Sediment modelling for Poole and Christchurch Bays

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Poole and Christchurch Bays (UK) have narrow beaches which attract many visitors to the area and are therefore essential for the local economy. However, the beaches suffer from ongoing erosion, making regular beach nourishments to maintain them necessary. Sea level rise may cause an increase in the required frequency of these nourishments. If one can determine where the sediment sinks are, i.e. the location where the eroded beach material ends up, it may be possible to recycle the material, by dredging in the area of the sediment sinks and returning this material to the area of the beach. For this purpose, a numerical model is developed that computes the waves, currents and sediment transport in the area between Swanage and the Isle of Wight. The model covers the English Channel with high resolution in the area of interest. To compute the yearly averaged transport, a 1 year simulation using the 2009 hydrodynamic and atmospheric conditions was run. This model will be the basis for future projects to determine the changes due to the proposed works, either in large scale engineering or beach nourishments.

I. Introduction

Poole and Christchurch Bays (Fig. 1) have narrow beaches which attract many visitors to the area and are therefore essential for the local economy. However, the beaches suffer from ongoing erosion, making regular beach nourishments to maintain them necessary. In the 2013/2014 winter, the Bournemouth beaches lost 144,000 m^3 of sand, while the Sandbank peninsula in front of Poole Harbour lost a further 30,000 m^3 [1]. Sea level rise may cause an increase in the required frequency of these nourishments. If one can determine

where the sediment sinks are, i.e. the location where the eroded beach material ends up, it may be possible to recycle the material, by dredging in the area of the sediment sinks and returning this material to the area of the beach.

There have been desk studies identifying the pathways [9]. These conclude that there is an eastward littoral drift, were the sand moves from Poole to Christchurch Ledge and then again along the beaches towards Hurst Spit. From there the sediment is then pushed out to sea past the Needles on the Isle of Wight A westward transport is thought to exist north of the Dolphin Sands and Dolphin Banks, although this is contradicted by the work of Gallop et al [4], who find clockwise sediment transport around Dolphin Sands. Thus, there still is much uncertainty about the destination of the sediments that have been eroded from the beaches.

Therefore, a numerical model is developed that computes the sediment transport pathways in the English Channel, and focusses on the area between Swanage and the Isle of Wight. This model, with fully coupled TELEMAC, TOMOWAC and SISYPHE will be the basis in future projects to determine the changes due to the proposed works, either in large scale engineering or beach nourishments.

II. The Model

TELEMAC-2D was used to model an area covering the

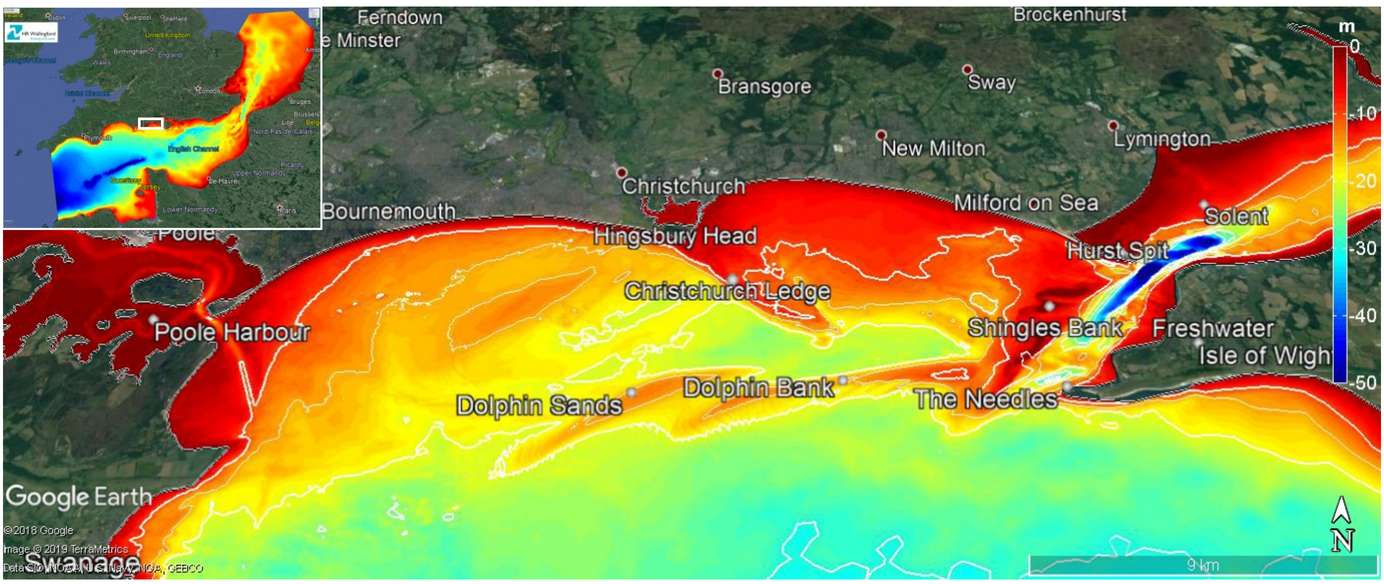


Figure 1 Model bathymetry for the area of interest, between Swanage and the Isle of Wight

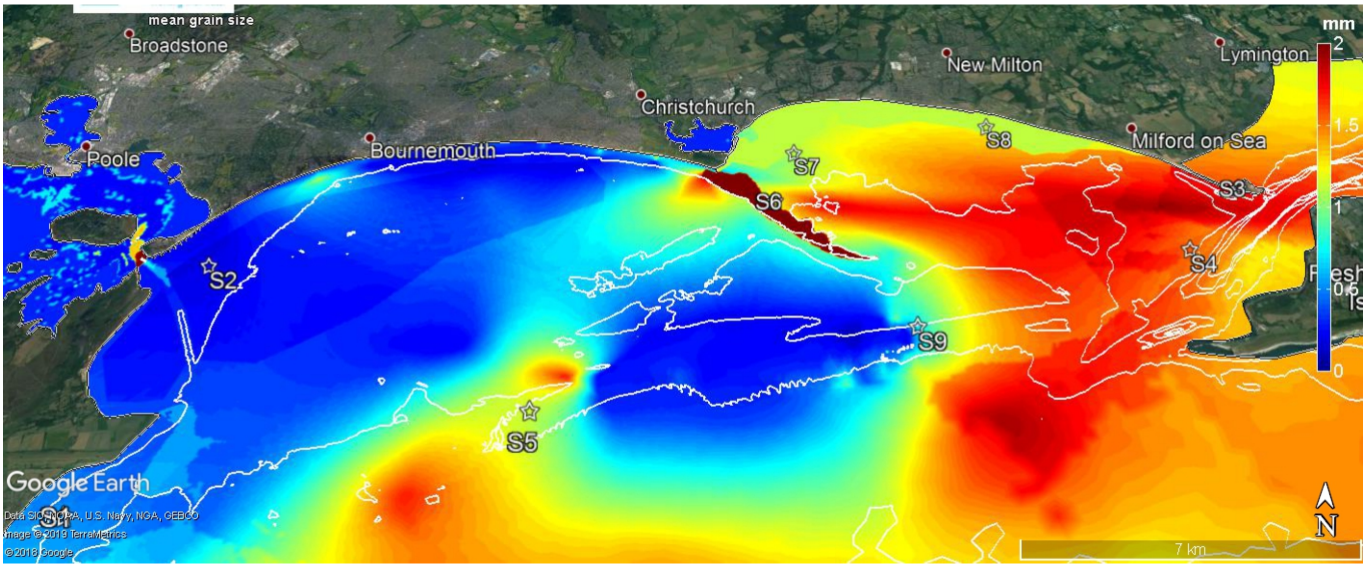


Figure 2 Mean grain size of the bed sediments

English Channel and the southern North Sea (Fig. 1 inset). The sediment transport near the coast is dominated by wave driven currents. To model these processes correctly, an accurate representation of the location of wave breaking is required. The original mesh has a resolution of 25 m, but to get an accurate representation of the longshore current and related sediment transport, the resolution is reduced to 5 to 10 m at the shoreline. At critical locations, such as Hurst Spit and Christchurch Ledge the resolution is approximately 5 m. At the more gentle sloping curved beaches the resolution is adjusted to 10 m. The resolution around the two offshore banks (Shingles Bank Dolphin Bank and Dolphin Sands) is about 50 m.

Bathymetry

Measured bathymetric data were collected from the UK Hydrographic Office (UKHO) and the Channel Coastal Observatory (CCO). The data sets are specified in Appendix **Erreur ! Source du renvoi introuvable.**, in **Erreur ! Source du renvoi introuvable.** and **Erreur ! Source du renvoi introuvable.**, respectively. The CCO data in the Solent, and Poole and Christchurch Bays were collected in a series of campaigns ranging from 2006 to the present, whereas the UKHO data were used in the wider model domain, surveyed since 2004. The resulting bathymetry in the area of interest is shown in Fig. 1.

Tidal conditions

The hydrodynamic conditions are dominated by tidal currents. These are included in the numerical model via water level variations at the offshore boundaries. The model has two open boundaries where water level boundary conditions are imposed, referred to as the western and eastern boundary, respectively. The offshore boundaries of the hydrodynamic model are driven by tidal levels extracted from the TPXO satellite altimetry dataset [10]. Tidal levels vary spatially and temporally along the offshore boundary. The TPXO global model of ocean tides is based on a best-fit of the Laplace Tidal Equations and measured data collected along remote sensing tracks from satellites TOPEX/POSEIDON and Jason.

The TPXO model resolution of the European Shelf has a resolution of 1/30 degree (approximately 3.7 km). The tides are provided as complex amplitudes of earth-relative sea-surface elevation for eight primary (M2, S2, N2, K2, K1, O1, P1and Q1) and 3 non-linear (M4, MS4 and MN4) harmonic constituents. Observations from more than 10,000 tidal gauges and other observed data have been used to validate the TPXO dataset.

Wave conditions

Wave boundary conditions for the model are taken from ERA5 ([5][6][1]). ERA5 (ECMWF ReAnalysis) gives an estimate of historical atmospheric activity based on numerical models combined with observations. ERA5 is the fifth major global reanalysis produced by ECMWF. Data processing for ERA5 is carried out by ECMWF, using ECMWFS' Earth System model IFS, cycle 41r2. ERA5 provides high quality medium-high resolution estimates of atmospheric and surface wave parameters, with a horizontal resolution 31km, 137 vertical levels and data archived hourly. The first batch of ERA5, covering the period 2000 to 2018 is currently available, and will extend from 1950 to present when complete. ERA5 is being developed through, and ERA5 data are provided by, the Copernicus Climate Change Service.

Time varying wave spectra from ERA5 are imposed at the boundaries of the TOMAWAC model.

Atmospheric conditions

Atmospheric pressure and wind speed and direction for the model are taken from ERA5 as well. ERA5 wind was calibrated against observations at Channel Light Vessel, leading to a correction, applied at high wind speeds. The derived wind speed correction factor increases linearly from 1 at 10m/s to 1.1 at 20m/s and above. Corrected wind speeds from ERA5 are interpolated spatially onto the model mesh and applied to estimate wind stress in TELEMAC and wave generation in TOMAWAC.

Bed composition

In the model 6 sediment classes were defined ranging from silt to coarse gravel: 40 µm (silt); 94 µm (very fine sand); 188 µm (fine sand); 375 µm (medium sand); 1.0 mm (coarse sand); 20 mm (gravel). The fractions of these classes were determined based on a bed composition map using the work of Wilson [11], who combined publicly available data with relationships between shear stresses and grain sizes as well as water depth and distance to the shore to create a sediment map for the shelf seas around the United Kingdom and Ireland. This map has been supplemented by data provided by Poole and Bournemouth borough council and the bed composition of Dolphin Sands as published by Gallop et al. [4].

This bed composition data was corrected for known anomalies. Areas of hard seabed around Hengistbury Head, offshore of Studland were assumed to consist of gravels, which are (almost) immobile in the model. This means that minor erosion of the seabed may occur, but avoids potential model instabilities at the interface of non-erodible layers and the surrounding mobile bed. Silt was placed in areas inside the natural harbours, where the flow velocities are below 0.3m/s. Gravel is assumed in areas where the maximum velocities are above 1.5 m/s and sand/gravel mixtures in areas where the peak velocity exceeds 1 m/s. The resulting mean grains size in the model is shown in Fig. 2.

III. Measured data

Poole Borough council commissioned a field campaign to validate the modelling. AWAC systems were placed in 9 locations (Fig. 2) in Poole and Christchurch Bays to measure water levels, currents and waves.Sediment concentrations were recorded using an OBS, which were calibrated using water samples. This calibration shows differences of up to 300%, in particular in cases of lower backscatter values. This indicates a significant uncertainty in the measured concentrations. To minimise the impact of the measurements errors, the measured concentration and velocity profiles were converted to estimates of the suspended transport load. These locations were identified as crucial locations to understand the sediment transport pathway: S1 Swanage; S2 Bournemouth beaches; S3 Hurst Spit; S4 Shingles Bank; S5 end of Dolphin Sands; S6 Christchurch Ledge; S7 Christchurch Harbour entrance; S8 Christchurch Bay beaches; S9 Dolphin Bank. The survey campaign by FUGRO [3] took place in December 2017 and January 2018. However, the AWAC system deployed at location S8 did not function properly. Therefore this Deployment 1 (D1) was followed by Deployment 2 (D2), wherein measurements were taken at locations S7 and S8 in February and March 2018.

IV. Calibration

The model was calibrated against short periods of the D1 survey campaign, each lasting several days. This calibration took place in phases. The flow model was calibrated against the measured data during a calm period (12/12/17 to 19/12/17) and a period with more significant wave conditions (24/12/17 to 31/12/17). Two short periods (9/12/17 to 17/12/17 and 24/12/17 to 31/12/17 were used to calibrate the wave model. Finally, the period from 24/12/17 to 31/12/17 was used to calibrate the wave driven currents and sediment transport.

In the calibration the following parameters and processes have been varied:

- For the flows: Bed friction coefficient (Nikuradse, 0.05m); Turbulence model (constant); Viscosity (1.E-6); Wind (spatially varying from ERA5); Atmospheric pressure (spatially varying from ERA5); and advection scheme (1;5).
- For the waves: Wind generation (WAM cycle 3); Dissipation due to currents (Phillips) and spatially varying waves (ERA5);.
- For the sediment: Bed friction; spatially varying bed friction (no); Friction correction factor (flat bed); advection scheme (13); and Bed composition (spatially varying).

V. Validation

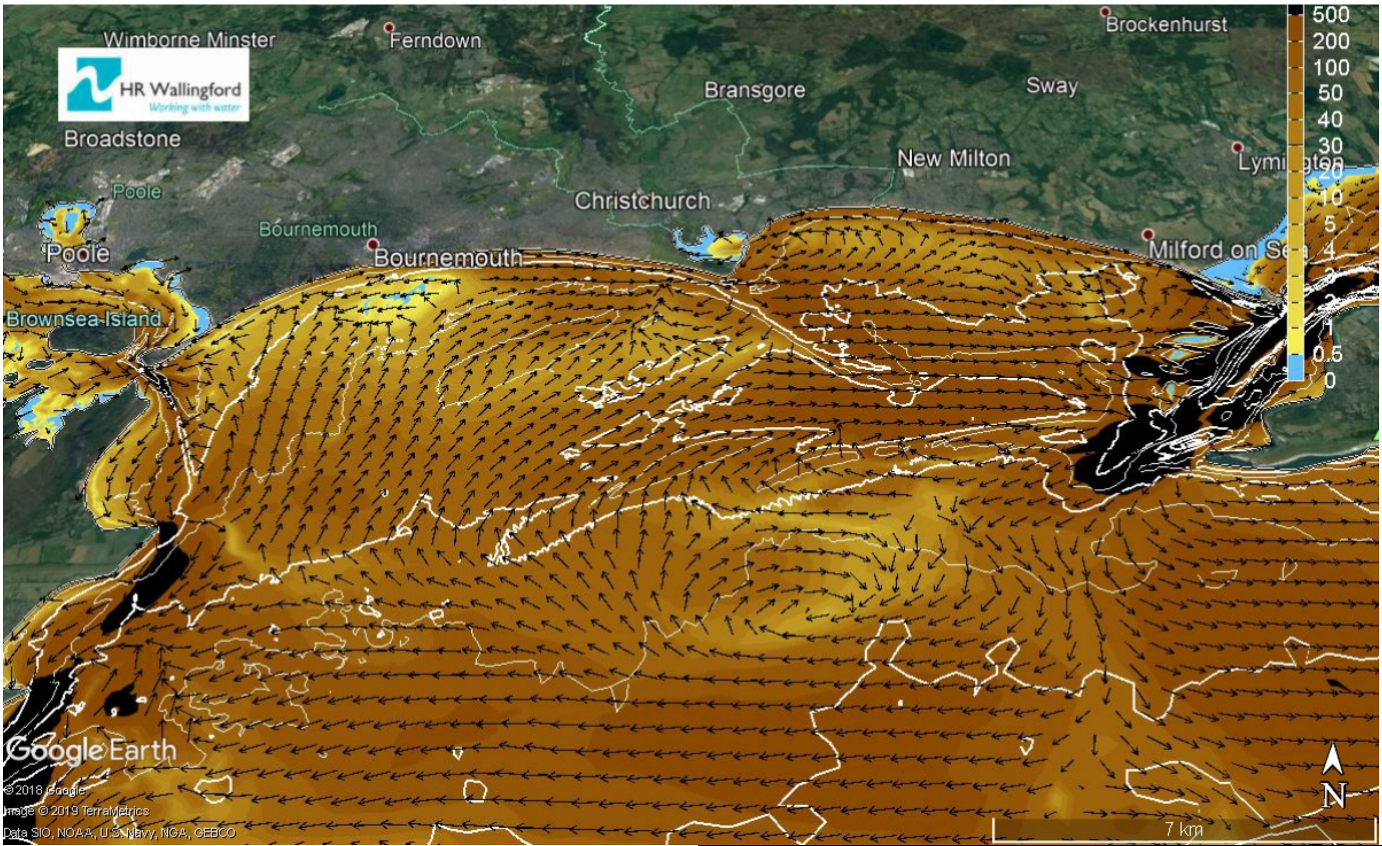
The validation of the model consisted of two parts. First, the model simulated the conditions during the survey deployment D1. This tests the capability of the model to simulate the temporal variability in the hydrodynamics and sediment transport of the area for locations S1 to S7 and S9. Table 1 shows the resulting error statistics, coefficient of determination (r-squared) and mean absolute error (mae).
The water levels are predicted accurately in all locations, but S3 and S4. In the other locations, the R-squared value is above 0.9, indicating almost all temporal variations are accounted for, and absolute errors are in the order of 0.1m.

In locations S1, S2 and S7, the flow velocities are low, which means that small errors have strong impact on the R-squared (Table 5.2). However the mae is still small. In location S4, the mae is larger, despite a reasonable R-squared value.

The model quality for the significant wave height is positive as well. The R-squared values are between 0.7 and 0.9 indicating a good fit, while the mae's are below 0.3, with one exception. The only exception is location S4. The R-squared values are slightly lower in areas with lower wave heights (1 to 3), but there the mae's are smaller there.

The error statistics for the sediment transport are based on a derived measurement. The measured transport rate is taken as the product of the depth averaged concentration times the depth averaged velocity. This assumes that the gradients in the velocity profile and the concentration profile are minimal. In practice, sediment concentrations often drop on going up the water column, while velocities are lower closer to the bed. This makes it likely that the actual transport rate will be a bit lower than the value calculated from the measurements. In contrast, the modelled suspended sediment transport rate is a direct output of the model.

Figure 3 Residual sand transport rates (colour) and direction (arrows) in Poole and Christchurch Bays



The differences between the measured and modelled depth integrated suspended sediment transport rates are larger than those for wave of currents. For areas with sufficient hydrodynamic energy, the R-squared value is above 0.5, which is a good fit for sediment transport purposes. Where currents and waves are small (locations S1, S2 and S7), the R-squared value is very small, indicating no relationship between observed and measured values. The relative mae, the mean ratio between the prediction errors and the measured values, however, does not increase much in these locations.

In the next phase, the model was applied to the period of the D2 deployment. This tests how accurate the model is in location S8, which has not been used in the calibration, providing a measure for the spatial sensitivity of the model (Table 2). The accuracy in location S8 is better than the comparable location S7.

TABLE 1 VALIDATION ERRORS DEPLOYMENT 1

location	S1	S2	S3	S4	S5	S6	S7	S9
Water level								
r^2(-)	0.90	0.91	0.41	0.94	0.91	0.90	0.92	0.93
mae(m)	0.10	0.11	0.55	0.79	0.10	0.18	0.12	0.12
Flow velocities								
r^2(-)	0.25	0.60	0.89	0.83	0.90	0.83	0.54	0.73
mae(m)	0.11	0.05	0.19	0.24	0.05	0.08	0.06	0.08
Wave height								
r^2(-)	0.75	0.78	0.74	0.75	0.86	0.85	0.83	0.88
mae(m)	0.17	0.14	0.11	0.28	0.26	0.21	0.26	0.25
Sediment transport rate								
r^2(-)	0.16	0.14	0.67	0.56	0.80	0.43	0.15	0.54
mae[a] (-)	0.34	0.62	0.72	0.44	0.39	0.41	0.49	0.38

a. For the sediment a relative mae is used

TABLE 2 VALIDATION ERRORS DEPLOYMENT 2

	Water level		Flow velocity		Wave height	
location	S7	S8	S7	S8	S7	S8
r^2(-)	0.96	0.96	0.81	0.87	0.71	0.86
mae (m)	0.22	0.23	0.10	0.10	0.15	0.13

VI. YEARLY AVERAGED SEDIMENT TRANSPORT

The averaged transport rates over the survey period are given in Table 3. The transport rates over the banks (location S5 and S9) are almost perfect, but with a small difference in the angle of the transport (below 30°). In location S3, near Hurst Spit, where the transport rates are high, the error in the transport rate is 60%, with a small error in the direction. In locations S1 the transport rates are smaller and the error in the rates drops to 20%, with a small 14° error in the direction. In locations S7 and S2, the errors in the transport are large with almost opposite directions, and the measured transport rate much higher than the modelled transport rate. In location S6, the direction is predicted well, but the modelled residual transport rate is much larger than measured.

The residual transport rates in Table 3 are generally of the same order as the mean absolute error in the instantaneous sediment transport rates given in Table 2.

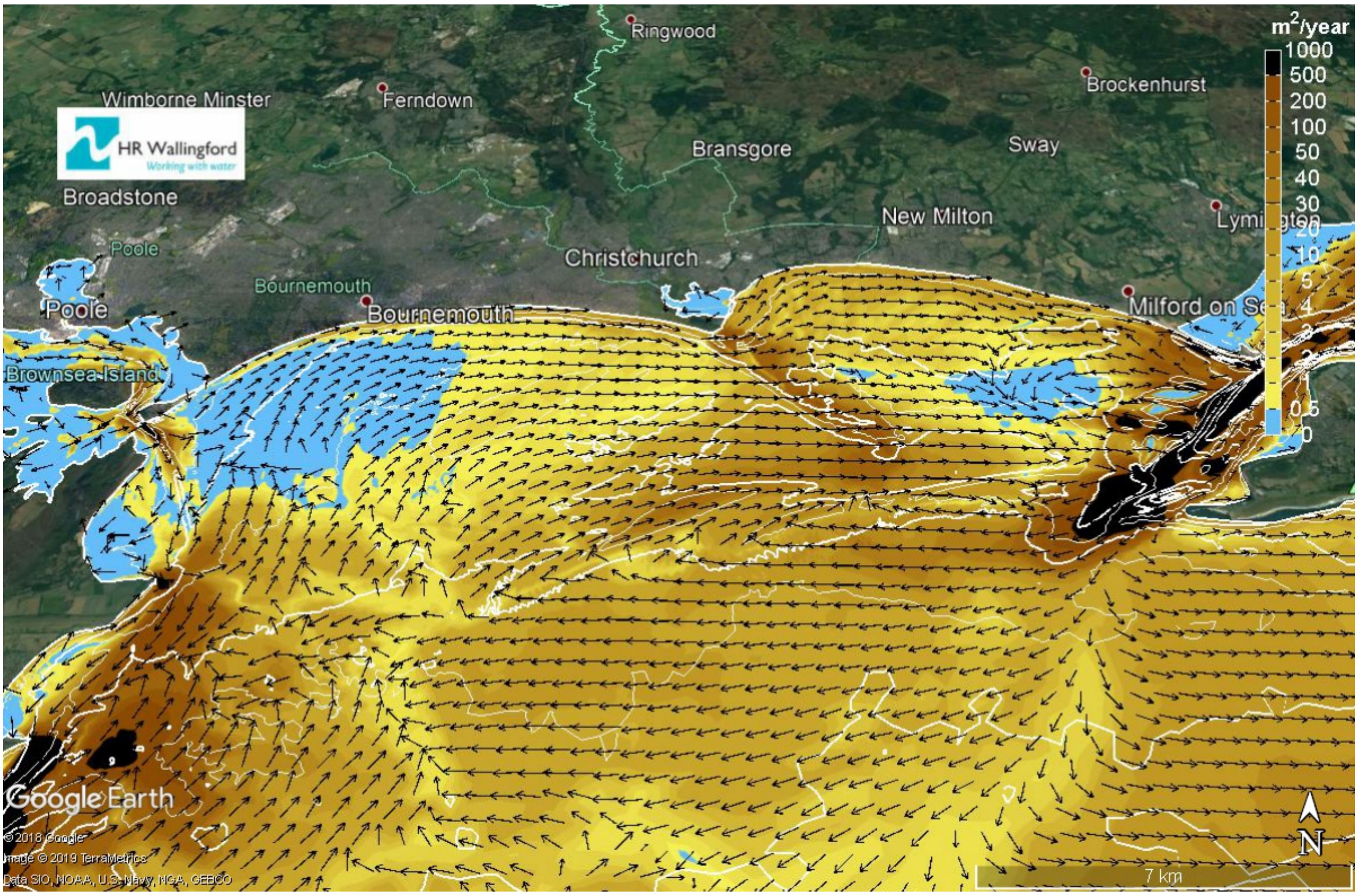


Figure 4 Residual sand transport rates (colour) and direction (arrows) in Poole and Christchurch Bays. The white lines show the bathymetry contours.

TABLE 3 VALIDATION RESIDUAL SEDIMENT TRANSPORT

	rate			direction		
	AWAC	model	ratio	AWAC	model	error
	$m^3/m/s$	$m^3/m/s$	-	ºN	ºN	º
S1	5.6E-06	7.0E-06	0.80	203	215	-14
S2	1.5E-06	1.0E-06	1.50	291	46	-116
S3	1.0E-04	6.3E-05	1.59	100	107	-7
S4	7.6E-06	2.3E-05	0.33	172	96	77
S5	3.1E-06	2.8E-06	1.11	341	9	-23
S6	1.0E-05	5.1E-06	1.96	96	86	7
S7	2.1E-06	4.6E-06	0.46	227	65	162
S9	1.3E-05	1.2E-05	1.08	108	81	27

VII. LONG TERM SEDIMENT TRANSPORT

To calculate the yearly residual transport pattern, the sediment transport was simulated for 2009. Based on total amount of energy in the wave conditions, the year 2009 was identified as representative for typical atmospheric conditions. The model was run for the whole year using TPXO water levels and ERA5 wind and wave conditions.

Fig. 3 shows the residual sediment transport for 2009. The total sediment transport shows a complicated pattern within the bays, with the typical transport direction from west to east interrupted by zones where the transport is west ward. The model indicates a nearshore sediment divide south of Bournemouth, which coincides with the small patch of coarse sediments visible in the seabed composition (Fig. 2); south of New Milton and north of Swanage Bay. Circulation cells are present on either side of Hengistbury Head.

When we isolate the transport rates of the sand fractions (Fig. 4), the pattern changes. There is a clear pathway of sand transport. The littoral drift takes the sand along the shorelines from west to east.

Within the bays the sand transport is consistently west to east, with the exception of the western part of Poole Bay and the eastern part of Christchurch Bay.

In the west of Poole Bay, the residual sand transport rates are very low, expect near the shore, where wave breaking drives the littoral drift. Along the Bournemouth shoreline the sand transport rate is increasing indicating that it is eroding gradually. There are indications that there is a sand drift divide in front of breakwaters of Sandbanks (Fig. 5). However, the precise location strongly depends on the wave conditions and will vary from one year to the other. The monthly patterns indicate that there is a drift divide in most months somewhere along the Bournemouth shoreline, but the location varies over the months.

In Christchurch Bay, the sand arriving around Hengistbury Head is spread around the western side of the bay, rather than hugging the shoreline. The sand is then transported east by the littoral drift along Hurst Spit, but then (partly) brought back by the tidal currents from the Solent, to then go west again further south.

sediment samples suggest the presence of a lot of very fine sand and silt and an absence of coarser sediments. Most likely

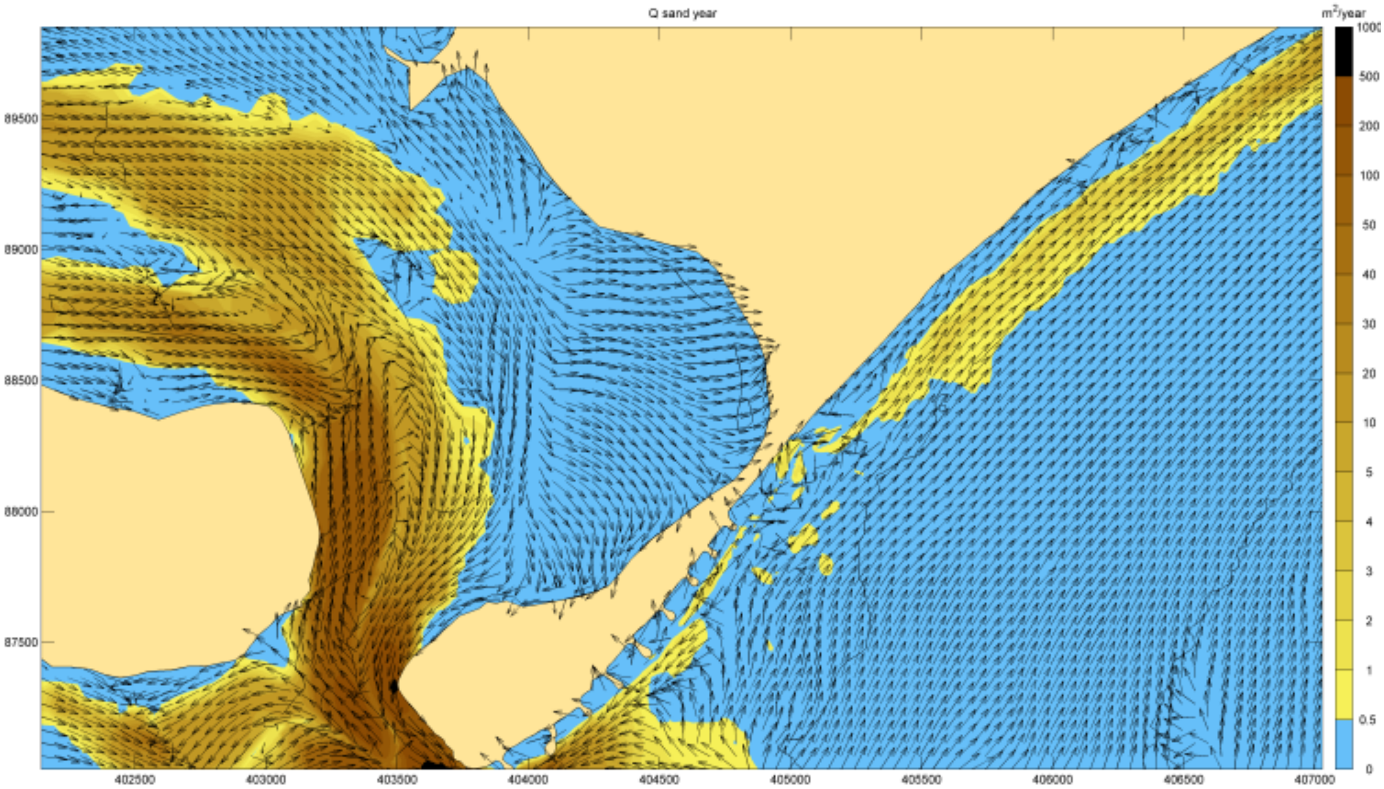


Figure 5 Drift divide in the sand transport along the Bournemouth beaches. The colours denote the residual sand trasnport rate (in m²/year), the vectors denote the transport direction

this is a clay outcrop; alternatively the sediment sample for this location is incorrect.

There are a lot of seabed changes in the area of Shingles Banks. This is no surprise, as shingles Bank is known to be a highly dynamic area. But on top of that, because of the active seabed and high energetic conditions, bathymetry and bed composition data is incomplete at that site.

Eventually, the sand is transported into deeper water past the Needles by the tidal currents. From there a fraction of the sand (estimated to be about 20%) is moved further east past the Isle of Wight. The remainder of the sediment is moving west, along Dolphin Bank and Dolphin Sands. Reaching the wester end of Dolphin sands it turns north to be moved west along the sandbanks again. As a result this material will end up on the sandbanks or in the sandwaves moving around the banks.

VIII. Erosion Deposition

Unfortunately, no validation data for morphological changes is available. Nevertheless, the resulting erosion deposition patterns (Fig. 6) look realistic. In general there is little change over the year as expected.

The navigation channel to Poole Harbour shows infill, which is in line with the knowledge that this channel requires maintenance dredging.

There is erosion of the seabed along the shoreline at the western half of Poole Bay, in line with the knowledge that the beaches have been nourished regularly

There are a few exceptions however, related to insufficient seabed data. There are significant bed level changes in the west of the Bays in front of Swanage. Here the bed composition map is inaccurate.

In between Dolphin Sands and Dolphin Bank, there is a circular erosion spot, which matches a location where

IX. Discussion

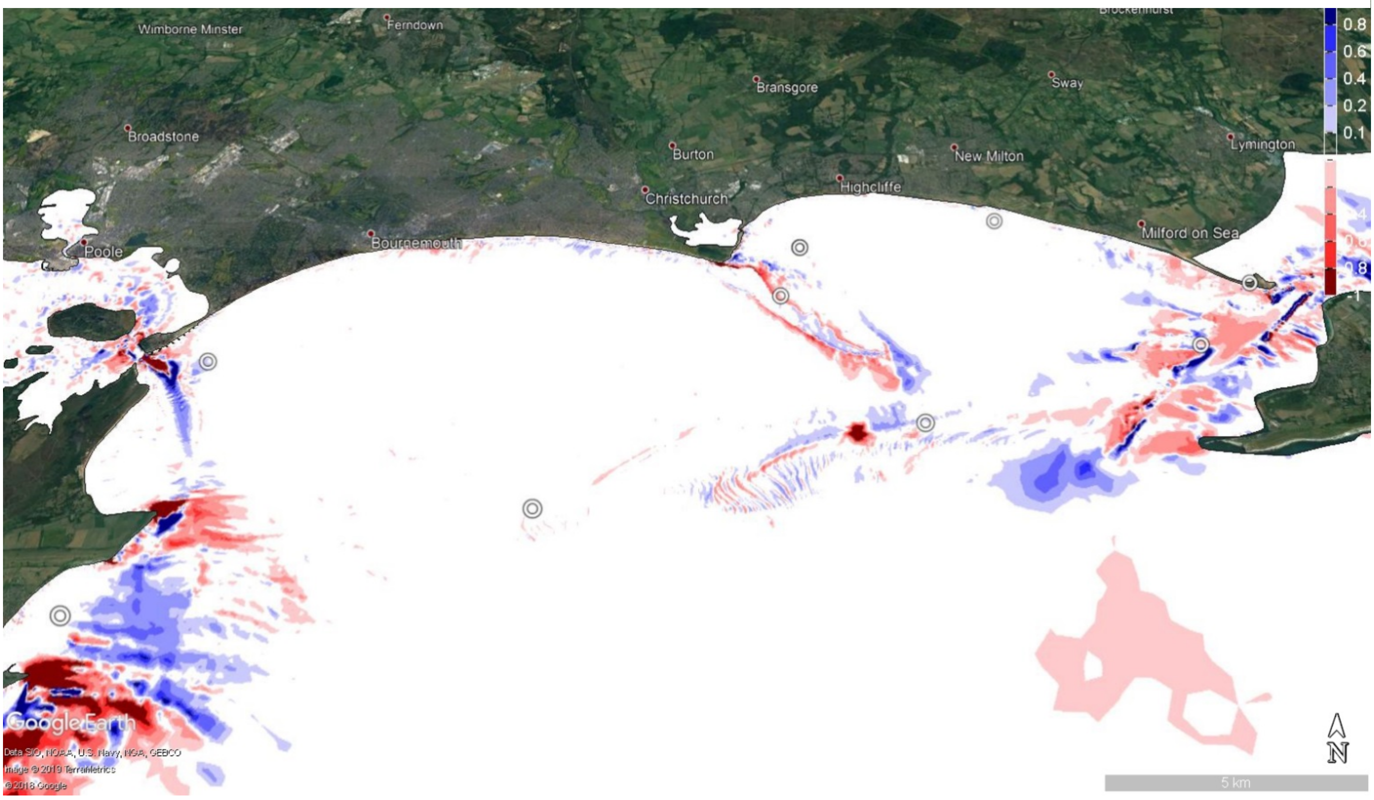
Model quality

The model reproduces the observed flows, waves and sediment transport well in most locations. In a few locations some issues remain. Most importantly, the lack of recent accurate bathymetry data for Shingles Bank causes disturbance of the flows and water levels in location S4 (Shingles Bank) and location S3 (Hurst Spit). This leads to an incorrect model representation of the sediment transport in this area as well.

In location S6, flows and waves are reproduced well. The predicted sediment transport, however, is still a bit high. The bed composition still allows more sediment to erode from Christchurch ledge than is happening in reality. This increases the transport in location S6 and S7. This additional transport could be the explanation for the incorrect transport direction in location S7.

The transport direction in location S2 is incorrect, but this location is in an area with inconsistent transport directions and

Figure 6 Erosion deposition pattern in metres



the transport rates are very small. So the results here are sensitive to small changes in the conditions. As the transport rates here are small and inconsistent, this error will have very little impact on the overall sediment transport pathways.

The sediment transport measurements are based on profile approximations of the flow velocities and concentrations in the water column higher than 0.5m above the bed. As most sediment transport occurs closer to the seabed, this is a large source of uncertainty in the measured transport rates. Still, the relatively good comparison between measured values and modelled values provides confidence in the model results as well as the measurements.

Currently, non-erodible layers such as rock and stiff clay are represented as gravel beds. This implies that during high energetic conditions they suffer from erosion. This makes the model less suitable for long-term erosion and deposition analysis.

Comparison with SCOPAC sediment pathways

The findings of the modelling in general supports the SCOPAC sediment transport [9]. However, there are a few differences:

- The modelled total sediment transport shows a sediment divide in front of Bournemouth for the total sediment transport, which is not present in the SCOPAC sediment pathways. This divide is not present for sand, but is driven by the transport patterns for the fine material. This divide is exactly in the location where the seabed composition is sandier than other areas (Fig. 2) which would support the divide for fines in this location.
- SCOPAC [9] indicates a westward transport in the deeper part of the bay, north of Dolphin Sands. The model results presented here show this transport to occur further offshore, south of Dolphin Sands. North of Dolphin Sands, the transport is to the east, completing the clockwise sediment transport around the sandbank in agreement with the findings of Gallop et al [4].
- Similarly, the transport around the whole of Dolphin Bank is clockwise, more pronounced than New Forest District Council suggests.
- The sediment transport that passes Hengistbury Head spreads out over a fairly wide region into Christchurch Bay and does not stick to the shore as much as SCOPAC [9] is assuming.

X. Conclusions

To analyse the sediment pathways of Poole and Christchurch Bay, a numerical model has been developed that models the waves, currents and sediment transport in the English Channel. The model has been calibrated and validated against measurements taken at 9 locations using AWAC systems. The model fits well with the wave and current observations and even reproduces most of the observed sediment transport.

The model works well as a tool to analyse the sediment transport pathways and to assess where material eroded from the beaches ends up. The model run of a whole year shows a clear pathway of sand along the beaches towards the east and back further offshore, south of Dolphin Bank and Dolphin Sands. Sediment is shown to circulate clockwise about Dolphin Bank and Dolphin Sands. Only a small part of the sand leaves the bay and is moved east along the Isle of Wight. However, lack of recent accurate bed level and sediment grain size information for Shingles Bank, leads to some inaccuracies at that location. In broad lines, the model results confirm the established views in literature on the sediment transport pathways. However, the model provides much more detail and adds some subtle nuances.

Although the model has not been developed to predict the future bed level changes, the resulting bed level changes are broadly in line with historic changes. Overall most changes are very subtle. There is some erosion of the beaches and the dredged navigation channel to Poole Harbour shows significant infill, a pattern confirmed by ongoing dredging requirements.

The results of this work suggest that, with the exception of the surf zone, the sediment transport modelling using the TELEMAC-TOMAWAC-SISYPHE coupling is accurate. It does however require high resolution bathymetry and bed composition data.

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