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Accounting for uncertainty in volumes of seabed change measured with repeat multibeam sonar surveys

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ABSTRACT

Seafloors of unconsolidated sediment are highly dynamic features; eroding or accumulating under the action of tides, waves and currents. Assessing which areas of the seafloor experienced change and measuring the corresponding volumes involved provide insights into these important active sedimentation processes. Computing the difference between Digital Elevation Models (DEMs) obtained from repeat Multibeam Echosounders (MBES) surveys has become a common technique to identify these areas, but the uncertainty in these datasets considerably affects the estimation of the volumes displaced. The two main techniques used to take into account uncertainty in volume estimations are the limitation of calculations to areas experiencing a change in depth beyond a chosen threshold, and the computation of volumetric confidence intervals. However, these techniques are still in their infancy and, as a result, are often crude, seldom used or poorly understood. In this article, we explored a number of possible methodological advances to address this issue, including: (1) using the uncertainty information provided by the MBES data processing algorithm CUBE, (2) adapting fluvial geomorphology techniques for volume calculations using spatially variable thresholds and (3) volumetric histograms. The nearshore seabed off Warrnambool harbour – located in the highly energetic southwest Victorian coast, Australia – was used as a test site. Four consecutive MBES surveys were carried out over a four-months period. The difference between consecutive DEMs revealed an area near the beach experiencing large sediment transfers – mostly erosion – and an area of reef experiencing increasing deposition from the advance of a nearby sediment sheet. The volumes of sediment displaced in these two areas were calculated using the techniques described above, both traditionally and using the suggested improvements. We compared the results and discussed the applicability of the new methodological improvements. We found that the spatially variable uncertainty derived from the CUBE algorithm provided the best results (i.e. smaller confidence intervals), but that similar results can be obtained using as a fixed uncertainty value derived from a reference area under a number of operational conditions.

1. Introduction

The topology of the seabed in the nearshore zone varies over a wide range of temporal and spatial scales as unconsolidated sediment is transported by tide- and wave-induced currents (Roy et al., 1994). These changes often impinge on artificial structures, affecting economic and recreational activity, which results in significant financial efforts being required to monitor, limit or compensate for sediment transfers. To date the key economic reasons for quantifying seabed change include the needs to monitor dredged shipping channels (Knaapen and Hulscher, 2002); the dispersal and fate of dumped dredge spoil (Stockmann et al., 2009); the volume of marine aggregate resources (Birchenough et al., 2010); and the seafloor response to engineering works introduced into the marine environment such as cables, pipelines and energy infrastructures (Ying et al., 2012). Scientific drivers include the needs to calibrate bedload transport equations and to gain insights into natural geomorphological dynamics such as bedforms (Barrie et al., 2009), delta channels (Hughes Clarke et al., 2009), landslides (Smith et al., 2007), lava flows (Le Friant et al., 2010), earthquake displacement (Fujiwara et al., 2011) and implications for benthic habitats (Rattray et al., 2013).

Fortunately, the tools available to precisely measure the change in seafloor topography have much improved since Langhorne (1982) hammered steel stakes into a sandwave to monitor its

Abbreviations: DoD, Difference of DEM; LoD, Limit of Detection

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Table 1
Review of studies that implemented DoDs from repeat surveys (including at least one swath hydrographic sonar survey) for visualisation, detection or quantification of depth change, ordered by year and first author initial. In the last column, the numbers in parenthesis indicates the threshold value used in case of volumes computed with a fixed threshold, and the uncertainty value used in case of confidence intervals.

Study	Application	Setting (depth), location	Techniques
Wienberg et al. (2004)	Dredged sediment disposal	Nearshore (~12 m), Germany	Volumes not including uncertainty
Ferrini and Flood (2005)	Ripple Scour Depressions	Nearshore (~15 m), US	No volumes computed
Mitchell (2005)	Channels evolution	Delta channel (0–100 m), CA, USA	Volumes not including uncertainty
Smith et al. (2005)	Canyon sedimentary processes	Canyon (30–440 m), San Francisco, CA, USA	Volumes with fixed threshold (±1 m) and confidence intervals (±0.5 m)
Smith et al. (2007)	Canyon sedimentary processes, landslides	Canyon (30–440 m), San Francisco, CA, USA	Volumes with fixed threshold (±1 m) and confidence intervals (±1 m)
Du Four and Van Lancker (2008)	Dredged sediment disposal	Nearshore (6–21 m), Belgium	Volumes not including uncertainty
Schmitt et al. (2008)	Quantifying MBES uncertainty	Nearshore sand bank (10–36 m), UK	No volumes
Shaw et al. (2008)	Sandwaves migration	Nearshore sand bank (~15 m), Canada	Volumes not including uncertainty
Xu et al. (2008)	Sandwaves migration	Canyon (30–440 m), San Francisco, CA, USA	Volumes with confidence intervals (±0.2 m)
Barrie et al. (2009)	Sandwaves migration	Sand bank (170–210 m), Canada	No volumes
Hughes Clarke et al. (2009)	Channels evolution	Delta channel (2–170 m), Alaska, USA	No volumes
Lepland et al. (2009)	Dredged sediment disposal	Fjord Basin (30–70 m), Norway	Volumes with confidence intervals (±0.1 m)
Stockmann et al. (2009)	Dredged sediment disposal	Nearshore (~18 m), Germany	Volumes not including uncertainty
Marani et al. (2009)	Landslides	Volcano flanks (350–2000 m), Italy	Volumes with fixed threshold (+5 m)
Conaway (2010)	Riverbed response to bridge building	River (2–14 m), Alaska, USA	No volumes
Le Friant et al. (2010)	Lava flows	Volcano (0–1000 m), Montserrat, BOT	Volumes with fixed threshold (+3.8 m)
Quinn and Boland (2010)	Sediment processes around shipwreck	Cont. Shelf, Arklow Bank (10–16 m), Ireland	No volumes
Yoshikawa and Nemoto (2010)	Sediment processes	Nearshore and Canyon head (5–35 m), Japan	Volumes not including uncertainty
Barnard et al. (2011)	Sandwaves migration	Nearshore sand bank (20–30 m), San Francisco Bay, CA, USA	Volumes not including uncertainty
Fujiwara et al. (2011)	Earthquake displacement	Trench (2000–8000 m), Japan	No volumes
Barnard et al. (2012)	Sediment processes	Delta and beach (0–30 m), San Francisco, CA, USA	Volumes not including uncertainty
Caress et al. (2012)	Lava flows	Volcano (1300–1800 m), Pacific Ocean	Volumes with fixed threshold (+0.2 m)
Casalbore et al. (2012)	Landslides	Volcano (12–320 m) and Canyon head (10–120 m), Italy	Volumes not including uncertainty
Conway et al. (2012)	Sediment processes in channels	Fjord (0–660 m), BC, Canada	Volumes not including uncertainty
Ying et al. (2012)	Sediment processes around port	Nearshore (10–87 m), Shanghai, China	No volumes
Franzetti et al. (2013)	Sandwaves migration	Sand banks (40–90 m), Brittany, France	No volumes
Bosman et al. (2014)	Lava flows and landslides	Volcano flanks (30–120 m), Italy	Volumes not including uncertainty
Mazières et al. (2014)	Canyon sedimentary processes	Canyon head (10–130 m), Bay of Biscay, France	Volumes with fixed threshold (±1 m)

evolution—nowadays, swath sonars systems such as multibeam echosounders (MBES) provide suitable data for most hydrographic studies (Mayer, 2006). A modern seabed change monitoring methodology consists in calculating and analysing the difference between two co-registered Digital Elevation Models (DEMs) obtained from repeat MBES surveys. The resulting "DEM of Difference" (DoD) quantifies the change in elevation with positive values showing deposition (or fill), negative values showing erosion (or cut, scour) and null values showing an unchanged surface. Table 1 presents a review of marine studies that computed DoDs from repeat MBES surveys to visualise seabed change and gain insights in a variety of phenomena affecting seabed elevation.

The volumes associated with surface change can be quite simply obtained by integrating the DoD over the areas of interest (that is, summing the depth-change grid cell values and multiplying by the area of one grid cell). However, the uncertainty in MBES bathymetry datasets often prevents the computation of reliable volume estimates. Many sources of errors affect the accuracy of MBES soundings, including the sonar system used, vessel configuration, vessel motion, tide, parameters of the water-column affecting sound velocity and absorption, low signal-to-noise ratio, bottom detection algorithm, etc. (Hare et al., 1995; Lurton, 2003; Lurton and Augustin, 2010). In addition, DEMs acquired with different systems, geo-positioning techniques, tide corrections or vessel configurations can present vertical or horizontal offsets that would translate into large errors when integrated over large areas (Smith et al., 2007; Brothers et al., 2011). As a consequence, many studies of seabed elevation change do not supplement their visual analysis of the DoDs with an estimation of the transferred volumes (9 out of the 28 cited in Table 1), or do not account for uncertainty in their calculations (11 out of the 28 cited in Table 1).

In the few studies that accounted for uncertainty in volume computations (8 out of the 28 cited in Table 1), two different approaches were used. A first approach consisted in limiting the volume computations to grid cells that showed an elevation change over a threshold, under the assumption that smaller elevation changes are more likely to be due to errors in the DEMs rather than actual change (Table 1). For example, Smith et al. (2005, 2007) and Mazières et al. (2014) used an *ad hoc* threshold purposefully adapted to the magnitude of the datasets' uncertainty (±1 m), while Caress et al. (2012) used a value equal to twice the vertical precision of the system used (±0.2 m) and Le Friant et al. (2010) used the standard deviation of the DoD over an area where it was assumed that no change had occurred (±3.80 m). The alternative approach consisted in calculating a confidence interval for any volume estimate as the total area of interest multiplied by the depth-change uncertainty, with different studies implementing a different measure of that uncertainty (Table 1). For example, Smith et al. (2005) used the mismatch in the depth of known features on the seabed (±0.50 m), Xu et al. (2008) used the DEMs' vertical precision (±0.20 m) and Lepland et al. (2009) used an estimate of the vertical offset between the two DEMs (±0.10 m).

Similar approaches have been implemented in other research fields concerned with measuring volumes involved in the change