1. Introduction

Locating fully submerged shipwrecks on the seabed is time consuming and expensive, made more difficult in the nearshore by navigation hazards, shallow depths and limited water clarity. The most common techniques used for locating and investigating underwater archaeological sites on a regional scale are waterborne swath acoustic techniques such as side-scan sonar (Quinn et al., 2011), and multibeam echosounder (Plets et al., 2011), and swath acoustic techniques such as side-scan sonar (Quinn et al., 2011). In the nearshore, waterborne techniques are compromised as search tools because their effective swath is a function of water depth, necessitating very close survey line spacing in shallow water, increasing cost accordingly. Additionally, in turbid coastal waters bathymetric LiDAR is ineffective as it relies on clear non-turbid water. Therefore, the nearshore turbid zone represents a challenging area for archaeologists in the search for fully submerged archaeological sites. In this study, we describe a new methodology to detect the presence of submerged shipwrecks using ocean colour satellite imagery in turbid waters. We demonstrate that wrecks generate Suspended Particulate Matter (SPM) concentration signals that can be detected by high-resolution ocean colour satellite data such as Landsat-8. Surface SPM plumes extend downstream for up to 4 km from wrecks, with measured concentrations ranging between 15 and 95 mg/l. The overall ratio between the plume and background SPM concentrations is about 1:4. During slack tidal phases sediments in suspension settle to create flufly mud deposits near the seabed. Scour pits developed around wrecks act as sinks where fine-grained material is preferentially deposited at slacks. The scour pits subsequently act as sources for suspended material when the bottom current increases after slacks. SPM plumes develop immediately before maximum ebb or flood current is reached, during maximum current and immediately after. Particulate matter is suspended in sufficient concentrations to be detected in ocean colour data. The ability to detect submerged shipwrecks from satellite remote sensors is of benefit to archaeological scientists and resource managers interesting in locating wrecks and investigating processes driving their evolution.

© 2015 Elsevier Ltd. All rights reserved.

ARTICLE INFO

Article history:
Received 1 July 2015
Received in revised form 13 November 2015
Accepted 14 November 2015
Available online xxx

Keywords:
Landsat-8
Suspended sediments
Shipwreck detection
Bathymetry
Scour pits

ABSTRACT

Waterborne swath acoustic and airborne laser systems are the main methods used to detect and investigate fully submerged shipwreck sites. In the nearshore, waterborne techniques are compromised as search tools as their effective swath is a function of water depth, necessitating very close survey line spacing in shallow water, increasing cost accordingly. Additionally, in turbid coastal waters bathymetric LiDAR is ineffective as it relies on clear non-turbid water. Therefore, the nearshore turbid zone represents a challenging area for archaeologists in the search for fully submerged archaeological sites. In this study, we describe a new methodology to detect the presence of submerged shipwrecks using ocean colour satellite imagery in turbid waters. We demonstrate that wrecks generate Suspended Particulate Matter (SPM) concentration signals that can be detected by high-resolution ocean colour satellite data such as Landsat-8. Surface SPM plumes extend downstream for up to 4 km from wrecks, with measured concentrations ranging between 15 and 95 mg/l. The overall ratio between the plume and background SPM concentrations is about 1:4. During slack tidal phases sediments in suspension settle to create flufly mud deposits near the seabed. Scour pits developed around wrecks act as sinks where fine-grained suspended material is preferentially deposited at slacks. The scour pits subsequently act as sources for suspended material when the bottom current increases after slacks. SPM plumes develop immediately before maximum ebb or flood current is reached, during maximum current and immediately after. Particulate matter is suspended in sufficient concentrations to be detected in ocean colour data. The ability to detect submerged shipwrecks from satellite remote sensors is of benefit to archaeological scientists and resource managers interesting in locating wrecks and investigating processes driving their evolution.

© 2015 Elsevier Ltd. All rights reserved.
water surface, where they can be detected by remote sensing techniques.

Mapping of suspended particulate matter (SPM) concentration from ocean colour satellite imagery such as SeaWiFS, Meris or MODIS-Aqua with 250–750 m spatial resolution has proven to be an excellent source of data to describe and understand the surface SPM distribution in the time and space domain (Triskati et al., 2005; Fettweis et al., 2007; Eleveld et al., 2008; Nechad et al., 2010; Fettweis et al., 2012). Satellites such as Landsat-8 with an even higher spatial resolution (30 m) show small-scale SPM concentration variations at the sea surface. These features are a sign of the natural heterogeneity of hydrological, seafloor, bathymetrical and biological conditions (Becker et al., 2013). Human activities, such as dredging and disposal of dredged material, sand extraction, aquaculture and offshore structures constructions impose further local changes in hydrodynamics and sediment transport, and affect turbidity, fine-grained sediment dynamics, and thus the SPM concentration in the water column, at the surface and on the sea floor (Forrest et al., 2009; Fettweis et al., 2011; Capello et al., 2014; Van Lancker and Baeye, 2015).

The effect of these small-scale changes can be detected by high-resolution satellites, such as Landsat-8. An example of the turbid water associated with offshore windfarms (Vanhellemont and Ruddick, 2014). The increase in SPM concentration in the wakes of these structures is caused mainly by the increase of hard substrate surfaces in a soft sediment environment and the associated massive bio-fouling (Baeye and Fettweis, 2015). Other studies have shown that objects on the sea floor induce local scour pits (Quinn and Boland, 2010) that can be periodically filled by fine-grained sediments resulting in an increase of the sea floor heterogeneity (Traykovskii et al., 2004; Baeye et al., 2012). The aim of this study is to investigate if fully submerged shipwrecks in the nearshore generate SPM concentration signals that can be detected by high-resolution ocean colour satellites such as Landsat-8. The availability of detailed bathymetric data and surface SPM concentration maps make the Belgian nearshore area a relevant site for investigating the link between the shipwreck, the scour signatures at the sea bed and the surface signature in SPM concentration and illustrate the potential of remote sensing mapping for underwater archaeology.

2. Material and methods

2.1. Wreck sites and bathymetric data

In this study, four shipwreck sites near the port of Zeebrugge are investigated: SS Sansip (1944), SS Samvurn (1945), SS Nippon (1938) and SS Neutron (1965). Sansip, a 135 × 17 m US Liberty cargo ship with a draft of 8.5 m sank after being mined on December 7, 1944. On September 11, 1997 the fishing vessel N12 Arthur struck the site and sank adjacent to Sansip. Samvurn, measuring 129 × 17 m, sank after being mined on January 18, 1945 underway from Antwerp to London. 7 crew and nine soldiers died. Nippon, a 138 × 18 m Swedish steamship sank on September 14 1938 after colliding with another vessel off the Wandelaar Lightship. Neutron, a 51 × 8 m Dutch steel cargo vessel, foundered and sank on August 3 1965 after hitting a wreck, presumed to be Sansip.

Full-coverge multibeam echosounder (MBES) data was made available by the Flemish Hydrography, Coastal Division, Agency for Maritime and Coastal Services, Flemish Ministry of Mobility and Public Works. The MBES surveys of the wreck sites were conducted using a dual head Kongsberg EM3002D, an RTK Septentrio AstReX2e GPS system and Applanix POS/MV 320 motion compensation system. The 1 m gridded data were rendered using ArcGIS v 10.1. Reference level of the water depths is Lowest Astronomical Tide (LAT).

2.2. Satellite data

Landsat-8 was launched on February 11, 2013 with a ground track repeat cycle of 16 days and a crossing time at 10:45 a.m. for the study area. The Operational Land Imager (OLI) on Landsat-8 is a nine band push broom scanner with a swath width of 185 km. Suspended particulate matter (SPM) is retrieved using OLI bands 4 (red) and 5 (near infrared) at 30 m spatial resolution. Processing included, among others, atmospheric correction and correction for scattering by molecules and aerosols to retrieve water-leaving radiance reflectance (details in Vanhellemont and Ruddick, 2014). A set of 21 cloud-free Landsat-8 images, covering the different seasonal, fortnightly and semi-diurnal conditions, was used in this study (Table 1). Fig. 1a is an original RGB Landsat-8 image of the Belgian coastal zone area, and the derived SPM concentration map is shown in Fig. 1b.

2.3. Hydrodynamic model

The tidal currents (direction and speed) and water elevation at the time of each Landsat-8 image were modelled using an implementation of the 3D COHERENS hydrodynamic model to the Belgian Continental Shelf (Luyten, 2013). The model covers an area between 51°N and 51.92°N and between 2.08°E and 4.2°E. Boundary conditions for this model were provided by the operational models OPTOS-NOS (covering the North Sea) and OPTOS-CSM (covering the North-West European Continental Shelf). Regarding the tidal currents, a counter-clockwise rotating tidal wave is associated with the amphidromic point in the southern North Sea resulting in a semi-diurnal tidal current ellipses that for the study area is oriented WSW (ebb) —ENE (flood). The tidal range in water elevation varies between 2.5 (super neap) and 5.0 (super spring) m, with an average tidal range of 3.6 m.

<table>
<thead>
<tr>
<th>Path</th>
<th>Day</th>
<th>Spring/neap</th>
<th>Season</th>
<th>Plume dir</th>
<th>Current dir</th>
<th>+ Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>199</td>
<td>200</td>
<td>neap</td>
<td>summer</td>
<td>042</td>
<td>047</td>
<td>0.40</td>
</tr>
<tr>
<td>199</td>
<td>216</td>
<td>neap</td>
<td>summer</td>
<td>060</td>
<td>064</td>
<td>0.82</td>
</tr>
<tr>
<td>199</td>
<td>232</td>
<td>spring</td>
<td>summer</td>
<td>076</td>
<td>068</td>
<td>1.08</td>
</tr>
<tr>
<td>199</td>
<td>248</td>
<td>spring</td>
<td>summer</td>
<td>121</td>
<td>124</td>
<td>0.13</td>
</tr>
<tr>
<td>199</td>
<td>280</td>
<td>fall</td>
<td>fall</td>
<td>208</td>
<td>219</td>
<td>0.34</td>
</tr>
<tr>
<td>199</td>
<td>344</td>
<td>fall</td>
<td>fall</td>
<td>278</td>
<td>264</td>
<td>0.52</td>
</tr>
<tr>
<td>200</td>
<td>159</td>
<td>spring</td>
<td>spring</td>
<td>161</td>
<td>161</td>
<td>0.18</td>
</tr>
<tr>
<td>200</td>
<td>303</td>
<td>fall</td>
<td>fall</td>
<td>54</td>
<td>54</td>
<td>0.54</td>
</tr>
<tr>
<td>199</td>
<td>75</td>
<td>spring</td>
<td>winter</td>
<td>105</td>
<td>108</td>
<td>0.24</td>
</tr>
<tr>
<td>199</td>
<td>91</td>
<td>spring</td>
<td>winter</td>
<td>213</td>
<td>224</td>
<td>0.43</td>
</tr>
<tr>
<td>199</td>
<td>107</td>
<td>spring</td>
<td>winter</td>
<td>217</td>
<td>221</td>
<td>0.28</td>
</tr>
<tr>
<td>199</td>
<td>139</td>
<td>spring</td>
<td>spring</td>
<td>239</td>
<td>232</td>
<td>0.67</td>
</tr>
<tr>
<td>199</td>
<td>235</td>
<td>neap</td>
<td>summer</td>
<td>074</td>
<td>072</td>
<td>0.81</td>
</tr>
<tr>
<td>199</td>
<td>251</td>
<td>spring</td>
<td>summer</td>
<td>085</td>
<td>078</td>
<td>0.59</td>
</tr>
<tr>
<td>200</td>
<td>34</td>
<td>spring</td>
<td>winter</td>
<td>241</td>
<td>241</td>
<td>0.72</td>
</tr>
<tr>
<td>200</td>
<td>82</td>
<td>neap</td>
<td>spring</td>
<td>253</td>
<td>244</td>
<td>0.75</td>
</tr>
<tr>
<td>200</td>
<td>162</td>
<td>spring</td>
<td>spring</td>
<td>066</td>
<td>066</td>
<td>1.02</td>
</tr>
<tr>
<td>200</td>
<td>226</td>
<td>spring</td>
<td>summer</td>
<td>235</td>
<td>231</td>
<td>0.73</td>
</tr>
<tr>
<td>200</td>
<td>258</td>
<td>neap</td>
<td>summer</td>
<td>240</td>
<td>241</td>
<td>0.75</td>
</tr>
<tr>
<td>200</td>
<td>290</td>
<td>fall</td>
<td>fall</td>
<td>287</td>
<td>287</td>
<td>0.17</td>
</tr>
<tr>
<td>200</td>
<td>306</td>
<td>neap</td>
<td>fall</td>
<td>348</td>
<td>348</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Table 1

Satellite imagery and hydrodynamic model metadata and derivatives. 2013 data is in italics, 2014 data in bold and * means no plumes were observed in Landsat-8 SPM concentration map. The correlation coefficient is 0.99 between modelled current direction (current dir; true north) and plume direction (plume dir; true north). Neaps and springs are classified based on the median difference between high water and low water elevation which is 3.6 m for the study area. Seasons are divided as follows: [355–80] is winter, [80–172] is spring, [172–266] is summer, [266–355] is fall.
3. Results

3.1. Bathymetry

The four wreck sites under investigation are located within 5 km of each other on a fine to medium sandy sea floor in less than 15 m of water (Fig. 2, Table 2). All four sites display scour pits aligned parallel to peak flow (Fig. 3). The sites of SS Sansip and SS Samvurn have the largest and deepest scour pits, with both wrecks exposed above the seafloor. SS Sansip and the remains of Arthur (Fig. 3a, Table 2) are broken into four sections over an area of 150 × 40 m, with the shallowest point on the vessel at 4.9 m LAT and the deepest scour pit at 13.8 m LAT. Scouring occurs all around the site, with the deepest pits immediately adjacent to the broken sections of the vessels at the southern end of the site. Bedforms are developed to the northwest of the wreck site, with crests orientated NNW-SSE. SS Samvurn, located 2 km southeast of SS Sansip, also displays a well-developed scour pit (Fig. 3b), with maximum scouring to a depth of 12.6 m LAT around the bow. The vessel appears largely intact, measuring 72 × 23 m, with the shallowest point at 3.8 m LAT.

SS Neutron (Fig. 3c) and SS Nippon (Fig. 3d) are both buried deeper in the seabed than SS Sansip and SS Samvurn and so less of their superstructure is exposed to influence scour processes. SS Neutron is imaged as two discrete sections in the MBES data, with the southern section measuring 15 × 9 m and the northern section measuring 7 × 9 m. The deepest scour pit is developed around the structure at the northern end of the site, with a maximum recorded depth of 11.3 m LAT. SS Nippon, the most easterly of the sites, appears intact, measuring 120 × 20 m. This is the lowest relief of all four sites, with a variation of 3.2 m from the deepest scour pit (11.8 m LAT) to the shallowest point on the wreck (8.6 m LAT).

3.2. Surface sediment concentration

SPM plumes are recorded originating from the sites of SS Sansip and SS Samvurn during both flood (Fig. 4a) and ebb (Fig. 4b) phases of the tide. No SPM plumes are recorded in association with the SS Neutron or SS Nippon wreck sites in any of the Landsat-derived SPM concentration maps. On the stronger flood tide, the plume from the SS Samvurn site is directed to the NNE with a concentration of about 35 mg/l, whereas the SS Sansip site associated plume is not (yet) well developed (Fig. 4a). On the weaker ebb tide, the SS Sansip and SS Samvurn plumes are directed to the SSW (Fig. 4b) with concentrations of about 40 mg/l at a distance of 200 m from the wreck sites (Fig. 5). In the northeast sector of the ebb tide SPM concentration map (Fig. 4b), increased SPM concentrations are associated with turbid wakes of deep-draft vessels. Based on all 21 images, the overall average ratio between the plume and background (i.e. inside vs. outside the plume) concentration at 200 m from the two wreck sites, is about 1.4. For spring tide periods (stronger currents) in winter (overall more SPM in watercolumn) SPM concentrations are much higher than for neap tides (weaker currents) during summer (overall less SPM), however that ratio remains more or less 1.4.

Fig. 6a synthesizes all observed plume directions in a polar plot, clearly evidencing the dominant ebb and flood tidal phase plumes. Note that SPM plumes were observed immediately before, during and immediately after maximum current velocities were reached (Fig. 6b). Plume directions and the associated tidal current directions from the hydrodynamic model (Table 1) correlate well.

<table>
<thead>
<tr>
<th>Wreck</th>
<th>d50 (μm) classification</th>
<th>Dmin (m)</th>
<th>Dmax (m)</th>
<th>ΔD (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS Neutron</td>
<td>329 Medium sand</td>
<td>7.7</td>
<td>11.3</td>
<td>3.6</td>
</tr>
<tr>
<td>SS Sansip</td>
<td>237-337 Fine-medium sand</td>
<td>4.9</td>
<td>13.8</td>
<td>8.9</td>
</tr>
<tr>
<td>SS Samvurn</td>
<td>249-399 Fine-medium sand</td>
<td>3.8</td>
<td>12.6</td>
<td>8.8</td>
</tr>
<tr>
<td>SS Nippon</td>
<td>197-331 Fine-medium sand</td>
<td>8.6</td>
<td>11.8</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Fig. 3. MBES-derived digital elevation models of the wreck sites: A: SS Sansip; B: SS Samvum; C: SS Neutron; D: SS Nippon. Depths in metre with reference LAT (lowest astronomical tide).

Fig. 4. (A) Flood phase during day 235 (2014) under neap tide and partly cloudy (see white areas); (B), ebb phase during day 91 (2014) under spring tide. ? is an unknown shipwreck. White circle around SS Sansip through plume at a distance of 200 m from wreck (see Fig. 5).
4. Discussion

4.1. Conceptual model

During slack tidal phases, sediments in suspension settle down and create fluffy mud deposits up to 30 cm near the seabed (Baeye et al., 2012). We propose that the scour pits play an important role in the development of the SPM plumes, as they act as sinks where fine-grained suspended material is preferentially deposited during slacks and alternately act as sources for suspended material when the bottom current increases again. The duration of the slack tide (dependent on the prevailing meteorological forcing) defines how much filling occurs. The SPM plume develops immediately before maximum ebb or flood current is reached, during maximum current and immediately after (see Fig. 6a and b). Therefore it is likely that a plume develops (i.e. becoming more turbid and growing in length); and as the current is turning anti-clockwise, they tend to be slightly bent to the right.

Furthermore, the tide is semi-diurnal assuming 4 SPM plumes that develop on a daily basis (2 during ebb and 2 during flood). Regardless the strong or weaker hydrodynamic forcing, SPM plumes occur under spring and neap tide conditions respectively.

The occurrence of plumes is further associated to all the seasons, the reason why there are less observations winter, is because of the lower amount of cloud-free images in winter for our study area. Shipwrecks on the seabed are hard substrates that are colonized by epifauna (Zintzen et al., 2008). The epifaunal species produce (pseudo-) faecal pellets that degrade, get in suspension and likely contribute to the SPM concentration in the area.

4.2. Wreck detection using ocean colour data

The very well developed SPM plumes from the SS Sansip and SS Samvurn sites likely reflect the large amount of wreck structure exposed at both sites, with the level of vertical exposure (ΔD) recorded as 8.9 m and 8.8 m respectively (Table 2). As a consequence, increased turbulence for resuspension of SPM explains the increased surface SPM concentration downstream from the two shipwrecks. Lower ΔD values of 3.2 m and 3.6 m respectively at the SS Nippon and SS Neutron sites indicate less bathymetrically complex sites, with more poorly developed scour pits and lower turbulent effects.

In addition to the size and geometry of the wrecks and their scour pits, tidal hydrodynamic forcing also controls the turbulence and vertical mixing capacity in the water column. SPM plumes are observed from space only when the SPM reaches the water surface; therefore water depth is another controlling factor in detecting wrecks using this technique. In Fig. 4a the plume associated with the SS Sansip site is not so pronounced as for SS Samvurn. The latter is located in slightly shallower water depths. In addition, the Landsat-8 image was acquired under neap tide conditions (tidal range of 3 m) with weaker tidal currents. Fig. 4b corresponds to spring tide conditions (tidal range of 4 m) and stronger currents resulting in a very pronounced SPM plume for SS Sansip. At times in the tidal cycle there is likely to be a complete absence of plumes, namely during slack tides when currents are strongly decreased (<0.25 m/s) (see Table 1). That is exactly what can be inferred from Fig. 6a — that the SPM plumes do not occur along the NNW-SSE axis. This is also confirmed by the fact that the null observations of plumes (see * in Table 1) correspond with lower water currents.
(<0.25 m/s).

The ability to detect the presence of submerged shipwrecks from space is of benefit to archaeological scientists and resource managers interested in locating wrecks and investigating processes driving their evolution. Landsat-8 data is free and therefore the method presented in this study is an inexpensive alternative to acoustic and laser survey techniques. Although satellite data cannot match acoustic and laser data in terms of resolution, it does offer the user a much broader view of the coastal landscape and could be used to supplement the traditional survey techniques, allowing researchers delineate high potential sites using the SPm technique for follow-up surveys using acoustics and bathymetric LiDAR. Another benefit of the SPm detection technique is that it provides insights into hydrodynamic and sedimentary processes acting on sites and quantitative data with respect to sediment dynamics and site evolution.

5. Conclusions

Surface SPm plumes associated with fully submerged shipwrecks were observed and described in terms of wreck size and geometry, associated scour pits and seabed grain size, and hydrodynamics. This particular type of SPm concentration heterogeneity at the surface is now explained and clearly distinguished from shipwakes generating SPm plumes since the latter do not align with water current. These findings allow marine archaeologists better mapping and monitoring of shipwreck sites. For example, seabed evolution is subjected to changes such as migrating sand dunes or longer-term sediment transport (un-) burying the wrecks. So SPm plumes are indicators that a shipwreck is exposed at the seabed and certainly not buried. This indicator may also be helpful to plan site visits, to discover new sites, and to protect shipwrecks.

Acknowledgements

This work was supported by the HIGHROC project (HIGH spatial and temporal Resolution Ocean Colour products and services), which is funded by the European Community’s Seventh Framework Programme (FP7/2007–2013) under grant agreement n° 606797. SPm concentration maps were supplied by Quinten Vanhellemont, and together with Kevin Ruddick, both are thanked for fruitful discussions. Laurence Vigin provided the geographic data on the shipwreck sites and Sébastien Legrand the tides and currents data from the operational hydrodynamic model. Full-coverge multi-beam echosounder (MBES) data was made available by the Flemish Hydrography, Coastal Division, Agency for Maritime and Coastal Services, Flemish Ministry of Mobility and Public Works.

References


