A NEW DREDGING INFORMATION SYSTEM (DIS) FOR ASSESSMENT OF ENVIRONMENTAL EFFECTS OF TURBIDITY

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ABSTRACT

This paper addresses the development of a new method for synoptic monitoring of turbidity represented by Total Suspended Solids (TSS). The method aims at optimising information from operational dredging data, earth observation data, modelling of currents and sediment transport and in-situ data by means of new data-model integration (DMI) techniques.

As a test case, Penny's Bay in the Hong Kong Special Administrative Region was selected. Background TSS levels are determined by using model simulations, archived optical earth observation (SeaWiFS, MODIS, Landsat and IKONOS) and in-situ data. The transport and concentration of dredging / disposal plumes is modelled using the water quality model Delft3D-WAQ. A new flexible input editor is presented to translate the relevant operational dredging data into consistent model information. An outline is given as to how earth observation imagery and in-situ data can be integrated into modelling results such that short period forecasting of the plume behaviour by the model is optimised. The results show that the Penny's Bay feasibility experiment was a realistic test case to assess the suspended sediment information that can be derived from in-situ data, earth observation imagery and plume modelling. At present the DIS is well-suited for use in project preparation and post-project evaluation. With increasing coverage of high resolution satellites and further reduction of the time between imaging and delivery of the satellite product, the potential for operational use will increase.

Keywords: Dredging, plume modelling, earth observation, monitoring, operational information system.

INTRODUCTION

The last decades show an increasing concern about environmental effects of dredging in coastal waters, often related to large infrastructure projects. Of specific concern is the (increased) turbidity caused by resuspension of bottom sediment as well as spillage from dredging and / or outflow from reclamation and the strict quality norms with respect to allowed turbidity and total suspended sediment (TSS) dispersion in the area. Dredging companies have to justify the environmental impact of their activities to local authorities who impose increasingly strict rules upon levels of turbidity and spillage. Compliance monitoring currently takes place based on measurements of TSS and turbidity in water using mobile samplers and (strings of) sensors arranged vertically and / or horizontally in the region surrounding the dredging ship. The current monitoring practice is based on point measurements which have several disadvantages.

Most water quality regulatory bodies related to dredging operations require compliance with norms related to TSS rather than turbidity. This is because TSS correlates better with environmental impacts, is comparable between different regions and sediment composition and can be interpreted in a more meaningful manner. A release of TSS of 100 mg l^{-1} in one area has approximately the same impact on the environment as a release of TSS of 100 mg l^{-1} in

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another area. Turbidity of e.g. 50 NTU (Nephelometric Turbidity Units) of sediment brought into suspension by dredging in one area is not comparable in its environmental impact to another suspension of 50 NTU in another area, which could have a different particle composition and size (Thackston & Palermo 2000).

A variety of other techniques and sensors are available for identifying locations and dimensions of dredging plumes. For instance, fathometers (which measure backscatter and provide qualitative information on TSS) can track a plume and delineate its dimensions. However, these cannot provide quantitative information on concentrations. Acoustic Doppler Current Profilers (ADCPs) provide details on the structure of a plume and the currents affecting the plume. It can also calculate TSS concentration based on empirically derived equations, but this is dependent on the conditions similar to turbidity sensors (Puckette, 1998). None of these instruments can provide accurate information on locations and dimensions of dredging plumes, *as well as* quantitative information on TSS concentration. On the other hand, if a combination of these instruments is used, a total information package can be obtained.

New innovative monitoring methods are called for, which should be more cost-effective, less time-consuming and provide extra information such as greater spatial and temporal coverage. Such innovations in monitoring can help a dredging company in various ways. Being able to distinguish between TSS that are caused by dredging activities and TSS that are already present in the area (due to natural conditions) a dredging contractor will have better understanding of the dynamics of the natural behaviour and so can better assess the environmental performance of the dredging activities and mitigate the impact on the natural environment, thereby proposing a more soundly based and economically more competitive project.

The present paper presents the approach and feasibility of a new Dredging Information System (the “DIS”), developed for the purpose of forecasting, nowcasting and hindcasting the effects of turbidity, represented by TSS concentration, caused by dredging activities. The DIS has been developed during a three-phase project called RESTSCOD, which consisted of an inception, demonstration and embedding phase. The nature of RESTSCOD was initially a feasibility study, investigating the possibilities to improve information on spreading of dredging induced releases of TSS by means of combining information from in-situ data, earth observation data and numerical modelling (Gerritsen *et al*, 2005; Tatman *et al*. 2005). The project has resulted in an operational service for the assessment of turbidity due to dredging for the dredging project preparation phase and post-project evaluation phase.

The DIS is based on optimising information from optical satellite earth observation data, in-situ data and water quality modelling of TSS transport, making use of known or expected uncertainties in the individual information sources. TSS is defined as the amount of inorganic material suspended in water expressed in mg l^{-1}. The combination of earth observation, in-situ and model data enhances the end-user information compared to the information contained in the individual sources, by optimising reliability, spatial and / or temporal coverage of the individual data. The new method presented here is expected to be used by the dredging industry in three ways: 1) as a forecasting tool in the dredging project preparation phase (i.e. before and during tendering), 2) as a near real-time nowcasting and planning tool during the dredging project execution phase and 3) as a hindcasting tool of the turbidity field in the post-project evaluation phase after dredging works have been completed.

In this paper, first of all an outline of the various building blocks of the DIS are presented. An introduction into the DMI approach will be given, followed by more detailed information on the DIS (how the idea for the DIS originated and the potential applications). Some operational and technical specifications which have determined the design of the DIS are also described. In the second part of the paper, the various steps in setting up and applying the DIS are explained, by means of an illustration of the workflow. This includes information on relevant oceanographic and meteorological data, flow, dispersion and earth observation data and their subsequent input to the DIS, the setting up of the models and the use of the input editor for setting up and running the plume dispersion model. Finally the DMI techniques and some results are presented and discussed.

DATA-MODEL INTEGRATION APPROACH

The concepts and potential of application of DMI for suspended sediment are addressed extensively in earlier studies (Vos *et al.*, 2000, Villars *et al*, 2003). Erftemeijer *et al.* (2002) specifically address the needs of the dredging industry. In the case of the operational monitoring or forecasting of dredging activities, DMI is used as a means of combining earth observation and in-situ data with dynamic water quality model data.

DMI is defined as the approach and methods required to use modelling in combination with earth observation and in-situ data in a structured way by making use of the uncertainties in both data and modelling, to obtain an optimal information product. The potential of DMI is to combine all available data sources and by doing this, to mutually enhance the data sources by filling in missing data and / or using known or assumed associated uncertainties, leading to reduced uncertainty in the combined product. For example, synoptic views from earth observation provide instantaneous spatial pattern information, models can provide the space-time behaviour of the parameter of interest, whereas in-situ data can provide the (very) local "ground truth" as well as, if measured in such a way, data throughout the water column as a means of obtaining information on the vertical depth variation. In this way, the model, earth observation and in-situ data can complement each other resulting in a more optimal information product. The conceptual approach for the DIS incorporating DMI techniques is shown in Figure 1.

Earth observation data is ideal for DMI purposes, for example for validation / calibration of models, for data assimilation purposes and forcing of models. In general, numerical models are used more and more to supply statistical and time-series information for specific locations or regions and over certain time intervals for policy development or management purposes, engineering design and development, or scientific research of, for example, coastal processes. The integration of the various types of data is done using mathematical techniques, which are based on prior statistical assumptions about the accuracy of the observations and the dynamical models.

The general approach of the DIS, incorporating the various sources of data and the DMI techniques and as illustrated in Figure 1 is as follows: model prediction at time (t) can be compared with an earth observation-derived concentration pattern and in-situ data of TSS concentration from time (t). Using the newly developed DMI techniques the model TSS concentration values are rescaled towards ground truth with the earth observation and / or in-situ data. In case of potential norm violation, and given the metocean parameters (wind, tide), variations to dredging schedules can be proposed and the model can be rerun, in order to obtain a model result that does show compliance with the norm. In this way, the earth observation and in-situ data is integrated with the model information to create an image of what given dredging operations have done or propose to do in the future.

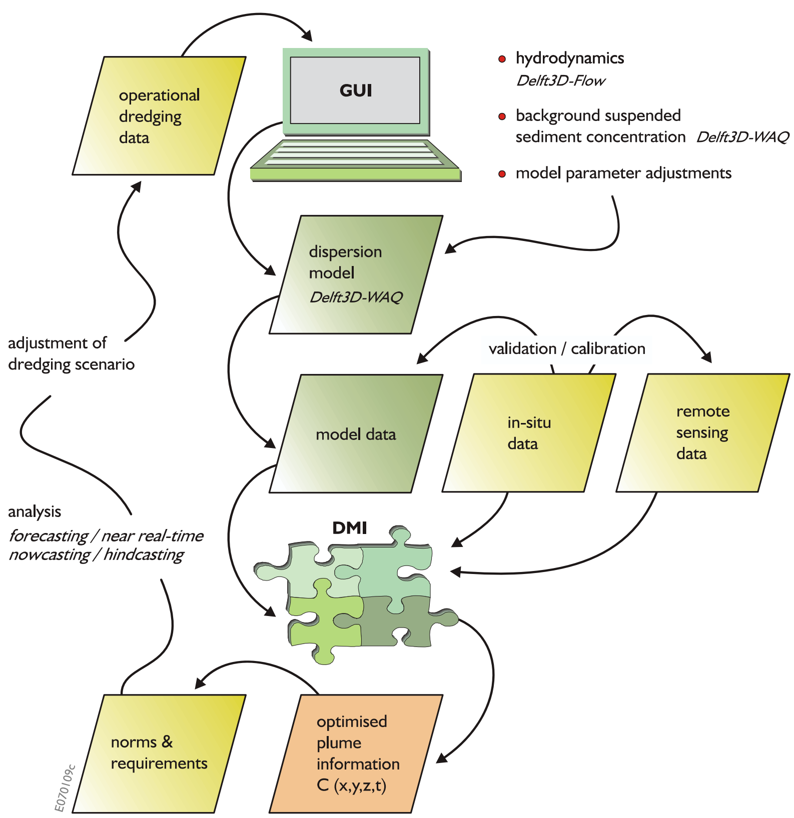

Figure 1. Conceptual approach for monitoring of total suspended solids related to dredging activities, based on the integration of earth observation, in-situ and model data. This entire system of linked information sources is referred to as the DIS (yellow = service input, green = the service, red = service output).

In the DMI process developed for the DIS, the knowledge of the amount and type of bottom sediment released in the water column (i.e. source function information delivered by the dredging operator) is used as input, via the graphical input editor or "Graphical User Interface" (GUI) to a dynamic water quality model. The GUI can be seen as a front end to the dynamic water quality model Delft-3D WAQ. The model calculates TSS concentration (C) in mg l^{-1} in space and time (x, y, z, t). This proxy for turbidity information can then be used to analyse potential effects and compared with specific norms.

DREDGING INFORMATION SYSTEM

Initially, the idea for the DIS originated from the question of the feasibility of an operational system for compliance monitoring in order to improve the environmental performance of the dredging activities and meet the norms for maximum levels of TSS during dredging works. Early on in the RESTSCOD project it became clear that this is currently too ambitious, mainly due to the difficulty in obtaining and processing the earth observation data within 24 hours as required by the dredging end user (Tatman *et al.* 2005). Although sporadically, very fast scenarios for high resolution satellite data delivery within a few hours are implemented, these were found not to be universal enough to form a solid basis for a system such as the present DIS. The end-user Van Oord subsequently recommended developing a tool that can aid in the provision of relevant information during tender phases for large-scale dredging projects. Fast access to information about the background turbidity levels and local spreading characteristics is required so dredging companies can provide detailed project proposals. A reliable and operational technique (which is area covering) for detailing the initial background turbidity levels and initial forecasting information could provide a big improvement in the proposals submitted by dredging companies in terms of time, budget efficiency and detailed knowledge about the proposed project.

The potential application of the DIS is coupled to the monitoring requirements in the dredging project phases of planning, execution and post-project evaluation and can therefore be used by the dredging industry in the following ways:

1. As a forecasting tool in the dredging project preparation phase (both the pre-qualification and tendering phase), for analysis of critical dispersion dynamics of the region for assessment of background TSS concentrations and initial effects on turbidity caused by dredging. Input to the DIS is baseline information on TSS and / or turbidity which is provided by earth observation data and (if available) in-situ data. Information output is forecasted information, to be included in project proposals, on the increase in turbidity and, if required, translation into the design of an optimum monitoring plan that satisfies the environmental criteria and which is cost-effective;

2. As a near real-time nowcasting and planning tool during the project execution phase, for compliance monitoring in order to improve the environmental performance of the dredging activities and meet the norms for maximum levels of TSS concentration and / or for compliance with the project's Terms of Reference. Input to the DIS is near real-time earth observation and operational dredging data. Information output is short-term (i.e. up to several days ahead) forecasted information on the extent of the spreading and concentration of the TSS plume;

3. As a hindcasting tool of the turbidity field in the post-project evaluation phase, when information is required about a dredging site after dredging works have been completed, e.g. due to an environmental compliance issue. The hindcast analysis is carried out by means of reconstruction of the conditions during the dredging operation. Input to the DIS is archived earth observation data and the actual operational dredging obtained during the dredging works. Information output is the reconstruction of the dredging plume and background conditions.

Although the second application, the near-real time mode, is currently limited due to the time constraint of obtaining near real-time earth observation data, the DIS is being set up to allow for such processing if it becomes possible to incorporate earth observation data within the required 24 hour time limit (for more details on end-user requirements, see Tatman *et al.* 2006).

CASE STUDY PENNY'S BAY

Selection of Area and Period

For the case study, Penny's Bay, Hong Kong Special Administrative Region, was selected, where extensive dredging and land reclamation was conducted in 2000 for the development of Disneyland Hong Kong. The choice for the area and period was made based on 1) potential availability of suitable earth observation data; 2) availability of an operational hydrodynamic and water quality model; 3) system knowledge of the area (i.e. knowledge of the local hydrodynamics and water quality); and 4) availability of a comprehensive field data set measured by Van Oord NV during and after the year 2000 whilst operational dredging was continuing. The field data set available for the project concerned the period 25th July – 3rd December 2000.

The size of the bay is about 1.5 km by 1 km (at the mouth). The overall Hong Kong coastal marine area is stratified for salinity and temperature. Astronomical tide is the primary driving flow force. The wet season (May to September) features a typical large-scale steady uniform background monsoon wind from SW and associated high flow and sediment discharge from the Pearl River, while during the dry season (October to March) this background monsoon wind is from NE, and the Pearl River discharges are low. The sea bed is characterised by a top layer of very fine so-called "powder sand", initially originating from the Pearl River and easily brought into suspension by wind effects. Hong Kong is frequently cloud-covered.

Available data

During the period 25th July – 3rd December 2000, extensive in-situ measurements were taken at three vertical levels in 24 positions in the area up to approximately 10 km from Penny's Bay proper.

From publicly available optical earth observation images a selection was made taking into account cloud cover. For the period in question, based on analysis of quick scans, 16 suitable SeaWiFS images out of 52 were processed (spatial resolution 1100 m), while two high quality Landsat7 TM images (resolution 30 m; 14th September and 1st November, e.g. see Figure 2) were acquired. During July – December 2000 reclamation with import of sand had not yet commenced and silt screens had not yet been placed around the project site.

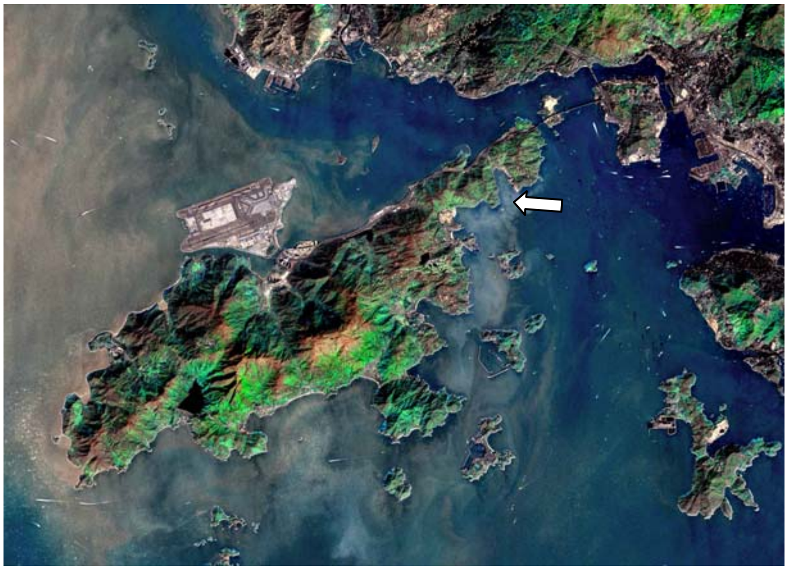

Figure 2 Landsat-7 fusion image November 1, 2000 (the arrow indicates Penny's Bay) (image courtesy of Van Oord NV / Data available from U.S. Geological Survey, EROS Data Center, Sioux Falls, SD).

OPERATIONAL AND TECHNICAL SPECIFICATIONS

Generally, operations related to large land reclamation projects may involve ten or more dredging vessels in the area, of different types, each with specific operating procedures, spillage reduction characteristics and dredging tracks. Other variables are the characteristics of the dredged material, operation times and production levels. An operational DIS for forecasting, near real-time nowcasting and hindcasting of turbidity resulting from the dredging activities must be able to cope with these practical issues. For example: a) the time intervals that are considered must be flexible; b) the information system must be able to deal with several sources of TSS discharge (more dredgers working simultaneously at different locations within the study area); c) it must be possible to model the release of TSS at different depths; d) it must be possible to represent differences in soil properties, i.e. variable particle size distributions and settling velocities for different sources.

Several technical issues are also of importance for the design of the DIS, and are translated into technical requirements for the DIS and incorporated into the design, the most important of which are listed in the following paragraphs.

Turbidity

Turbidity of the water column can be caused by human activities such as dredging, waste discharge and urban runoff, or by natural dynamic processes such as erosion and sedimentation, and biological processes such as organisms that stir up sediments or algal growth. Monitoring the turbidity of the water provides a quick way to describe the condition of the affected water.

Turbidity is expressed in units of NTU or FTU (Formazine Turbidity Unit). Turbidity is measured by an optical sensor that can be operated in-situ. The turbidity unit is a ratio-expression of the incoming (vertical) bundle of light in a water column and the fraction of dispersed light, measured perpendicularly to the direction of the incoming bundle. A higher level of light at the perpendicular angle means more dispersion and a higher NTU. Figure 3 shows levels of 5, 50 and 500 NTU, which are standards. The turbidity reading is relative to the reading of the sensor in a standard calibration fluid.

Figure 3. NTU levels of 5, 50 and 500 NTU (source: Wikipedia).

Measures of maximum allowed turbidity set by authorities vary between 5 and 500 NTU or are set as a percentage increase above ambient levels. Another criterion that may be implemented is that turbidity may not exceed the average baseline condition in more than 80% of the observations. For example, in the state of Florida, USA, the measure is 29 NTU at a fixed distance from the dredge. According to the Global Programme of Action for the Protection of the Marine Environment from Landbased Activities (GPA – UNEP) the turbidity at a distance of 250 meters from the dredge site should not exceed 30 NTU. In sea grass and coral areas a limit of 10% increase above baseline conditions may be specified. Depending on the contract requirements mitigating measures may have to be implemented in case the turbidity threshold values are exceeded.

Total Suspended Solids

Suspended solids in the water column can consist of solid particles of many different sizes and of different origin. Solids are defined as inert particles and exclude organic matter. Part of the sediment particles suspended in the water following dredging activities will be large and heavy enough to rapidly settle to the bottom. Other smaller particles will settle either very slowly or not at all. This fraction of small solid particles causes the water to appear turbid and is likely to form a plume when discharged at some point during the dredging, transportation and disposal process. Concentrations of TSS levels vary both temporarily and spatially. Temporally, TSS concentrations can differ on a seasonal scale, over tidal cycles and are subject to weather events. Spatially, variations will occur vertically throughout the water column, with the near-bed values generally greater larger than the sea surface values.

TSS concentrations are expressed in units of mg l^{-1}. The conventional method of TSS determination is to establish the dry weight of sediment from a known volume of a sample in the area of interest. The test is carried out under controlled laboratory conditions. The sample may have been derived from different depths. Figures of maximum allowed TSS, implemented by regulators may vary between 5 mg l^{-1} and 1000 mg l^{-1} depending on local legislation and conditions.

Accuracy of TSS Measurements

Different types of accuracy are distinguished; the geographic accuracy, the accuracy of the control of increase of TSS, and the accuracy related to the correlation of turbidity versus TSS concentration:

1. When a turbidity or TSS value is to be obtained, the coordinates of the in-situ monitoring location or sample location need to be specified. Modern kinematic differential GPS systems allow for very accurate determination of (x, y and z) coordinates. The dynamic behaviour of sediment in the water does not require an extremely high accuracy of coordinate measurements. It is however important to do a detailed verification of relative positions in case of multiple parameter measurements.
2. The accuracy in determining the TSS concentration is very much dependent on the concentration. The accuracy is a function of the weight of the residue on the filter relative to the filter weight. As a rule of thumb the accuracy of the standard method is 5 mg l^{-1}. This is normally more than sufficient for concentrations above 50 mg l^{-1}. NB: the accuracy of the DIS is as yet undetermined.
3. Correlation of turbidity versus TSS. Water samples are often collected for indirectly estimating the TSS concentration, by means of measuring the associated turbidity. This relation between the TSS concentration and associated NTU varies as a function of various conditions, such as soil type and various water quality parameters. Normally it has a linear character. For determining a good linear regression, water samples need to be collected in a wide range of NTU (ranging from clear water to extremely turbid). When turbidity readings (in NTU) and associated TSS (mg l^{-1}) are plotted on a graph, the relation between the two parameters will become obvious. With the aid of these correlation graphs, TSS can be estimated with turbidity readings only. Relations are influenced by the type of sediment in suspension. If there is a very wide scatter it may be the case that samples contain different types of material. In this case, TSS concentration test results need to be discriminated on the basis of more detailed information on the origin of the water sample. Figure 4 illustrates a correlation between TSS concentration and turbidity.

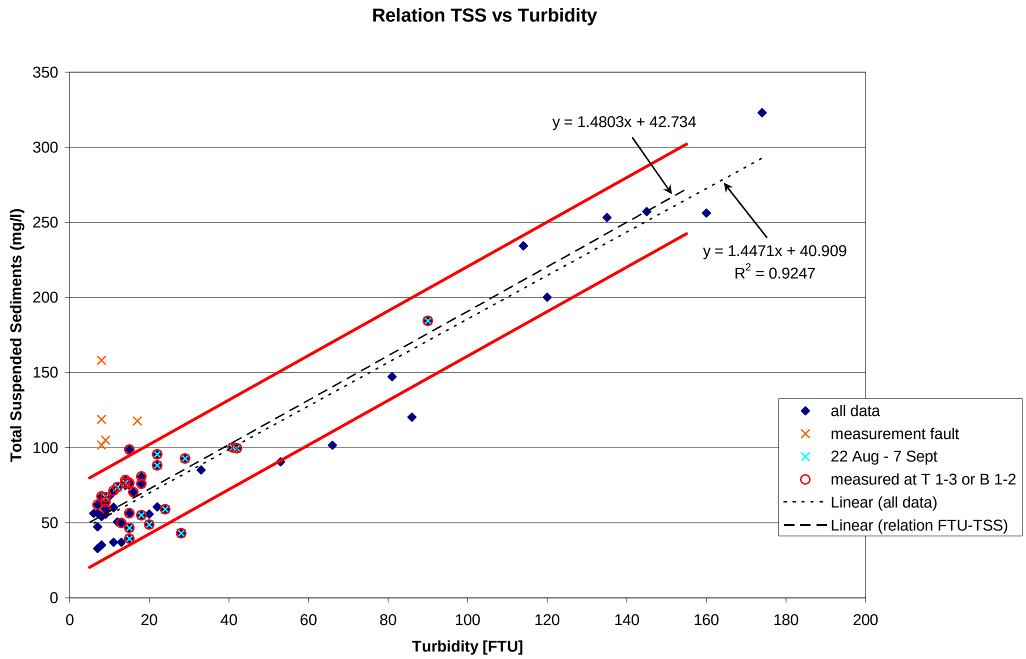

Figure 4. Example of correlation graph between turbidity and TSS for a project in South Africa.

WORKFLOW SEQUENCE

The DIS consists of some ten activities that are linked to each other. These are shown in Figure 6 as the green "service" boxes in the flow diagram. These main activities, as well as a number of other activities, are schematised in a flow diagram in which the chain of activities becomes clear (Figure 6).

The flow diagram in Figure 6 represents the procedures required to apply the DIS for each new dredging project. Each activity of the flow diagram has been detailed extensively in the so-called user handbook (Noorbergen 2006). The handbook is available as an appendix to the RESTSCOD Embedding Phase final research report (Tatman et al. 2007). By documenting the workflow procedures carefully, the DIS can be set up and applied quickly for each new dredging project and location. Furthermore, the handbook includes such aspects as criteria for a successful application of the DIS in a region or particular type of dredging project (e.g. availability of a model or requirements for setting up a new model, availability of earth observation and in-situ data, spatial scale of the dredging project, risk of cloud cover, etc.).

In the handbook the three project phases (project preparation, project execution and post-project evaluation) are distinguished (note that in Figure 6 each box in the flow diagram shows, whether the activity is necessary and / or contributes to each of the project phases, by inclusion of the symbols ①, ② and ③). The handbook is a living document, and changes in information or supplementary information can be included easily, ready for use in a new dredging project.

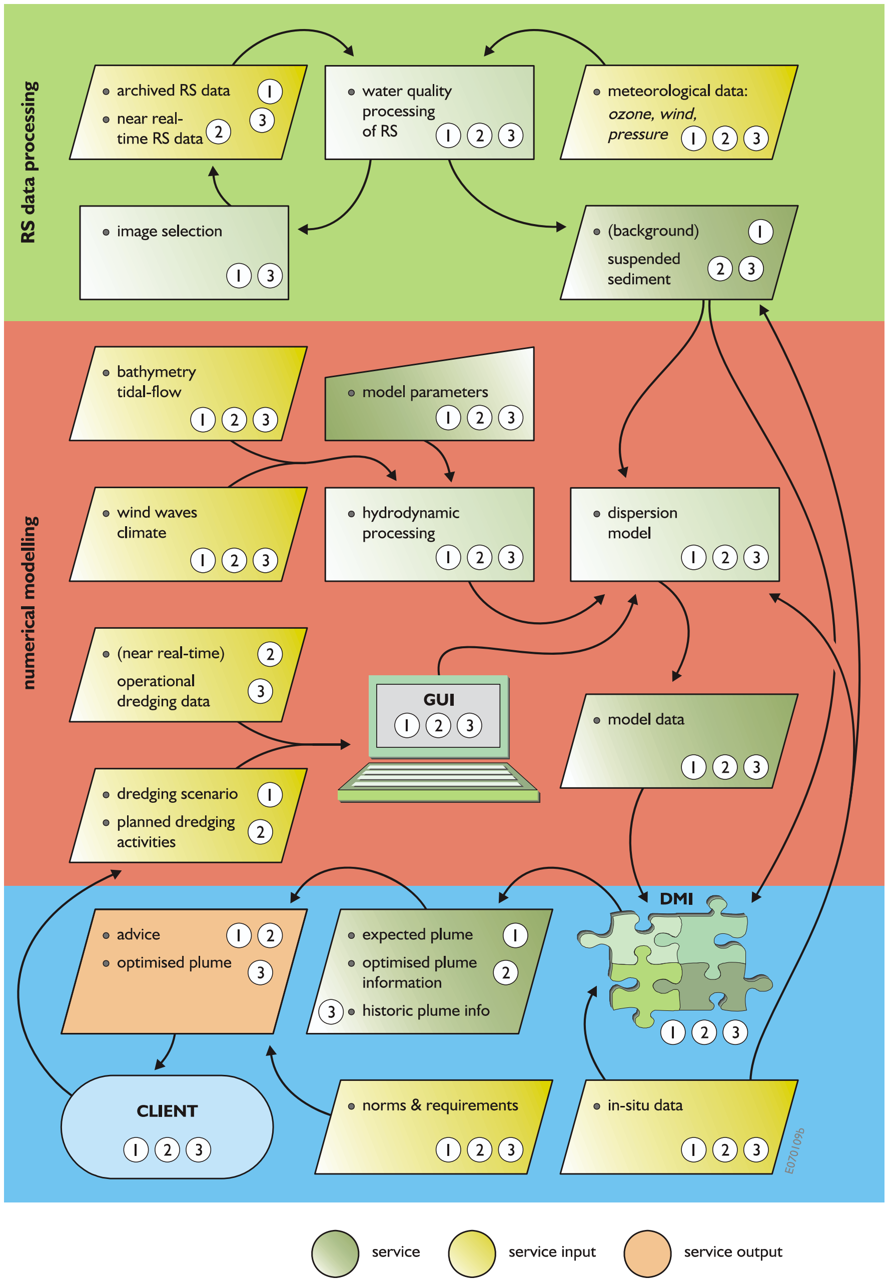

Figure 5. Workflow sequence (① = application in the project preparation phase, ② = application in the project execution phase and ③ = application in the post-project evaluation phase).

The chain of activities set out in Figure 6 and the handbook, include:

- Information gathering: the selection of meteorological data, bathymetry data, wind and wave climate data, and operational dredging data for input into the hydrodynamic and dispersion model and the selection and acquisition of earth observation data and in-situ data, to be used in the DMI procedures (shown as yellow boxes as "service input" Figure 6);
- Earth observation data processing using state-of-the-art water quality processing algorithms for earth observation data, i.e. the (pre)processing of the raw satellite earth observation data to obtain discrete values of

TSS concentration that can be used in the DIS. The procedures involved in the earth observation data (pre)processing are shown in Figure 6 (top part of the flow diagram with the green background);

- Hydrodynamic processing: set-up and execution of the selected model and procedures to enable exchange of sediment flow- and transport information between different grids (different areas). This generally concerns the transition between a larger (model) area and a smaller (nested model) area. Actual wind forcing is preferred for the more accurate simulation of the region, to take into account the effects of local wind phenomena on the sediment transport, especially near the water surface. The hydrodynamic processing results in a hydrodynamic database with results for the case study region and period;
- Graphical User Interface (GUI): dispersion model input parameters such as hydrodynamic database, time frames, observation points, and sediment release data such as discharge points, sediment composition and release period. Model forecasts of the dispersion plume are performed with the Delft3D-WAQ (water quality) model, based on the user defined input of the GUI. The complete modelling procedure is shown in Figure 6 (middle part of the flow diagram with the red background);
- Data Model Integration (DMI): comparison of earth observation and model-based TSS concentrations through visual and quantitative characterisation and evaluation. Adjustment and fine tuning of modelled and earth observation concentrations and establishment of relative weight to apply for optimal integration.

Each of these activities is described in more detail below.

Information Gathering and Processing

Depending on the phase of the dredging project (project preparation, project execution or post-project evaluation), different information related to turbidity is required for input into the DIS using the GUI:

- Project preparation phase: baseline turbidity field data, historic satellite images, dredging production forecasts, soil parameter forecasts;
- Project execution phase: field turbidity data, near real-time satellite image(s), actual operational dredging production to date, dredging production forecast data, soil parameters;
- Post-project evaluation phase: field turbidity data history, satellite images before-, during- and after project completion, dredging production history, soil parameters.

Baseline (or "background") turbidity is the amount of suspended sediment that is already present in a water body before the (present) dredging operation. The spatial distribution of the suspended sediment is of specific importance for gaining insight in the reigning conditions in an area of interest. Baseline turbidity information can be derived from in-situ measurements and / or optical earth observation data.

In-situ measurements are taken on site with the help of turbidity sensors. Waters samples for determination of TSS concentration can be obtained by samplers such as the Niskin water sampler or by a pump system. Near real-time supply of background turbidity information from in-situ measurements is achieved by the installation of turbidity sensors that continuously record and transmit turbidity data. *Near real-time* collection of TSS concentration data is almost impossible since these measurements are done in the laboratory. Laboratory test results are rarely available within 24 hours. For the post-project evaluation phase, the availability of in-situ measurements depends entirely on the quality of the water quality monitoring program carried out during the dredging operation.

Optical earth observation data can be derived from satellite archives that, for certain satellites go back some 30 years. With historic in-situ measurements as local-point ground truth, the satellite images can be calibrated which will improve the reliability of the satellite information. For the post-project evaluation phase, information derived from satellite archives is generally easily available through the search in the various earth observation data archives. Earth observation data can provide information on the background TSS concentration, as well as on the extent and concentration of a plume in the case of dredging activity during project preparation and post-project evaluation phases.

Data gathered during dredging is of importance for the modelling. Sediment losses that are the result of the dredging process are essential input for the model. Accurate input of the sediment source in the dispersion model through the

GUI is difficult: sediment release terms are known to be complex to define, and are currently being researched by the Dutch dredging industry (through the foundation "Stichting Speurwerk Baggertechniek") under the TASS (Turbidity Assessment Software) research project (Dirks, personal communication).

Data that needs to be logged is the following:

- Continuous GPS recording of the geographic location of the dredging vessel and thus also monitoring of the vessel manoeuvres;
- The dredged material; concentration values of inorganic material like silts, clays, sands or gravel or organic material; particle size distributions of the in-situ material, determination of discharged material and spilled material if possible;
- The equipment used and release rates that are coupled with the equipment. Release rates, i.e. the sediment source, are a function of soil type, hydrodynamic conditions, equipment, method of operation etc. Expert judgement and engineering skills are required to assign release ratios to production figures;
- Recording of anomalies that influence the production data: for example, cavitation of pumps or changing sediment-water ratios during transport;
- Volumes of displaced excavated material.

Measured dredging production data are used in the project execution and post-project evaluation phases. In the project planning phase, forecast production and loss figures are used.

Earth Observation Data

Some ninety earth observation satellites are commercially available at the moment of writing. The exact number changes continuously. However, not all of these satellites are suitable for use in an operational dredging application. Earth observation data is selected on the basis of criteria, which were determined during RESTSCOD. These include temporal-, spectral- and spatial resolution of the satellite data, which require that the image:

- has sufficient spectral resolution, namely wavelength intervals from 10 to 100 nm and preferably spectral bands in the blue, green, red and near-infrared parts of the electromagnetic spectrum for the atmospheric processing of the imagery data, and the subsequent TSS concentration extraction;
- covers the usual area of interest sufficiently, 10 by 10 km or more;
- has a spatial resolution or pixel size of 300 meters at most for the areas where the actual dredging works are carried out;
- is available on a weekly basis for the project preparation- and post-project evaluation phases and is available daily for the project execution phase.

Other selection criteria include:

- Data accessibility: ease of use of when browsing in data catalogues; good interaction with data suppliers and / or data brokers.
- Coverage: region of interest is covered during one overpass of the satellite.
- Data delivery: administrative procedures at data suppliers and data distributors have influence on the speed within the distribution chain (browse, product selection, order, payment, delivery); delivery available in required format (ftp or on media such as CD-ROM, DVD, other);
- Price and quality: level of pre-processing; accuracy (geometric and radiometric); pixel depth; occurrence of clouds and haze (and pricing rules that data providers impose on that).

After review of the available earth observation data, the period for which data of the Penny's Bay project was selected to be used in the RESTSCOD case study was 1st until 15th September 2000.

When all criteria were applied on the selection of images, ten earth observation images were selected for processing from raw imagery data to TSS surface concentration fields (Table 1).

Table 1 The images processed plus selection of images that were initially suitable and those actually used for DMI processing.

Satellite	Date time (GMT)	Date Time (local)	Resolution (metres)	Selected for DMI	Used in DMI
MODIS Terra	28 July 3:20	28 July 11:20	250/500		
SeaWiFS	21 Aug 4:25	21 Aug 12:25	1100		
IKONOS	04 Sept 2:42	04 Sept 10:42	4	yes	--
SeaWiFS	04 Sept 4:41	04 Sept 12:41	1100		
IKONOS	07 Sept 2:50	07 Sept 10:50	4	yes	--
MODIS Terra	**12 Sept 3:35**	**12 Sept 11:35**	**250/500**	**yes**	**yes**
Landsat7	**14 Sept 2:43**	**14 Sept 10:43**	**30**	**yes**	**yes**
Landsat5	**15 Sept 2:24**	**15 Sept 10:24**	**30**	**yes**	**yes**
SeaWiFS	15 Sept 4:26	15 Sept 12:26	1100		
MODIS Terra	19 Sept 3:40	19 Sept 11:40	250/500		

The SeaWiFS images (1100 m resolution) effectively did not cover the Penny Bay's area and the immediate surroundings. The same held for the 19th September MODIS image.

The IKONOS sensor has limited spectral bands and therefore does not allow for atmospheric processing using presently available algorithms. In the end, the IKONOS images were not used due to extensive cloud cover on the day of image recording. Also, in the clear parts of the IKONOS images, sediment reflection in and around Penny's Bay, which was initially visible in the raw images, disappeared after the TSS concentration extraction procedures (most notable in the 7th September image). IKONOS may be used in the future, if TSS concentration extraction procedures become available.

Thus, high resolution imagery such as IKONOS record at high detail, at a spatial resolution of 5 m or less, but for relatively small areas. Such imagery meets the specific spatial demands for dredging works. However, the benefits (i.e. fast access and delivery of the data, required spatial resolution) at present do not outweigh the drawbacks such as limited spectral resolution and difficulty in the correction of atmospheric effects and subsequent processing for TSS concentration extraction.

The remaining images for 12th, 14th and 15th September were used. On time scales of days the concentration fields are expected to be correlated, even though the relevant sediment time scales are small.

For details on the TSS extraction procedures the reader is referred to Tatman *et al*. (2005, 2006).

One of the main potential problems to the use of the DIS is the availability of cloud-free earth observation images. This issue has been addressed in the RESTSCOD project. NLR has developed a simulator called CLIMAS (Algra *et al*. 2004), which can be used to derive information about cloud-cover statistics for any area in the world. This can be of interest for dredging companies that want to gain insight in local climate conditions for an area of interest during the project preparation phase. Statistics are based on the overpass of one satellite that passes the area of interest once per 24 hours, with a local overpass time between 11.00 and 12.00 hours (local sun time), thus the time of day when polar orbiting satellites pass. The cloud data set that is behind the simulator consists of two years of available cloud-imagery: two year-periods between February 1994 and January 1995 and between July 1997 and June 1998. Although more information is needed to derive better statistics, at present this is not available. In Figure 6 the local cloud statistics for Hong Kong can be found for both year-periods.

Figure 6 shows seasonal effects very well and there is an apparent difference between the two year-periods. The result for Hong Kong shows that the number of cloud-free days varies highly throughout the season; in particular in the summer where the number of cloud free days drops below eight on average.

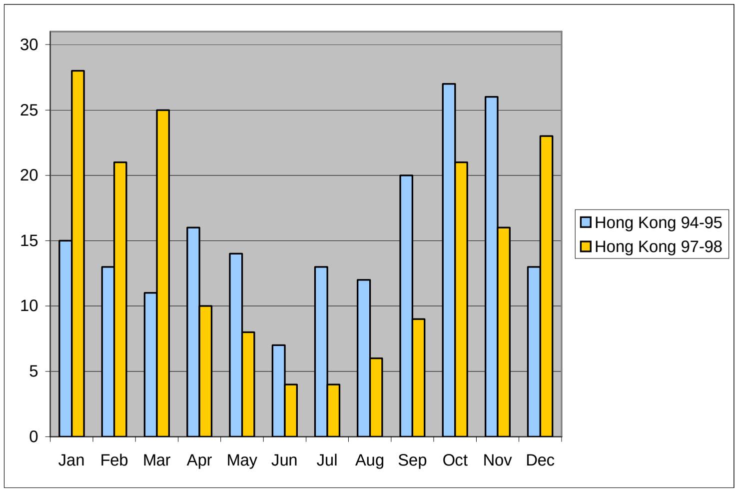

Figure 6 Number of cloud-free days per month for Hong Kong; based on two years of data.

Using a cloud-information simulator such as CLIMAS can be very useful in the preliminary analysis when assessing the feasibility of using earth observation data in combination with model and/or in situ data. In the project execution phase the simulator could also allow for quantitative assessment of the satellite mission performance by allowing for cloud avoidance scheduling of the satellite sensor.

Hydrodynamic Model

The Delft3D integrated marine modelling suite (Lesser *et al,* 2004, WL | Delft Hydraulics, 2003) was used to model the hydrodynamics and water quality (i.e. the transport of TSS). Preceding the simulation of the suspended particles dispersion, the hydrodynamics has to be simulated with a flow model. The flow model that is developed for this case study is based on an existing and calibrated baroclinic large-scale 3D flow model of the overall Hong Kong waters that was developed for the Hong Kong Special Administrative Region (WL | Delft Hydraulics, 1998). The hydrodynamic and water quality parts of the Update Model were extensively calibrated and validated against measurement data from the Long Term EPD Routine Monitoring Network, which covers all Hong Kong SAR waters. The main characteristics of the model, which is generally referred to as the Update model, are:

- The model was set up, calibrated and validated for both an average dry (October to March) and an average wet season (May to September), each represented by appropriate Pearl River discharges, monsoon wind forcing and open ocean surface gradients;
- For both cases, the model simulates a full spring-neap tidal cycle;
- The main output variables of the model are water levels, currents, salinity as a function of space and time. Temperature is only modelled for the wet season conditions, due to the occurrence of temperature stratification;
- The flow model is a 3D model, using 10 sigma-layers, distributed evenly over the entire local depth.

For the case study a more detailed model is required to resolve in more detail the coastline and bathymetry within the Penny’s Bay study area. Therefore a suitable local (“nested”) model area was determined. The Penny’s Bay model is nested within the Update model which means that the initial and boundary conditions are taken directly from the results of the Update model. The resulting detailed local or nested model domain and grid resolution are presented in Figure 7. The size of the grid cells varies from about 50 m in Penny’s Bay to about 250 m near the open model boundaries.

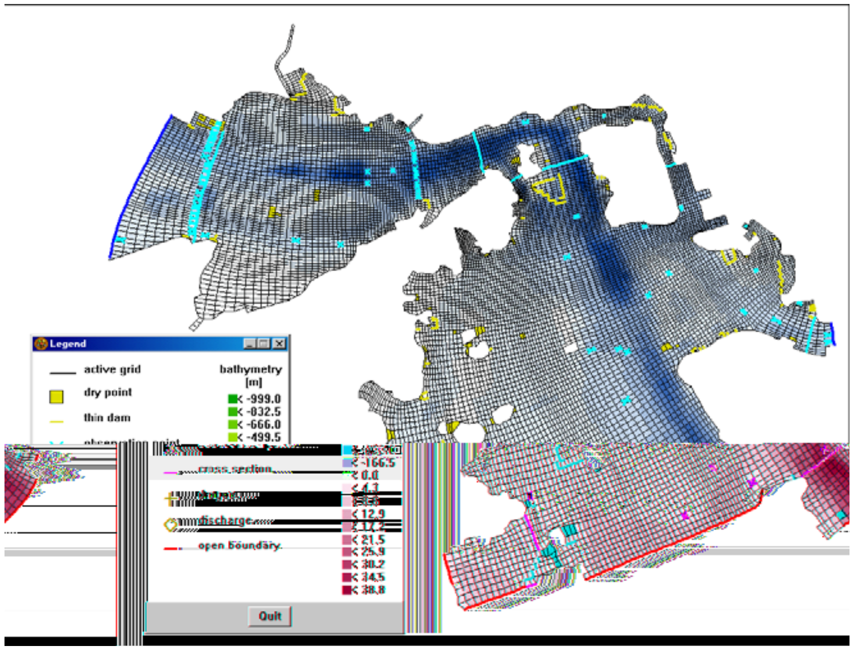

Figure 7. Penny's Bay nested model grid and bathymetry (depths in m below Principle Datum).

The extent of the Penny's Bay model is based on estimated transport times of dredge plume spreading. In the vertical direction, a 10 σ-layer (i.e. terrain following) model is applied with finest grid thickness near the surface and the bed. Both for the flow modelling and the subsequent TSS concentration modelling, the lateral model forcing of the local model is based on results of associated overall model simulations. Equally, other relevant data such as external sediment loads and mean atmospheric forcing were taken from earlier modelling studies conducted in the area. The initial condition of the Penny's Bay model specifies the spatial distribution of water levels, currents, salinity and temperature at the start of the model simulation for all 10 layers of the model. The boundary conditions specify the water levels, salinity and temperature as a function of time. The model is fully 3D, with the same characteristics as the Update model.

Graphical Input Editor for Plume Modelling (the GUI).

As described above, sediment discharges from dredging operations come from a complex combination of locations, times and depths, possibly including different sediment types. Since the types and variability of discharges are very different from those traditionally included in a water quality study, a graphical user interface (GUI) was designed to enable robust transformation of the key operational information to a corresponding consistent input for dispersion plume modelling, based on a series of discussions between model developers and dredging engineers to scope the user requirements. The GUI, which can be considered a front end to the dynamic water quality model Delft-3D WAQ used for the dispersion modelling, is only available in conjunction with Delft3D. Thus a potential user would require the full modelling suite of Delft3D-FLOW, Delft3D-WAQ as well as the GUI, and the GUI is therefore not available as a standalone tool.

Following recommendations by dredging engineers, several aspects have been incorporated in the current version. The functionality of the GUI includes: 1) Model set-up: set-up the model environment (hydrodynamics) and timers (e.g. start and stop time, length of time step); 2) Sediment release: multiple discharges with individual operating times and release rates; 3) basic GIS functionality for specifying discharge locations, corresponding release periods (timings of the discharges for a certain location) and observation points (model output is generated for observation points); 4) additional GIS layers (model grid, dredge areas) and additional information (tooltip texts).

A basic input file, used as a template, has been designed through which the user is able to define, adjust and remove dredging locations and specify discharge details. The prototype GUI was evaluated together with dredging engineers. Figure 8 presents one of the characteristic screens. In particular the prescription of sediment properties and their release characteristics appeared to be of key importance. In the sediment release window (Figure 8), the values of four quantities in the template will be shown: a) the duration in hours of the release for the particular release period; b) the rate of the surface release in kg s-1; c) the rate of the mid-depth release in kg s-1; d) the rate of the bottom release in kg s-1.

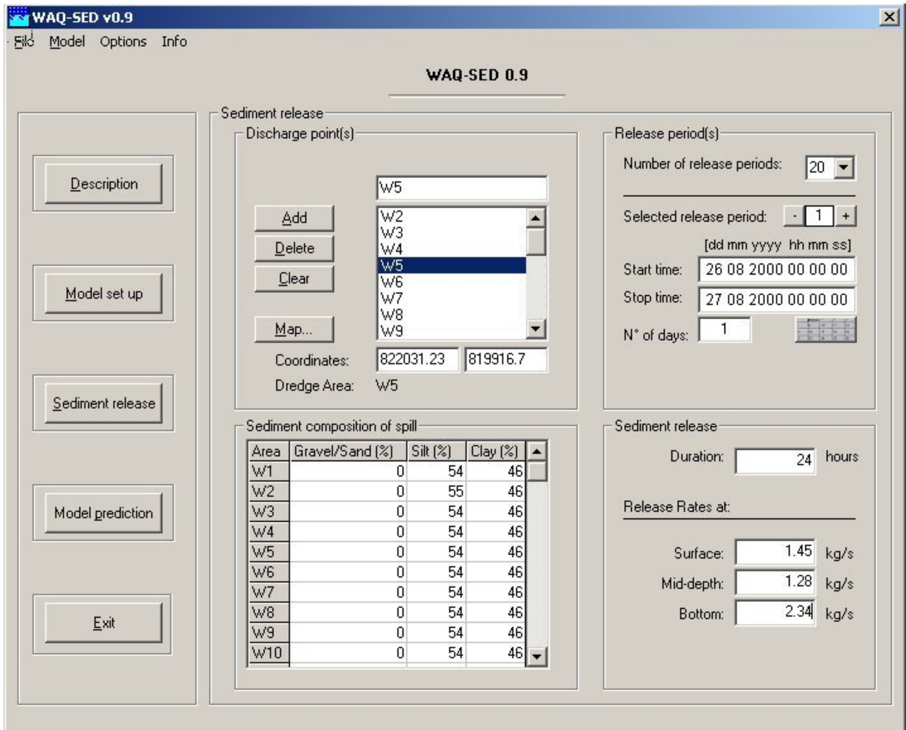

Figure 8 The WAQ-SED user interface, showing the "Sediment release" screen.

The four items can be clicked and adjusted values can be provided in these units. These values then override the template values for the model simulation. The following changes in the screen are then also effected:

- the new duration will be translated in a new end time for the particular period;
- the sediment composition will hold and be effected for all the vertical spill levels;
- the default for gravel / sand is fixed to a value 0 and it is verified that after user changes the total percentage is 100. If not: the user is asked to adjust the settings.

The internal calculation is then:

1. silt-surface = silt % * surface release rate (kg s^{-1});
2. clay-surface = clay % * surface release rate (kg s^{-1}), and similar calculations for the other two levels.

For more information on the technical design of the GUI, the reader is referred to Gerritsen (2006).

Data-model Integration

The main procedure for DMI approach used within the DIS, is to establish the characteristics of the TSS concentration in the model and earth observation data, in quantitative form and visually, and to quantitatively assess the agreement and differences between the model and earth observation-derived concentration fields.

A method has been developed to adjust the modelled concentrations in such a way that the adjusted model concentrations show a better agreement with the earth observation-based concentrations. A key aspect is that it is based on a systematic, structured, and reproducible approach, which in the future can be used (semi)-automatically in a software tool.

For dredging operations in the field, this would allow for improving a simulated TSS concentration distribution at some time step by adjusting it on the basis of a most recent earth observation image, which then can serve as a consistent initial state for a short term model forecast of the TSS spreading during the dredging operation. The idea is that with such intermediate adjustments of the simulated concentrations the subsequent model forecasts will be significantly better than when no earth observation images (or other observations) are used for a correction of the simulation

In short, the DMI procedures entail the following:

- Mapping earth observation data to the model grid (a process named "binning"): averaging the earth observation pixel values and copy to a single grid cell, and storing these together with a quality label and statistical properties such as the total number, maximum and minimum value, and standard deviation;
- Zooming in on the area of interest: the interpretation of processed earth observation images by automated techniques is hampered by artefacts near land-sea transitions, compare e.g. the left upper frame in Figure 9 in the (unbinned) MODIS 12th September image with the associated numerical model TSS concentration (upper right). To allow for easier focusing on the processes of interest that is, spreading of dredged materials from Penny's Bay we applied a circular filter, centred in Penny's Bay. Within a radius r_1=2 km all values in the remaining circle sector are retained at their original value, between r_1=2 and r_2=8 km the values taper to zero using a $\cos^2$ taper. The results in the two lower frames show that visually the comparison is now much easier, the reader is not distracted by concentration peaks far away which we know either to be artefacts, or to be of far less importance than that what happens in and around Penny's Bay;

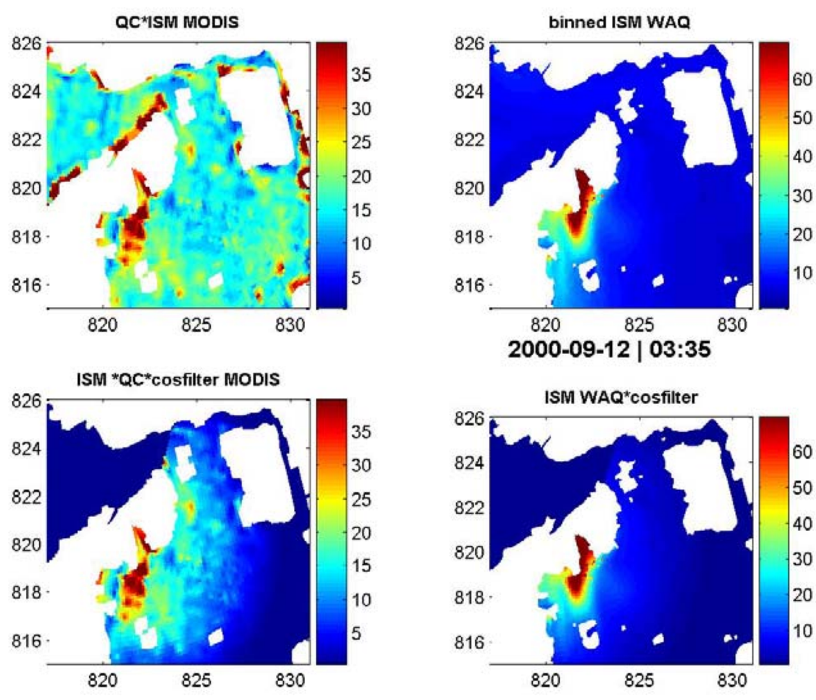

Figure 9 Processed earth observation image and numerical model surface concentrations for 12th September; original (upper frames) and after application of a circular filter to facilitate focusing on area of interest (lower frames).

- Scaling of results and spatial shifting: modelled TSS concentration fields may differ from sediment concentration fields that are derived from satellite imagery. Both concentration values are scaled, compared and if feasible, the model concentration values are rescaled towards the ground truth with the earth observation and / or in-situ measurement, leading to significant (statistical) correspondence with the earth observation and in-situ concentrations. This fine-tuning or adjustment of the model is nearly fully automated;
- Forecasting with rescaled model TSS concentration fields: (successive) rescaling adjustment of the model concentration fields in terms of improvement of forecasts are applied. This means the model simulation is restarted from the "earth observation-adjusted" concentration field. To illustrate this, the results of a simulation run from 12th to 14th September are shown: the model simulation is started using the rescaled model results (i.e. the model is rescaled using the earth observation-adjusted concentration field, applied for the whole domain and to all concentration model layers) on 12th September, 11:36 hrs, and then continued to 14th September 14, 10:42 local time. This allows for comparison between the modelled top layer concentration distribution with the concentration field derived from the Landsat image taken at September 14, 10:43 hrs. The differences in concentration distribution in the circular area of interest near Penny's Bay are quantified and visualised by establishing a scaling curve.

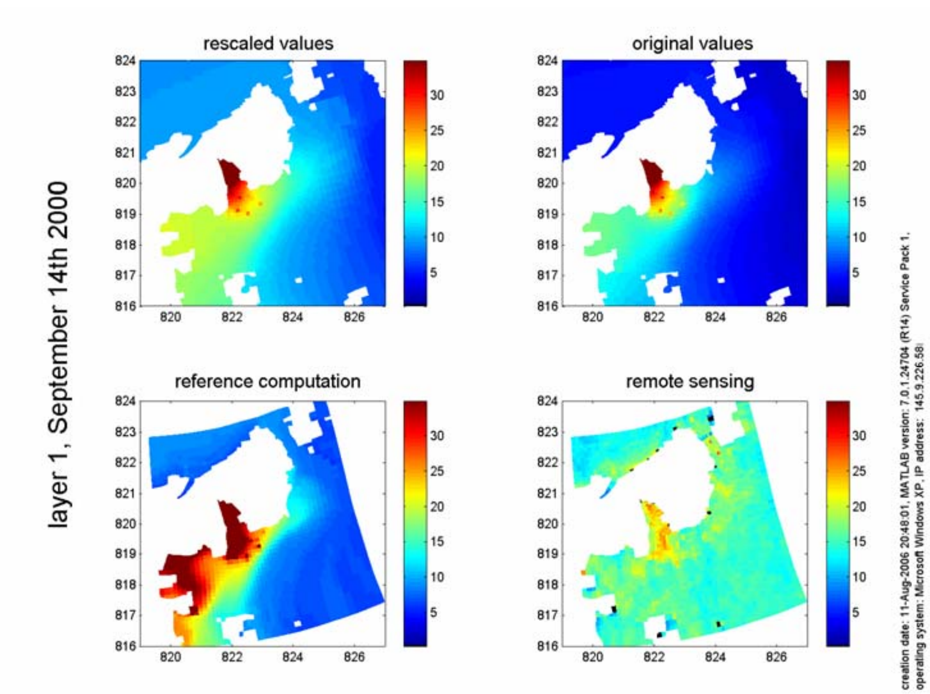

Figure 10 Modelled surface concentrations at 14th September, 10:42 hrs. Lower left: simulation without any scaling; upper right: simulation restarted from rescaled concentrations at September 12; upper left: simulation restarted from rescaled concentrations at September 12, and again rescaled at September 14; lower right earth observation-based concentrations for September 14, 10:43 hrs local time.

It is clear from Figure 10 that the continuation with rescaled concentrations at 12th September leads to improved agreement with the earth observation-based concentrations; rescaling again at September 14 further improves the agreement of the surface concentration with the earth observation-based concentration.

DISCUSSION

In this paper an innovative new approach to compliance monitoring during dredging operations is proposed, based on a combination of the use of numerical flow and dispersion modelling, earth observation imagery and in-situ monitoring. The basic concept is that all three sources provide independent information on the spreading of sediment releases, and that the data can be optimally integrated to provide much more detailed space-time covering information using a tailored DMI technique. A practical and relatively simple DMI approach is outlined, based on correction of the simulated model result for the surface layer against earth observation-based concentration patterns. This rescaling approach is basically a form of adjustment for differences in mass content, or actually the distribution of all spatially pooled TSS information. We have shown the potential of rescaling adjustment for obtaining a better agreement of modelled concentrations with earth observation-based concentrations. Systematic or successive adjustment, whenever earth observation data are available, leads to further agreement.

The remaining issue is the agreement of model concentrations and earth observation-based concentrations in some absolute sense. Comparing the upper left and lower right frames in Figure 10, it is clear that the modelled surface concentration is essentially higher than the earth observation-based concentration. A comparison of the earth observation data, in-situ and modelled data has been made using the in-situ concentration measurement data in 16 operational measurement stations during the dredging activities (results not shown here). The results confirmed that rescaling adjustments are an important step to realise better agreement between modelled concentration fields and in-situ concentration. It also indicates that rescaling as such may not be enough – a spatial correction for e.g. incorrectly modelled positions of peak concentrations or centres of mass of a plume, or plume orientation may be required as well. In that respect, an extension of the DMI approach should be considered.

In open sea, the possible mismatch in centre of mass or location of the peak concentration of a patch can be quantified easily by determining the centre of mass for both patches and applying a corresponding horizontal shift of the modelled concentration pattern as a whole. Similarly, a different orientation of the patch can be corrected for by a rotation. To do so in a real life case, where varying coastlines and local inlets strongly affect the spreading and the form of the patch, is much more difficult. For a complex coastline with inlets and bays, rescaling is still a feasible approach, as shown in the present project, although automated rotation and translation of the concentration patch as a whole will in most cases not be possible, as it will require much ad-hoc manual intervention. Thus, for more complex coastlines, manual intervention, and therefore the involvement of a trained project engineer remains necessary.

To summarise, there are some main benefits as well as key problems involved in the successful implementation of the DIS. The benefits include the integration of the various types of data, leading to a more optimal, synoptic information product, and the fact that the DIS can ‘fill the gaps’ in time and space by use of the model, which in-situ and earth observation data alone cannot do. Drawbacks to the DIS include initial set-up costs, the availability of in-situ and earth observation data, timeliness of data delivery (particularly delivery of earth observation data within 24 hours for project execution purposes), cloudcover, accuracy of in-situ and dredging source data and availability of a numerical model. The DIS requires a large amount of data and information to work in practice, as well as a calibrated and validated numerical model of the region of interest. For certain regions, models are readily available, reducing the project preparation costs of setting up the DIS. The problem of cloudcover, as discussed above, can be partly overcome, by the use of a cloudcover simulator tool for predicting or assessing satellite imagery for a specific region.

With respect to the cost of the DIS, the initial set-up costs seem relatively high, due to the large amount of data initially required. However, operational costs for in-situ monitoring before and during dredging are also relatively high. It is therefore foreseen that the DIS may be used to design more cost-effective monitoring plans and programs, thereby providing potential cost-savings.

At present, the DIS is only feasible for large-scale dredging projects which require a monitoring component with a relatively large monitoring budget. Despite the relatively high costs of in-situ monitoring and the use of the DIS, it is foreseen that in the longer term dredging companies may be more willing to invest in the application of the DIS, if current trends in environmental management of dredging projects and stricter quality norms continue.

CONCLUSIONS AND END-USER EVALUATION

Evaluation of the results in the RESTSCOD project leads to the following main observations and conclusions.

- The present DIS user interface effectively bridges the gap between the world of the project engineer and the modeller in the preparation of modelling simulations. It assists the project engineer to prepare model input in a flexible and consistent way and so ensures integrity of the water quality / TSS spreading simulations;
- The model simulations are started via the GUI. Options for efficient and intuitive visualisation of the results will be added in the near future. The same holds for efficient user visualisation of the earth observation based concentrations;
- We have presented a DMI methodology for improving model simulation concentrations by systematic and structured adjustment, using information from earth observation-based concentration distributions. With the assumption that the earth observation-based concentrations are a reasonable to good representation of the real surface concentration, this adjustment provides an effective continuous validation and upgrading of the model results, providing a consistent and optimal initial distribution for a nowcasting or forecasting simulation of the spreading of dredged material;
- Some significant steps have been achieved in the development of DMI techniques. The method is practically feasible and allows for automated adjustment procedures. The rescaling adjustments have also been shown to lead to better agreement between modelled concentration fields and in-situ concentrations. The rescaling as such, on the other hand, may not be enough to obtain adequate spatial agreement for practical application in all cases; an extension of the DMI approach to allow spatial corrections of centres of mass or locations of peak concentrations given earth observation or in-situ information, is recommended;
- Evaluation, or (repeated) evaluation of model surface concentrations against earth observation-based concentrations and subsequent adjustment of the modelled results by rescaling and shifting cycles to minimise the misfit, remains a complex process and requires intermediate interpretation to guide the steps of the process. Explicit support of the project engineer by a modelling specialist remains necessary for this;
- At this moment the DIS can be considered to be operational for the project preparation phase and the post-project evaluation phase for relatively large-scale projects. For the project execution phase, a very short delivery time of the various input data is required and this cannot yet be performed with earth observation data. Improvements in timeliness of satellite data are foreseen in the future. Sporadically, very fast scenarios for high resolution satellite data delivery within a few hours are implemented, but these are not universal enough to form a solid basis for a system such as the present DIS.

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ACKNOWLEDGEMENTS

The three-phase RESTSCOD project was co-funded by the Dutch government's User Support Programme (GO-2) under NIVR contract numbers 52303WL, 53513WL and 53609WL. The permission of the Environmental Protection Department of the Government of the Hong Kong Special Administrative region to use its so-called Update Model in the present study is gratefully acknowledged.