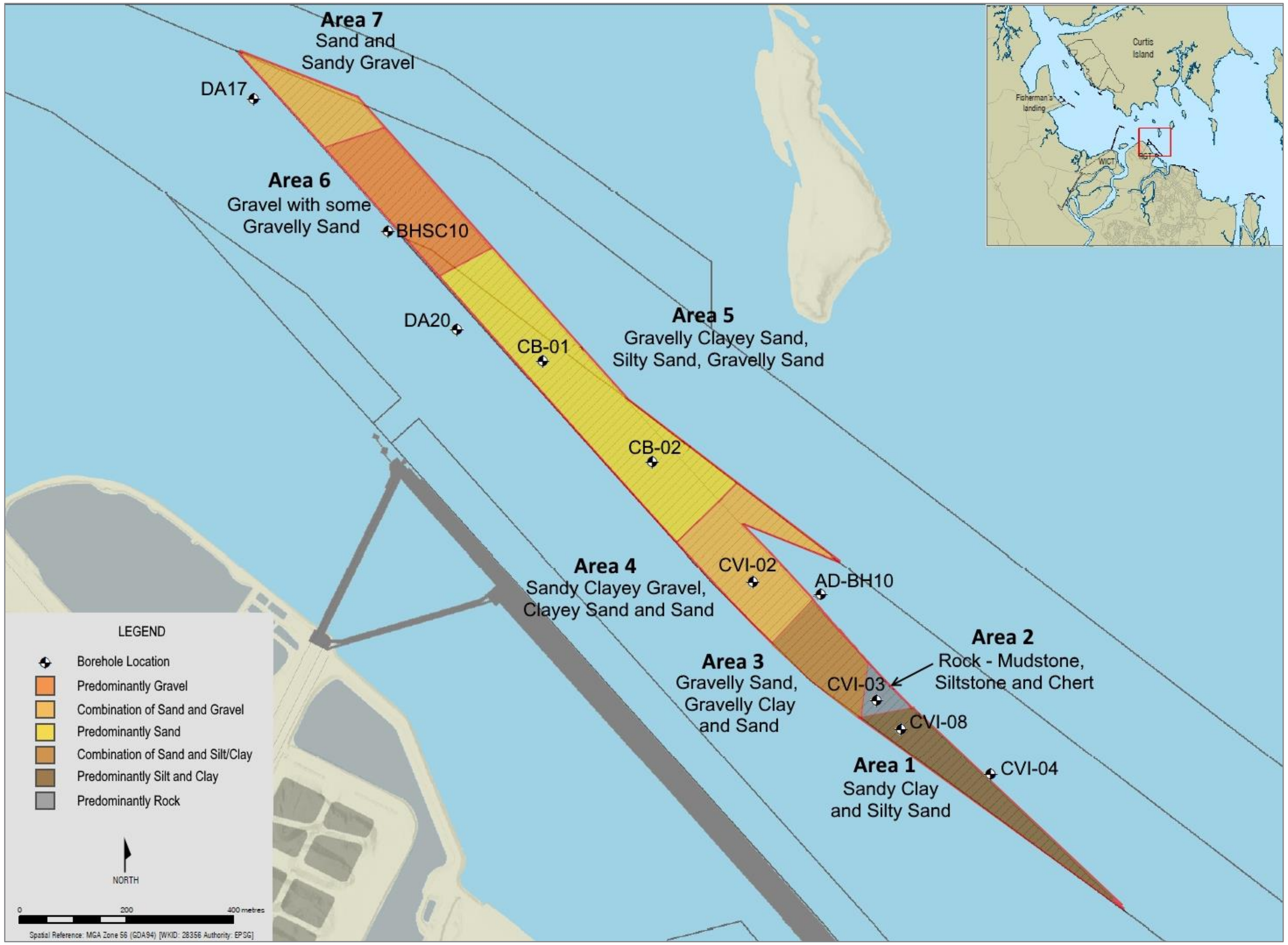

Figure 2. Map summarising the different sediment types within the CVIP dredge footprint (PCS, 2018a).

The dredging plant and approach adopted for the CVIP will depend on what is proposed by dredge contractors when the work goes out to tender. As such, there are a number of different approaches which could be adopted:

- Approach 1: Cutter Suction Dredger (CSD) to break up rock and stiff clay and a Trailing Suction Hopper Dredger (TSHD) to remove the sediment and pump it into the WBRA. The dredge duration is estimated to be 17 weeks. There will be a tailwater discharge from the WBRA which will commence 7.5 weeks after dredging has commenced and will continue until four weeks after dredging is completed;
- Approach 2: TSHD to dredge as much sediment as possible (estimated to be approximately 85%) and pump it into the WBRA. A Backhoe Dredger (BHD) to then dredge the remaining sediment/rock and load it onto barges, where it will be transported to the WBRA. The dredge duration is estimated to be 32 weeks in total, with 24 weeks for the TSHD and 8 weeks for the BHD. There will be a tailwater discharge from the WBRA which will commence 7.5 weeks after dredging commenced and continue until four weeks after dredging is completed; and
- Approach 3: BHD to dredge all sediment/rock and load it onto barges from where it will be transported to the WBRA. The dredge duration is estimated to be 14 weeks. There will be no tailwater discharge from the WBRA as part of this approach.

1.1.2. Fine-grained Sediment Release Estimates

To estimate the mass of fine-grained sediment released by the dredging associated with the CVIP, it was necessary to assume rates that sediment was suspended by the various dredging plant. The assumptions made were based on data from previous dredging projects where measurements have been taken. Source terms are used to define the sediment released by the various dredge plant and stages of the dredging (e.g. cutter head, drag head, overflow, propeller wash etc). The source terms are expressed as a percentage of the total silt and clay (i.e. finer than 63 µm) in the bed sediment which is suspended by the dredging activity. The following source terms were adopted for the CVIP fine-grained sediment assessment (PCS, 2018a and BMT, 2019):

- TSHD
  - Drag head and propeller wash: 2% of the silt and clay sized sediment;
  - Overflow: 80% of the silt and clay sized sediment is lost to the overflow and 15% of this goes into the passive plume[1].
- CSD
  - Cutter head cutting rock and breaking up stiff clay: 2% of the silt and clay sized sediment; and
  - It was assumed that 3% of the chert and silicified mudstone and 10% of the siltstone would be broken down to particles finer than 15.6 µm by the cutter head and that a percentage of these would subsequently be resuspended by the dredging (e.g. 2% by the cutter head).
- BHD
  - Bucket removing sediment: 3% of the silt and clay sized sediment. It was assumed that there would be no mobilisation of fine-grained sediment expected due to the removal of the stone as the BHD would not be expected to break the stone into particles finer than 15.6 µm.
- Tailwater Discharge

[1] passive plumes have minimal density or momentum differences relative to the surround seawater and therefore the transport of passive plumes is controlled by the local hydrodynamics and the settling velocity of the particles (Kemps and Masini, 2017). Sediment suspended by cutter heads and drag heads typically become passive plumes immediately, while the release of suspended sediment from the overflow of TSHD typically results in a dynamic plume and of this a portion will be a passive plume.

- Calculations were based on a discharge of 0.54 m^3/s and a concentration of 100 mg/l (assumed to be entirely fine-grained sediment) which commenced 7.5 weeks after commencement of the TSHD dredging. The discharge rate was assumed to reduce to 0.27 m^3/s (concentration remaining at 100 mg/l) at completion of the dredging and cease four weeks after completion of the TSHD component of the dredging. Details of the TSHD dredge duration for the range of possible dredge approaches are provided in Section 1.1.1. It is important to note that the dredge contractor may need to manage the WBRA in a differently to these assumptions and so it is possible that the tailwater discharge may change.

The mass of fine-grained sediment estimated to be released by the dredging activity and tailwater discharge for the three possible dredge approaches were calculated by PCS (2018a) and BMT (2019) and are detailed below:

- Approach 1 (CSD and TSHD): 16,880 tonnes from the dredging activity and tailwater discharge;
- Approach 2 (TSHD and BHD): 13,760 tonnes from the dredging activity and tailwater discharge; and
- Approach 3 (BHD): 3,130 tonnes from the dredging activity (no tailwater discharge).

1.2. Aims

The overall aim of this monitoring plan is to detail the monitoring required to be able to validate the quantity of fine-grained sediment (defined by DOEE as sediment finer than 15.6 µm) released due to the CVIP. It is therefore necessary for the plan to consider the range of different dredging approaches which could be adopted and if necessary specify different monitoring methods for different dredging approaches. The monitoring will be required to detail the measurements needed for the different potential sources of fine-grained sediment resulting from the Project, these will include sediment released by the dredging activity and from the tailwater discharge from the WBRA (if required).

It is important to note that this plan is only aimed at detailing the monitoring required to allow the validation of the mass of fine-grained sediment released by the CVIP and does not provide details of other monitoring related to compliance or adaptive management.

1.3. Report Structure

The report is set out as follows:

- Section 1 introduces the scope of work and outlines the aims;
- Section 2 reviews available literature relevant to the Monitoring Plan;
- Section 3 details the methods proposed for the monitoring;
- Section 4 discusses how the data will be used following the field monitoring campaign; and
- Section 5 summarises the components of the Monitoring Plan discussed within the previous sections.

2. Literature Review

2.1. Overview

As detailed in Section 1.2, this Monitoring Plan is aimed at providing sufficient field data to validate the mass of fine-grained sediment estimated to be released by the dredging and tailwater discharge associated with the CVIP. The monitoring will therefore be required to do the following:

- to monitor the plumes suspended by the various aspects of the dredging activity and the tailwater discharge and differentiate them from the natural ambient suspended sediment;
- to measure the particle size distribution (PSD) of the suspended sediment in the plumes to determine the mass of fine-grained sediment;
- to understand how the plumes vary depending on the sediment type being dredged; and
- to ensure that suitable and sufficient data are collected to enable the total mass of fine-grained sediment estimated to be released by the CVIP to be validated and if necessary refined based on the monitored data.

The following sections provide details of the relevant literature along with a summary of the recommended monitoring techniques and any limitations or uncertainties which are considered important.

2.2. Monitoring Background

There have been numerous field monitoring campaigns which have been aimed at quantifying the source terms generated by different dredging activities. The monitoring has typically been undertaken to further calibrate and validate numerical models which have been adopted to identify any potential impacts of the dredging.

In an attempt to standardise the monitoring approaches which were adopted, HR Wallingford and Dredging Research developed the '*Protocol for the Field Measurement of Sediment Release from Dredgers'* (HR Wallingford and Dredging Research, 2003). This document has been widely adopted to inform monitoring activities and can be considered the main guidance document.

Despite the number of field monitoring campaigns associated with dredging, there have not been any studies which have required the mass of sediment finer than 15.6 µm released by the dredging to be measured. As such, the Monitoring Plan required for the CVIP can adopt the overarching monitoring approaches detailed in the literature, however, additional detailed measurements will also be required to ensure sufficient data are available to determine the PSD of the sediment in the plumes.

2.3. Reviewed Literature

The reports, papers and other documents which have been considered as part of this literature review are listed below in date order (oldest first):

- HR Wallingford and Dredging Research, 2003. Protocol for the field measurements of sediment release from dredgers.
- Aarninkhof, 2008. The day after we stop dredging: a world without sediment plumes?
- Bray, 2008. Environmental aspects of dredging.
- SKM, 2008. Dredging verification studies at Cape Lambert.
- BMT WBM, 2011-2017. Maintenance dredging plume monitoring studies (various ports).
- Spearman et al., 2011. Validation of the TASS system for predicting the environmental effects of trailing suction hopper dredgers.

- INPEX, 2013. Dredging and spoil disposal management plan – East Arm.
- De Wit, 2015. 3D CFD modelling of overflow dredging plumes.
- Kemps and Masini, 2017. Estimating dredge source terms – a review of contemporary practice in the context of Environmental Impact Assessment in Western Australia.
- Fearns et al., 2017. Optical remote sensing for dredge plume monitoring: a review.
- Fearns et al., 2018. Plume characterisation – laboratory studies.
- Beecroft et al., 2019. Suspended sediment transport in context of dredge placement operations in Moreton Bay, Australia.

2.4. Monitoring Techniques

As an overarching philosophy for the monitoring of sediment plumes resulting from dredging, HR Wallingford and Dredging Research (2003) suggest the following:

- measure as much as possible as close as possible to the practical source of the sediment being released and at varying distances away from it;
- measurements have to be supported by full details of the dredging operation, otherwise they are of no use; and
- measurements will be more reliable if they are made in open, unobstructed locations with uniform soil conditions and low natural suspended sediment concentrations (SSC).

The literature details a number of monitoring techniques which can be adopted to monitoring plumes resulting from dredging or tailwater discharges, these are summarised in the following sections. Typically, a number of these measurements are made concurrently, and the exact measurement requirements depend on the dredging approach. The monitoring requirements for the CVIP are detailed in Section 3.2.

2.4.1. Acoustic Doppler Current Profiler

In order to determine the flux of sediment released into suspension from the dredging it is necessary to obtain measurements of both the current speed and the SSC throughout the cross-sectional area of the plume. Depending on the dredging approach the resultant plume could either be small and of a relatively short duration in the order of minutes to tens of minutes (e.g. BHD) or large and of a much longer duration in the order of tens of minutes to hours (e.g. overflow from a TSHD).

The only technique which can be adopted to measure this variation in plume characteristics is to use Acoustic Doppler Current Profilers (ADCPs). These devices can be fixed in a downward facing position to a survey vessel or hull-mounted to allow measurements of the water current in discrete cells through the water column. In addition, ADCPs are also able to measure the intensity of the acoustic backscatter resulting from particles in the water column, and this measurement can subsequently be calibrated to determine the SSC (Thorne et al., 1991). Specific software has been developed (e.g. SediView) to assist with the calibration of backscatter to SSC (Taylor et al., 2013), although additional measurements of water temperature and salinity are required as well as the SSC derived through water sampling.

It is preferable for the ADCP transects to be undertaken when there is some natural current as this will transport the plume resulting from the dredging away from the dredger. The transects should be undertaken at varying distances away from the dredger and extend beyond the extent of the plume at both ends of the transect to ensure the natural background turbidity is also measured. It is recommended that preliminary testing is undertaken to determine how close to the dredger the ADCP transects can be undertaken. This is because dredging has the potential to generate bubbles in the water column which can result in erroneous (very high) backscatter readings.

2.4.1.1. Suitability

This monitoring technique can be adopted to monitor the plumes resulting from all types of dredging and is especially suitable for semi-stationary dredgers (e.g. BHD, CSD and grab dredger). It was noted by HR Wallingford and Dredging Research (2003) that due to the large amount of air bubbles generated by both the propeller and overflow from a TSHD it is only possible to monitor the far-field plume decay (in the order of minutes after the plume is formed) using ADCPs. This monitoring technique has been shown to be able to successfully measure plumes from overflowing TSHDs (e.g. INPEX, 2011; Spearman et al., 2011; and de Wit 2015), but it is important that initial sensitivity testing is undertaken prior to dredging to ensure the monitoring is not being contaminated by air bubbles which would result in unrealistically high backscatter measurements.

The ADCP measurements require the following additional measurements to be collected to ensure the backscatter can be converted to SSC:

- water samples are required to be collected during each transect so the total SSC can be determined in the laboratory and correlated back to the backscatter measurements;
- temperature and salinity data need to be collected through the water column during the transects as these are required to allow the backscatter to be correlated to SSC; and
- turbidity profiling is required to measure the near surface and near bed turbidity in the plume, as the ADCP is not able to measure the upper 1 to 2 m or the bottom 5-15% of the water column.

This monitoring technique has been adopted for numerous dredging campaigns for the Ports in Queensland, the rest of Australia and Europe (SKM, 2008; BMT WBM, 2011; Spearman et al., 2011; INPEX, 2013; de Wit, 2015; BMT WBM, 2016; BMT WBM, 2017a; and BMT WBM 2017b).

2.4.2. Turbidity Sensors

Turbidity in the water column can be measured in-situ by a range of different optical sensors, these are typically based on the scattering of light to derive a measure of water turbidity which is reported in nephelometric turbidity unit (NTU) (Fearns et al., 2018). The turbidity sensors provide a measurement of the turbidity at a single point. Some instruments with turbidity sensors also include other sensors such as temperature, salinity and pressure which means that some of the additional data required to support the ADCP measurements can be undertaken by the same instrument. For monitoring dredge plumes, it is recommended to use the sensors either as a towed array or as a profiling instrument:

- Towed array: a series of sensors are spaced along a cable which is towed behind a survey vessel to allow concurrent turbidity data to be collected at varying depths through the water column (minimum would be three sensors at near bed, mid-depth and near surface layers of the water column); and
- Profiling: the turbidity sensor is raised and lowered through the full water column as the survey boat slowly passes through the plume.

For both monitoring approaches it is important that each turbidity sensor is accompanied by a pressure sensor so the depth of the measurements can be determined.

2.4.2.1. Suitability

The use of turbidity sensors can be adopted for all types of dredgers and for monitoring tailwater discharges. However, it is important to note that similar to the ADCP backscatter measurements, turbidity sensor data can also be contaminated by air bubbles generated by the dredging and so it is important to ensure that measurements are not collected too close to the vessels, this is particularly important for the TSHD due to the propeller wash and overflow.

As the instruments are only able to measure the turbidity at a single point, they are not able to provide the level of detail required to accurately define the plume. As a result, the turbidity measurements are often collected in addition to the ADCP transect to provide additional information, increasing the level of confidence and assisting with the calibration of the ADCP backscatter data.

It is necessary to collect water samples to calibrate the turbidity measurements and allow a conversion from NTU to SSC (in mg/l) to be developed. The calibration between NTU and SSC is complex and due to variability in parameters, such as the sediment type, concentration and particle shape, it is often necessary to develop multiple conversions for a range of conditions (e.g. for background SSC and for SSC from dredging).

Both turbidity sensor plume monitoring approaches have been widely adopted globally and they have typically been adopted in addition to ADCP backscatter measurements. In Australia turbidity sensors have more commonly been adopted as a profiler (e.g. SKM, 2008; BMT WBM, 2011; BMT WBM, 2016; BMT WBM, 2017a; and BMT WBM 2017b), although an array of turbidity sensors has also been successfully adopted (INPEX, 2013).

2.4.3. Water Sampling

Determining the SSC through direct sampling of the water column involves collecting a known volume of water, passing the water through a filter to remove the particulates and then weighing the solid residue (Fearns et al., 2017). Water samples at different depths in the water column are commonly either collected using bottle-type samplers or water pump samplers. The bottle-type samplers are able to provide near-instantaneous samples while the water pump samplers take longer to collect the samples, as such it is recommended for dredge plume monitoring that bottle-type samplers are usually adopted, these can be housed in a multi-bottle rosette type sampler which can enable up to 12 samples to be collected through the water column very quickly (~1 minute).

Water sampling alone is not able to provide sufficient information to allow an understanding of the plume resulting from dredge activity. It is however a critical component to ensure other in-situ measurements (e.g. ADCP backscatter, turbidity data) can be reliably converted to SSC. In addition, some of the water samples can also be analysed for particle size distribution (PSD) to provide an understanding of the PSD of the sediment suspended in the plume.

Direct water samples can also be collected from the overflow of the TSHD (in vessels which have an open hopper) to allow the actual mass of sediment lost from the overflow (both in the dynamic and passive plume) to be estimated (HR Wallingford and Dredging Research, 2003; and Arninkhof, 2008). In addition to the water samples, the flow rate of the overflow needs to be known, this will be the same as the flow rate into the hopper and as such the dredger should have instrumentation which continuously measures this flow rate.

2.4.3.1. Suitability

Water sampling is an essential component of all plume monitoring studies as it is the only approach which directly samples the suspended sediment and subsequently can be used to calibrate other measurements. The approach can be adopted for all dredging approaches and for tailwater discharges. In addition, water sampling can also be used to determine the PSD of the suspended sediment although this is not always possible if the SSC is too low.

2.4.4. Laser Diffraction

Optical sensors have been developed based on laser diffraction to determine scattering and transmissometry, these can be used to determine the in-situ PSD and volume concentration of suspended sediment. It was noted by Mikkelson and Pejrup (2001) that laser diffraction instruments need to be adopted in the field if reliable assessment of PSD and flocculation are to be made. In many cases this is not a direct requirement for the monitoring of dredge plumes, but if it is important to have a good understanding of the variability in PSD of the sediment suspended by dredging then this type of measurement would be very useful.

An example laser diffraction instrument is the laser in-situ scattering and transmissometry (LISST). The instrument provides a measurement of the volume concentration and PSD of the in-situ, unagitated suspended sediment at a single point. The instrument can be used to provide continuous measurements and used as a profiler or as an instrument in a towed array.

In order to convert the volume concentration into SSC it is necessary to collect and analyse water samples. The water samples can also be analysed for PSD in the laboratory using agitation and a dispersant to break-up existing flocs (fine-grained cohesive particles can stick together to form flocs) and prevent flocculation. These data can then be compared with the corresponding field measurements collected by the LISST instruments to provide an understanding of the number and size of flocs in suspension. This approach was adopted at the Port of Brisbane where large low-density flocculated material was identified as the key transport form of fine cohesive sediment at a dredge placement area (Beecroft et al., 2019).

2.4.4.1. Suitability

As with turbidity sensors, this approach is suitable for monitoring all types of dredging as well as tailwater discharges. However, it is important to note that similar to the ADCP backscatter and turbidity measurements, the PSD and volume concentration data can also be contaminated by air bubbles generated by the dredging and so it is important to ensure that measurements are not collected too close to the vessels, this is particularly important for the TSHD due to the propeller wash and overflow.

As the instruments are only able to measure at a single point, they are not able to provide the level of detail required to accurately define the plume. The LISST instruments are therefore typically adopted to provide additional PSD and volume concentration data to compliment additional ADCP and turbidity measurements.

It is necessary to collect water samples to calibrate the LISST measurements and allow a conversion from volume concentration to SSC (in mg/l) to be developed. In addition, the water samples can also be used to provide an understanding of the relative importance of flocculation on the in-situ PSD data.

The approach has not been widely adopted for monitoring dredge plumes globally, but it has been adopted for a number of dredge plume monitoring studies in Australia such as Onslow, Dampier, Cape Lambert (Fearns et al., 2018), Port of Brisbane (Beecroft et al., 2019) and Port of Gladstone (PCS, 2018b).

2.4.5. Remote Sensing

The monitoring techniques discussed in the previous sections all involve direct sampling through in-situ methods which can provide accurate measures of plumes from dredging, but their spatial coverage is limited. There are optical remote sensing approaches which can provide reliable spatial maps of a plumes extent and the SSC/turbidity (Fearns et al., 2017).

Remote sensing for marine and coastal environments can be undertaken by sensors mounted on satellites, aircraft, unmanned airborne vehicle (e.g. drones) and boats. The sensors rely on having an uninterrupted view of the water surface and so it is not possible to measure using a satellite mounted sensor when there is cloud cover. Existing satellite mounted sensors have a set spatial resolution and measurement frequency which when combined with possible cloud cover limitations, could be restrictive for monitoring dredge plumes.

The data from remote sensing measurements are not a direct measure of the water column and so the water conditions are inferred based on algorithms. There are therefore inherent uncertainties and limitations associated with the data and as with all data, it is preferable if the processed data can be validated using in-situ measurements, to increase its reliability.

2.4.5.1. Suitability

Remote sensing provides an approach which can be used to determine the spatial variability in a dredge plume and as such it could be used for any dredging approach. The data can be used to provide an indication of the spatial extent of any plumes and the turbidity close to the water surface, but it will not be able to be used to determine the mass of sediment released by dredging. As such, remote sensing techniques are considered to be best suited for calibrating and validating numerical models.

Existing satellite sensors which have a daily measurement frequency only have a spatial resolution of 250 – 300 m, which would be unlikely to be able to directly identify a plume from dredging. The existing high-resolution satellite sensors (10 – 30 m spatial resolution), which would be able to identify larger plumes from dredging (e.g. from the overflow of a TSHD), have measurement frequencies of once every five to eight days. Based on this, any satellite derived turbidity data would only be able to provide additional information to the in-situ measurements.

Non-satellite remote sensing techniques could also be adopted by mounting sensors onto other vessels, but the cost of this is typically high if reliable, georeferenced, quantitative data are required. An alternative would be to obtain qualitative data by using a drone to film the plume dispersion when other in-situ measurements are also being undertaken, this would provide a useful reference to the in-situ measurements and could be used to assist in any future numerical model validation, but would not be able to directly contribute to any quantitative calculations.

3. Methods

3.1. Introduction

Based on the information available from existing literature and previous monitoring campaigns, a Monitoring Plan has been developed to validate the quantity of fine-grained sediment (defined by DOEE as sediment finer than 15.6 µm) released due to the CVIP.

The approach for the Monitoring Plan is detailed in Section 3.2, while the timeframes and any limitations associated with the monitoring are discussed in Sections 3.3 and 3.5. How the measurements will be used to validate the mass of fine-grained sediment released by the CVIP is detailed in Section 4.

3.2. General Approach

Based on information from the available literature no single monitoring technique is able to provide an accurate measurement of the fine-grained sediment released by the CVIP on its own. Therefore, a combination of monitoring techniques is required. It is also important to note that due to the complexities of dredge plumes generated by the dredging activities and limitations of the monitoring techniques, the monitoring will only be able to provide data which can subsequently be analysed and processed to estimate the mass of fine-grained sediment released by the dredging, rather than providing a direct measure of the mass released. This is discussed further in Sections 3.4 and 3.5.

A generic approach for the Monitoring Plan has been developed, which requires the same measurements to be collected regardless of the dredging approach adopted. As plumes resulting from the dredging will vary spatially and temporally it will not be feasible to install fixed position loggers. Consequently, it is proposed for mobile monitoring to be undertaken using a survey vessel. The survey vessel will undertake the monitoring to characterise the dredge plumes, this will include multiple measurement techniques including an ADCP, optical sensors and water sampling to measure turbidity and PSD. The survey vessel and the dredge vessel will need to be in regular contact to coordinate the monitoring activities relative to the dredging being undertaken. The measurements required to monitor the dredging activity are detailed in Section 3.2.1.

If the dredging approach adopted results in a tailwater discharge from the WBRA (Approaches 1 and 2) then the release of fine-grained sediment from the WBRA will be monitored using a fixed position turbidity meter as well as water sampling. Further details of the measurements required to monitor the tailwater discharge are detailed in Section 3.2.2.

3.2.1. Dredging

During the period when the monitoring is being undertaken it will also be important to obtain detailed information from the dredge vessel including the dredge log (e.g. dredger location, when dredging or pumping and flow rate into hopper (if applicable).

It will be important to ensure that the period selected for the monitoring is during a period with relatively calm conditions when natural turbidity will be low. It is therefore suggested that the monitoring is planned to commence around the first set of neap tides after the dredging commences as this is when turbidity is typically low in the CVIP area.

3.2.1.1. ADCP Measurements

To measure the current speed and the optical backscatter throughout the cross-sectional area of the plume (which will subsequently be converted to SSC), a vessel mounted ADCP will be used. The ADCP should be configured with real time navigational data from a differential Global Positioning System (GPS) to ensure that the measured backscatter data are referenced to actual coordinates.

The ADCP will be used to measure transects perpendicular to the dredge plume, with the transects starting and ending outside of the plume (Figure 3). The transects should be undertaken at variable distances away from the dredger, although the majority of measurements should be undertaken as close to the plume generation point as possible (how close this can be is discussed later in this section). When monitoring dredging which results in small plumes (BHD and CSD) it will be important for the survey vessel to pass through the plume as slowly as possible (while maintaining steerage) to increase the resolution of the ADCP measurements.

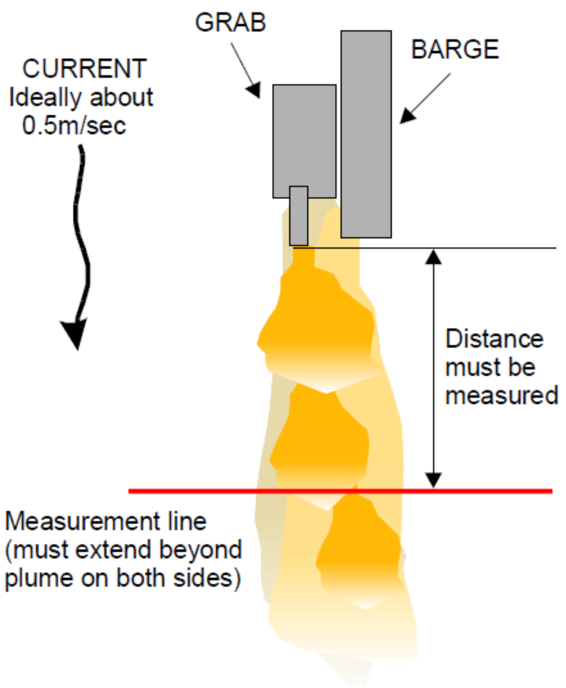

Figure 3. ADCP transect of sediment plume down-current from a dredger (HR Wallingford and Dredging Research, 2003).

Prior to dredging commencing it is recommended that trial transects are measured when the dredge vessels which have the potential to generate bubbles in the water column (BHD and TSHD) are operating but not dredging any sediment, (i.e. undertaking the same actions they would when dredging but without disturbing the seabed, the TSHD would still be overflowing water and sailing as they would when dredging). This will provide an indication of the time since the plume was generated (and an indication of the distance away from the dredger) that the ADCP can measure transects without any contamination from bubbles. For a BHD previous studies have found this to be 100 – 200 s after the plume was generated (so 50 – 100 m away from the dredger if a 0.5 m/s current speed is assumed) (HR Wallingford and Dredging Research, 2003). For a TSHD it is harder to define the point when air bubbles have dissipated and it is largely dependent on the dredger, but it is noted by HR Wallingford and Dredging Research (2003) that measurements within the first 15 minutes of the plume formation should be treated with caution. Backscatter measurements should be constantly reviewed in real-time by experienced engineers as an ongoing check of the data quality throughout the field monitoring period.

3.2.1.2. Optical Sensor Measurements

Concurrent turbidity, PSD/volume concentration, temperature and salinity data should be collected with each ADCP transect. Instruments could either be setup as a towed string array with multiple turbidity meters (and temperature, salinity and pressure sensors if not included in turbidity meter) and LISST instruments at varying depths through the water column, or a turbidity meter (and temperature, salinity and pressure sensor if not included in turbidity meter) and LISST instrument could be used to profile the water column repeatedly during each transect (Figure 4). The profiling approach would be preferable as this would be more likely to be able to measure close to the seabed and near the surface where the ADCP will not be able to measure.

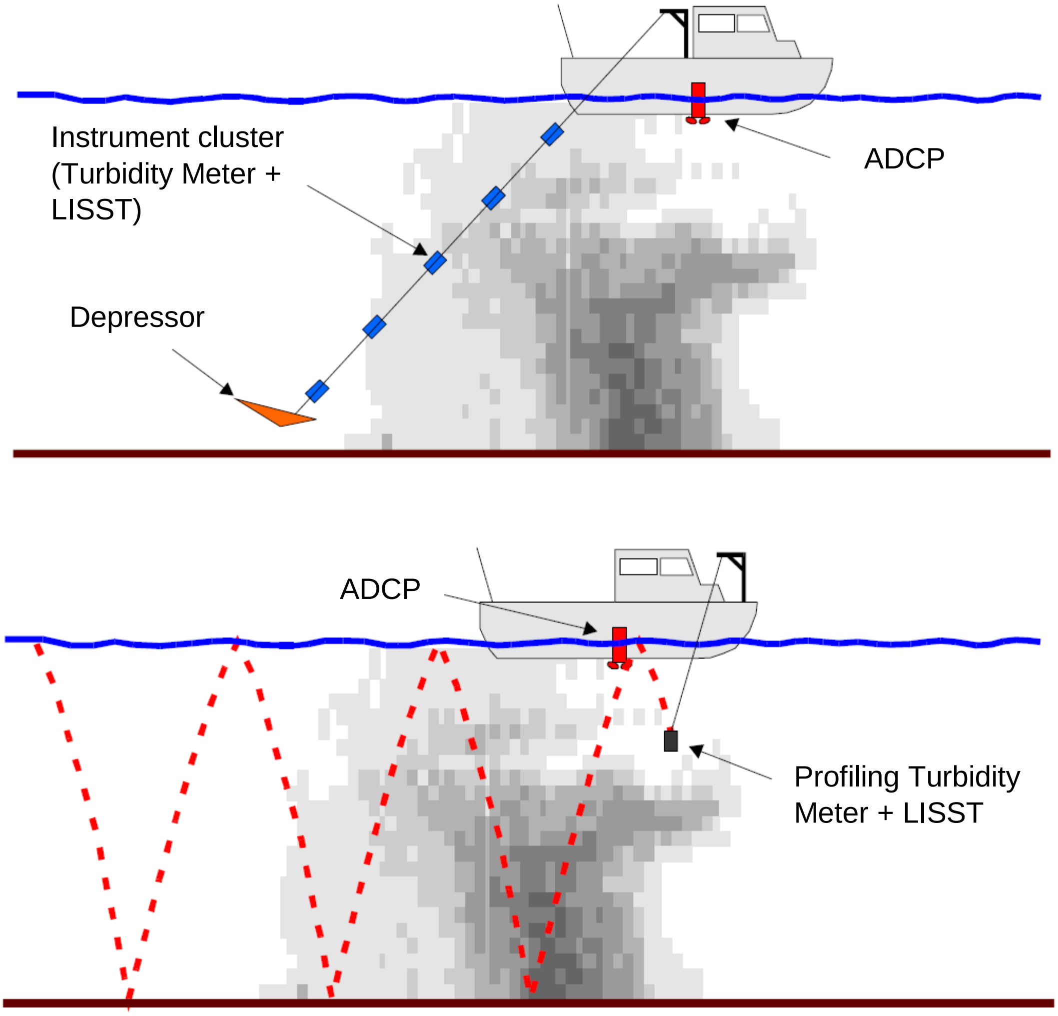

Figure 4. Schematic showing example of towed array (top) and profiling turbidity meter (bottom) (HR Wallingford and Dredging Research, 2003).

3.2.1.3. Water Sampling

To calibrate the ADCP, turbidity and LISST data it will be necessary to collect numerous water samples throughout the field monitoring period. It is recommended that the water sampling is undertaken using bottle-type samplers, with a multi-bottle rosette type sampler to allow multiple samples to be collected through the water column very quickly while undertaking the ADCP transects and optical sensor measurements. It is recommended that at least three water samples are collected during each ADCP transect across the dredge plume and that these are collected at variable depths and concentrations of the plume.

The water samples would subsequently be analysed in the laboratory to determine the SSC (all water samples) and the PSD of the suspended sediment (selected water samples).

3.2.2. Tailwater Discharge

As the tailwater discharge from the WBRA will be through a discharge pipeline, which will not move over the duration of the dredging, dual (to allow for redundancy) fixed position turbidity meters should be used to accurately measure how the turbidity in the tailwater discharge varies over time. The turbidity meters could either be telemetered to provide near real-time data or they could be self-logging with data downloaded during each servicing trip. It would be preferable for the turbidity meters to have wiping mechanisms to reduce biofouling of the sensors over time.

To calibrate the turbidity data and also to define the PSD of the suspended sediment it will also be necessary to collect water samples from the tailwater discharge. These should be collected during tailwater discharge periods. The water samples should be analysed in a laboratory to determine the SSC (all samples) and the PSD (some samples) of the sediment in suspension. It is suggested that daily water samples are collected during the first week that there is tailwater discharge and after this weekly water samples are collected until the tailwater discharge ceases.

It will also be necessary to measure the discharge rate through the tailwater discharge pipe. It is assumed that discharge data will be collected as part of the land reclamation work as this will likely be a compliance requirement. If this is not the case then the discharge will need to be measured as part of this monitoring.

3.3. Measurement Duration

The duration of time that the monitoring of the dredging activity is required will vary depending on the dredging type. This is because the extents and durations of the resultant plume will vary significantly, as well as the sediment being dredged. Additional measurements of individual plumes are required for dredgers which work in an intermittent manner and create separate short duration plumes (e.g. BHD) and less measurements for dredgers that operate relatively continuously (e.g. CSD) (HR Wallingford and Dredging Research, 2003). An indication of the duration that monitoring should be undertaken for each dredge type is provided below:

- BHD: the BHD will be excavating individual buckets of sediment from the seabed and then pulling these through the water column and placing them into barges. Therefore, the BHD will create regular short duration plumes which are likely to be variable depending on the bed sediment. Vessel based monitoring over a single day near the start of the dredging should be appropriate to monitor a large number of separate plumes, which should be sufficient to characterise the sediment released by the dredging. As the BHD is only removing sediment from a small section of the seabed at any time, the composition of sediment being dredged will vary over the duration of the dredging. It is therefore recommended that additional monitoring be undertaken during the dredging when the BHD is dredging different sediment types such as stiff clay and rock.
- CSD: the CSD will be operating almost continuously cutting/breaking up stiff clay and rock. Therefore, the plume from the dredging should be well formed and therefore well developed (i.e. reach a quasi-equilibrium), making the monitoring more straightforward. Vessel based monitoring over a single day near the start of the dredging should be sufficient to characterise the sediment released by the dredging. An additional day of monitoring should also be undertaken when the CSD starts to dredge a different bed type (i.e. when it goes from rock to stiff clay or vice versa) to allow the fine-grained sediment released by both activities to be characterised.

- TSHD: the TSHD is expected to be dredging for just under five hours during each dredge cycle and then sailing to and from the WBRA and pumping the hopper load into the WBRA for the next five to six hours. The TSHD is likely to undertake the dredging for the CVIP by sailing along the length of the dredge area and dredging continuously. Therefore, the plume resulting from the TSHD is unlikely to change significantly over the duration of the dredging as variable sediment types will be dredged during each run along the length of the dredge area. It is recommended that at least three days of vessel based monitoring is undertaken near the start of the dredging to characterise the sediment released by the dredger. It is hoped that this would allow monitoring of at least five plumes created by the first dredge run along the length of the dredge area when no overlap of previous plume footprints would occur. It is expected that the TSHD will undertake multiple runs along the length of the dredge area while filling the hopper, and so it is possible that some of the plume from the previous run could combine with the newly formed plume, which would make it difficult to accurately determine how much suspended sediment the dredger is releasing.

After the initial monitoring is undertaken at the start of the dredging campaign, the data will be processed to estimate the mass of fine-grained sediment released into suspension from each type of dredger (this may only be one type of dredging depending on the approach). Based on the potential errors of the various aspects of the monitoring (see Section 3.4) and the differences between predicted and measured sediment fluxes from dredgers noted in the literature (average of 31% with a range from 1% to 60% (de Wit, 2015), see Section 3.4 for further details), a relative error for the measurements of ±30% is proposed. If the calculated mass of sediment released by the dredger using the measured data is within 30% of the predictions then no additional monitoring is required, but if the difference between the predicted and measured masses is greater than this it is recommended that the following should be undertaken:

- numerical modelling over the monitoring period to compare with the measured data. The model set up should be run with source terms based on the original estimates and updated values based on the measured data (and potentially an average of the two values if there is a significant difference), to provide a comparison. This comparison can be used to determine which source term provides the better comparison with the measured data; and
- additional targeted vessel-based monitoring should be undertaken to provide additional data to verify the mass of fine-grained sediment released by the dredging. The monitoring should be undertaken specifically for the dredging technique where the estimated and measured masses released differ by more than ±30% and the duration of the measurements should be similar to those undertaken during the initial monitoring campaign.

Following any additional monitoring required the same process should be undertaken to determine if the mass of fine-grained sediment released is comparable to either the original estimates or the updated values based on the previous measured data. If there is still a significant discrepancy and no reasonable explanation (e.g. different sediment type being dredged) then additional numerical modelling and monitoring should be undertaken as noted above. If after three iterations of the numerical modelling and monitoring the mass of fine-grained sediment released is still not comparable to either the original estimates or the updated values based on the previous measured data then it will be assumed that the source terms released by the dredging are highly variable and the data from the three monitoring periods and associated numerical modelling will all be used to calculate the mass of fine-grained sediment released.

3.4. Data Confidence

During dredging activities sediment can be released or mobilised at a number of locations, at varying rates through the dredge cycle and at varying depths in the water column (HR

Wallingford and Dredging Research, 2003). This combined with the spatial and temporal variability of the natural environment where the dredging is being undertaken, means that dredge plumes are highly complex in their spatial extent and variability in the water column, creating the potential to result in large gradients in SSC over small distances. Based on this, it is important to consider the relative confidence which can be placed in the data collected during the monitoring programme. The following examples from case studies can be used to provide an indication of the potential errors associated with data collection, processing and interpretation. These potential errors can be used to estimate the level of confidence which can be placed on the data:

- laboratory comparison of SSC measurements (Fearns et al., 2018): under laboratory conditions triplicate water samples for varying SSCs were collected from a 1.7 x 1.5 m tank and analysed to determine the mass of sediment in each sample. More than 80% of the SSC of the triplicate samples varied by less than 15% from their mean, although some samples varied by approximately 60% from their mean. This highlights the spatial variability in SSC which can occur over a small area and suggests that a water sample has a potential error of at least ±15%.
- calibration of ADCP backscatter to SSC (HR Wallingford and Dredging Research, 2003): it was noted in the field measurement protocol that for an ADCP backscatter to SSC calibration to be satisfactory, at least 80% of the ADCP SSC estimates should be within ±20% of the measured SSC from the water samples. This indicates that there is at least a potential error of ±20% in ADCP SSC estimates.
- predicted and measured SSC during TSHD overflow (de Wit, 2015; and Spearman et al., 2011): using field measurements (ADCP, optical sensors and water samples) made during the overflow of a TSHD, the release of sediment from the dredging was calculated and compared to predictions based on empirical data (derived from previous field measurements) and computational fluid dynamics (CFD) modelling. The prediction of the overflow concentration based on the empirical data was (on average) within 17% of the peak concentration measured (based on 17 cases). As this is an average of the difference, it is expected that for some cases the differences would have been significantly larger. The prediction of the sediment flux from the overflow based on the CFD modelling was (on average) within 31% of the sediment flux derived from the ADCP SSC measurements (based on 6 cases), with the differences varying from 1% to 60%. This highlights the variability of plumes generated by a dredger and the difficulty in accurately predicting the flux of sediment released.

As well as understanding the relative confidence which can be placed in the data and therefore the calculated release of sediment from the dredger, it is also important to ensure that any limitations associated with the monitoring are understood so that the data collected are reliable. The limitations associated with the various monitoring techniques proposed are discussed in Section 3.5.

3.5. Monitoring Limitations

Details of limitations associated with each type of monitoring are provided in Section 2.4 and a summary of the key limitations associated with the proposed monitoring for the CVIP are provided below:

- Generation of air bubbles: most dredge techniques result in the creation of air bubbles in the water column which create the potential to corrupt acoustic and optical measurements. A trial ADCP monitoring campaign has been proposed to determine how close to the various dredgers monitoring can reliably be undertaken. It is expected that the plume footprint resulting from a TSHD operating in overflow mode will not be able to be measured close to the vessel, which means that the monitoring will be focused on the far-field passive plume. It is the passive plume which is of interest for the monitoring, as any sediment which is in the dynamic plume (which is rapidly deposited close to the dredger) has not been included in the estimated mass of fine-grained sediment released by the CVIP.

- Survey vessel manoeuvrability: it can be challenging to accurately monitor very small plumes as the survey vessel is required to sail very slowly through the plume which can result in a loss of steerage. If approach 3 (BHD to undertake all dredging) is adopted then it would be preferable to select a vessel which is able to maintain control while sailing very slow (e.g. 1 knot).
- Flocculation: in-situ measurements of PSD will be influenced by any flocculation of cohesive sediment and can therefore show a larger amount of coarse silt and sand sized sediment than is actually present. This will be addressed by comparing the in-situ PSD measurements to laboratory derived PSD measurements (obtained from water samples) where dispersing agents and agitation are used to prevent flocculation.
- Multiple device sample collection: it is impossible to collect measurements using multiple devices (e.g. ADCP, optical sensors and water samples) to collect samples which are from exactly the same position of the plume (especially for small plumes generated by CSD and BHD). As the plume varies in three dimensions and concentration gradients can be high within the plume this could result in some data not corresponding. The Monitoring Plan has taken this into consideration when defining the monitoring duration for each dredge type to try and ensure that sufficient data are collected so this is not an issue.
- Low SSCs: if the SSC is low then it might not be possible to undertake a PSD analysis on the sample. This could be partially mitigated by ensuring that large samples are collected for any low ambient SSC and for when the SSC at the tailwater discharge is low.

4. Discussion

The previous section has provided details of the field-based monitoring which is proposed as part of the CVIP fine-grained sediment validation Monitoring Plan. Following the monitoring programme, the data will be used to calculate the mass of fine-grained sediment released from the dredging activity and the tailwater discharge from the WBRA.

It is recommended that two of the approaches detailed by HR Wallingford and Dredging Research (2013) are adopted to calculate the mass released by the dredging and the average of these two approaches is adopted (unless there is a reason as to why one approach is more reliable than the other, such as instrument error). This will increase confidence in the results and provide an indication of the possible error in the calculations. The two recommended approaches to calculate the release of sediment from the dredging are as follows:

- Approach 1: involves using SSC (after calibration using water samples) and current data measured by the ADCP; and
- Approach 2: involves using SSC (after calibration using water samples) from the optical sensors (either setup as a towed array or profiling) and current data measured by the ADCP.

The calculations should be based on all the field monitoring undertaken and used to define the total mass of sediment released by the dredging, as well as the mass of fine-grained sediment (finer than 15.6 µm), so that all sediment types are included in case these are required for subsequent numerical modelling.

In order to calculate the mass of sediment released by the tailwater discharge it will first be necessary calibrate the measured turbidity (in NTU) to a mass using the SSC calculated from the water samples. The SSC can then be multiplied by the corresponding discharge rate to determine the total mass of sediment released by the tailwater discharge. The PSD results from the water samples can then be used to determine the percentage of the sediment in the tailwater discharge which is finer than 15.6 µm and how this has varied over time to enable the mass of fine-grained sediment released by the tailwater discharge to be calculated.

An updated version of the CVIP Fine-grained Sediment Assessment (PCS, 2018a) will be prepared after the analysis of the measured data has been undertaken. This report will present the results from the measured data to provide the final best estimate of the mass of sediment finer than 15.6 µm released by the dredging activity and tailwater discharge associated with the CVIP.

5. Summary

This report has presented a Monitoring Plan to allow the mass of fine-grained sediment (sediment finer than 15.6 µm) predicted to be released by the CVIP to be validated through field measurements. DOEE requested that this Plan be prepared as part of the preliminary documentation for CVIP.

As part of a literature review it was found that despite the number of field monitoring campaigns which have been undertaken related to dredging, there have not been any studies which have required the mass of sediment finer than 15.6 µm released by the dredging to be measured. As such, this Monitoring Plan has been able to adopt the overarching monitoring approaches recommended in the literature, however, additional detailed measurements are also required to ensure sufficient data are available to determine the PSD of the sediment in the plumes and in the background SSC.

The Plan provides details of the monitoring required for the range of possible dredging approaches which could be adopted for the CVIP (including a TSHD, BHD and CSD). The proposed monitoring includes the following:

- Dredge Activity: a mobile monitoring approach is proposed using a survey vessel to monitor the spatially and temporally varying plumes generated by the dredging. The survey vessel will undertake the monitoring to characterise the dredge plumes using multiple measurement techniques, including an ADCP, optical sensors to measure turbidity and PSD and water sampling (which will be analysed to determine SSC and PSD); and
- Tailwater Discharge: the release of fine-grained sediment from the WBRA will be monitored using a fixed position turbidity meter located within/adjacent to the discharge pipeline, as well as regular water sampling (which will be analysed to determine SSC and PSD) throughout the duration of the tailwater discharge.

The Plan also provides an overview of the data processing required following the monitoring to allow the mass of sediment released by the dredging activity and tailwater discharge to be calculated. Following this the results from the monitoring will be used to define the final best estimate of the mass of sediment finer than 15.6 µm released by the CVIP.

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