

Conclusions and future research perspectives

9.1. Conclusions

Data from quasi-continuous multi-sensor benthic measurements increased the knowledge of the natural variability of SPM processes for three stations in the Belgian coastal zone. Together with findings obtained from analysis of surface SPM concentration maps, spatial dynamics of the coastal turbidity maximum (CTM) zone were then captured. Analysis of the different data sets (benthic frame and tripod, satellite and vessel), in combination with hydro-meteorological information, resulted in reaching the following conclusions:

The alongshore flow direction was considered to categorize flow regimes induced by winds. An overall good correlation was found between alongshore winds and flows. It was observed that sustaining winds with a north component (N-NE winds) induce a subtidal flow towards the southwest (towards France). This wind sector accounts for 15% of the time, and its magnitude is on average 7.1 m s^{-1} ($\pm 3.3 \text{ m s}^{-1}$). The opposite subtidal flow regime (towards the Netherlands) is mainly triggered by winds from the west-southwest (23%), and are generally stronger ($9.5 \pm 4.3 \text{ m s}^{-1}$). A northeast-directed flow regime is characterized by increased salinity and reduced SPM concentration. This is because of the advection of Atlantic waters (through the English Channel and Strait of Dover) co-mingling with the coastal waters in the study area. However, these winds can persist and are strong enough to generate waves (average significant wave height of 0.85 m), resulting in increased combined (wave and current) shear stresses acting on the soft cohesive deposits. In addition, synoptic SPM concentration maps under these meteorological conditions show an extension of the coastal turbidity maximum zone towards the Dutch waters. Also, the freshwater 'plume' of the River Scheldt is influenced by these meteorological conditions. However, in this regime the extension of the plume is limited (although freshwater discharge is high); hence there is no link between the CTM zone and the freshwater plume. The Scheldt river system is known not to generate a classical river (turbidity) plume, as found elsewhere in the southern North Sea (e.g. Humber, Thames, Elbe etc.). Further, transport of marine fine matter into the River Scheldt is expected.

During major west-southwest wind events (or storms), it was observed and concluded that cohesive sediment and the primary particles and flocculi (larger flocs are destroyed) are transported away towards the northeast, and that fine sands dominate the particle size distribution. This has implications towards the used instrumentation: the OBS-3 (optical backscatter sensor) systematically showed reduced SPM concentrations under these conditions; whereas, the acoustic response (from the acoustic Doppler velocimeter) becomes dominant since the instrument-specific properties (e.g. frequency of output signal) are more sensitive to a uni-modal particle size distribution in the coarse silt – fine sand range and to solid particles rather than flocs.

Regarding the southwest-directed flow regime, the coastal waters are less affected by Atlantic waters resulting in lower salinities. Freshwater from the Scheldt (and Rhine-Meuse) is more pushed towards the south. Again, the CTM zone is not linked with the freshwater plume, since the CTM zone is not connected with the river mouth. The CTM zone itself covers now a much smaller area close to the shore. In the CTM zone, it was found that SPM background concentrations are generally higher. It was suggested that a release of fine sediments from the Scheldt River mouth contributes to the turbidity. Multi-modal particle size distributions are observed and are related to the cohesive sediment dynamics, with flocculation and disaggregation processes being more important. Because of these dynamics, the OBS-3 will perform well, since no sands in suspension interfere. Nevertheless, flocculation will affect the optical response in a negative way, and obtained SPM concentrations will be less accurate.

It is concluded that the study area is subdued to different hydrodynamic controls (different flow regimes), which on their turn will affect SPM nature and concentration. The SPM concentration is mainly associated with the advection of water masses, and hence salinity and SPM concentration may be considered as co-variables.

Storminess is mostly present during the high-energy season (winter), and is expressed by the manifestation of gravity waves affecting the shallow study area. Highest waves

occur with winds from the north (+2 m waves). Aforementioned, the northeast-ward flow regime also includes major southwest storm events, and the associated waves have a wave period of about 4 s. It is observed that the northerly winds may generate somewhat longer-period waves, because of the larger fetch (open North Sea). They impact on the seabed significantly, because of the larger wave orbital velocities. As a result, more fine matter is resuspended and the CTM zone extends spatially and witnesses the highest surface SPM concentrations. It is further suggested that the consolidated cohesive (Holocene) muddy sediments of the large mud plate in the coastal zone, and the soft mud deposits in the navigational channels, are eroded under these meteorological conditions.

More significant alongshore displacement in CTM position towards the Dutch coastal waters is observed in winter months with stronger-than-average southwesterly winds. Winter periods also exist in which southwesterly winds are less abundant, resulting in different spatial patterns of the CTM. The latter is based on the climatological index, North Atlantic Oscillation (winter), even substantially influencing CTM position for longer periods (4 months).

Towards near-bed processes, the study revealed the occurrence and importance of high-concentration mud suspensions (HCMS) layers. These suspensions have concentrations up to a few g l⁻¹. It is concluded that they may correspond to different time-scales:

- intra-tidal (slack tide)
- associated to storm events
- neap tides

The first HCMS type is common in the CTM zone and is observed on a regular basis (quarter-diurnal), especially when current ellipses are elongated; thus with long phases of slack tide (i.e. reduced turbulent energy). The gravitational settling of SPM, out of the water column, on the sea bed is further enhanced by flocculation. The larger the flocs, the faster they will settle. The second type has been observed to occur when wave-induced shear stresses fluidize the cohesive and muddy bed, resulting in HCMS layers. Also, post-storm phases with HCMS layers were observed and were explained by the massive amount of SPM available in the water column. The sediments from the navigation channels contribute to this type of HCMS formation. The last type is associated with reduced turbulent energy conditions under neap tide in which SPM settles down and covers the seabed with HCMS (and eventually fluid mud), until the subsequent spring tide will resuspend it again. Worldwide, HCMS are associated with rapid and massive siltation in harbour basins and navigation channels. As a consequence, intensive dredging-disposal cycles are necessary to ensure the accessibility to the harbours. An experiment of alternative ways of disposal of dredged material included the disposal of mud over the breakwater of Zeebrugge harbour. It has been statistically proven that also the disposal activities induced the formation of HCMS layers, and possibly fluid mud, at some distance away from the disposal site. The statistical method allowed accounting for the complex natural dynamics and showed the need to evaluate human impact quantitatively. Ultimately, SPM concentration can be used as an indicator of environmental changes. Therefore the natural variability must be known fully, pleading for long data series covering consecutive hydro-meteorological conditions. Ultimately, a study on mine burial in the CTM zone revealed the importance of occurrences of HCMS (fluid mud) towards the detection of sea mines or other objects. Optics-based burial-registration mines can be used to detect HCMS layers; this, in combination with acoustics from benthic observatories, opens up new avenues in the research on the behaviour of HCMS. All types of ammunition will potentially (periodically) be buried and exposed cyclically when suspended sediment is abundantly present, regardless of shape, density and orientation. The danger of missing ammunition during tracking surveys is greatest in areas and under circumstances where and when HCMS are relatively persistent. The latter should be monitored and analysed in detail as part of follow-up studies. For Belgium, the highest risk for mine burial is within the CTM zone during neap tides. Burial is then potentially the most prolonged.

9.2. *Future research perspectives*

SPM dynamics in the coastal area including the influence of the Westerschelde estuary:

- Consequences of the (long-term) variations in the spatial extension of the CTM (coastal turbidity maximum) zone should be further completed by targeted analyses, e.g. how is the SPM budget of the Westerschelde estuary varying with meteorology/climate and freshwater discharge; has the SPM budget of the estuary changed?
- Shorter temporal (several tides) variations in the alongshore position and extent of the CTM, and advection of suspension clouds should be investigated with gradient-wise (alongshore and/or cross-shore) deployment of several identical tripod systems. Also, in relation with the functioning of the Westerschelde (temporal storage of SPM, and followed by SPM release) this measuring strategy could be considered.
- Organic matter and biological particles (plankton) have a strong influence on flocculation and thus SPM transport. Future research should focus on the interaction of biological and mineralogical induced flocculation and on the effects of variations in organic matter concentration due to e.g. algae bloom on the SPM dynamics. Is deposition of SPM enhanced during these periods of high organic matter concentration and what is their influence on the carbon cycle? What and how have algae blooms, which are caused by eutrophication of coastal waters from human activities, changed the SPM dynamics and thus the ecosystem?
- Up to now, the HCMS and fluid mud dynamics were investigated in a few locations, however density of these layers could not be assessed with the instrumentation used. The mapping of the geographical extension and of the occurrence of HCMS or fluid mud layers along the Belgian coast (CTM) will provide information on the SPM dynamics in the area. This is especially of importance to understand the siltation of navigation channels and harbours as a function of environmental and meteorological conditions; and will allow improving measures to reduce dredging volumes. The mapping could be carried out using free-fall penetrating density probe. During tidal cycles, the penetrometer measurements could also reveal how fluid mud (or HCMS) built up and erodes in relation to the local hydrodynamics. The measurements may further reveal the density of the different mud suspensions/layers allowing to estimate the concentration of the suspensions and thus to calculate which part of the total SPM transport occurs in the benthic layer.
- Further studies on object/mine burial by HCMS/fluid mud should include simultaneous benthic tripod measurements together with research (BRM) mines. Then, multivariate statistical approaches must be considered and following parameters must then be integrated: tidal range, wind speed and direction, subtidal flow strength and direction, wave boundary layer, salinity, and flocculation in order to identify and predict burial as a function of various parameters.
- Towards anthropogenic activities such as disposal of dredged mud (and associated suspended sediment plumes), field campaigns should be organized with hull-mounted ADCP transects measurements nearby or across the disposal site(s). This data must evaluate and support the existing modelling results on the dispersal/dispersion of the disposed sediments (sediment plume).

Improving measurement techniques and accuracy:

- Standardized methods for the processing of acoustic and optical backscatter signals should be developed. The latter is requested to formulate sound conclusions on long-term changes in SPM concentration and composition at a single location, collected by the emerging coastal or sea observatories.
- Towards accuracy of OBS sensors, it is further suggested to deploy OBS sensors that are calibrated in different ranges, since significant changes in suspended concentrations occur in the CTM zone. This will allow better

estimating sediment fluxes during future deployments. Or calibrate directly from OBS signal (voltages) to SPM concentration in order to achieve an improved standard error in SPM concentration conversions.

- Varying particle size spectra and their influence on measurements of turbidity (OBS, AD(C)P) are often related to flocculation processes but are also linked to the mineralogical characteristics. It is suggested that a combination of different sensors (optics, acoustics, particle sizer) is necessary in order to understand the nature of suspensions. Dependent on system frequency, range in particle size for optimal detection by the sensor must be further studied (e.g. two-phase diagrams obtained from correlation study with particle size data and acoustic backscatter).
- Measurements in laboratory and in-situ are required in order to define acoustically the top of sediment suspension layers (i.e. lutoclines related to fluid mud or HCMS layers) as a function of the acoustic frequency of the instrument and the composition of the SPM/HCMS. The in-situ measurements can be carried out using e.g. free-fall penetrating density sensors.
- A combination of different measuring techniques, such as hull-mounted ADCP together with ferry-box data (e.g. the AUMS system on board of the R/V Belgica) collected while the vessel is navigating, will result in extended data sets that have been proven to be useful in other areas.