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Towards safer swimming – Terrigal region

Calibration and verification of a 2D hydrodynamic model for Terrigal Bay

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Authorship and citation

This document was prepared by Shivanesh Rao.

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Cover photo: Aerial shot of Terrigal Beach, 6 June 2019 when Terrigal Lagoon was starting to discharge after the council dredged the berm. Cameron Board/SkyMedia Productions

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Summary

Terrigal Bay is a small and sheltered embayment on the NSW Central Coast that is popular with families, swimmers, surfers and fishers. In recent years, Beachwatch has consistently rated Terrigal Beach as Poor according to safety for recreational use (DPIE 2019), and these poor scores have been attributed to inputs from stormwater inputs and lagoon discharge during and following rainfall events.

In January 2019, the Central Coast Council commenced a water quality audit, expanding the Beachwatch enterococci sampling at a single site (Terrigal Surf Club) to include 10 additional sites along the Terrigal–Wamberal Beach from the Terrigal Lagoon mouth to the Haven as well as sites at Forresters Beach to the north and North Avoca Beach to the south. Enterococci sampling was also undertaken at the major stormwater drain outlets discharging into Terrigal Beach and the Haven to assess their potential as sources of enterococci. In April 2019, scientists from NSW Department of Planning, Industry and Environment (DPIE) and the Central Coast Council developed a detailed work program to expand council's water quality audit. Some objectives of DPIE and the council's audit were to:

- determine if microbial contamination in nearshore waters and stormwater outlets was from human sewage or other animal faeces
- determine if microbial contamination of nearshore waters extended into deeper waters of Terrigal Bay
- determine residence times of contaminants
- assess pollutants in sediments at Terrigal–Wamberal Beach and the Haven
- assess the spatial extent and temporal persistence of water quality issues in Central Coast lagoons
- identify and prioritise major microbial source locations in Terrigal Beach, the Haven, Terrigal Lagoon and Avoca Lagoon catchments.

As part of this audit, a depth-averaged hydrodynamic-wave coupled model was developed to understand the circulation patterns and residence times of pollutants in the Terrigal Bay embayment. The model considers the influence of tides, winds, waves, stormwater discharges and Terrigal Lagoon discharge into the nearshore. The modelled output was verified against observations to assess the capability of the model.

Our results indicate that the depth-averaged model can resolve the mean circulation in the bay. Particle tracking experiments showed that the embayment flushes in less than 24 hours, so pollutants are likely to be advected away or diluted. Several numerical scenarios carried out for a range of swell and wind conditions also showed similar flushing timescales. This suggests that in cases where the pollutant plumes were observed in the nearshore region for extended periods, i.e. a few days, the cause is likely the continued event catchment discharges into the nearshore (via drains or lagoon–oceanic exchange).

Background

Central Coast Council, in partnership with Beachwatch, monitor and report on recreational water quality along the NSW Central Coast in accordance with the National Health and Medical Research Council's *Guidelines for Managing Risks in Recreational Waters* (NHMRC 2008). Waters are tested for enterococci bacteria as an indicator of faecal contamination and graded to provide a guide to potential risk to human health from swimming.

During the past decade, Terrigal Beach has been routinely graded as Poor in the annual NSW State of the Beaches Report (DPIE 2019). This has led to considerable concern by local and state governments as well as beach goers, recreational swimmers, surfers, fishers and the broader community.

In January 2019, the Central Coast Council commenced a water quality audit, expanding Beachwatch enterococci sampling at a single site (Terrigal Surf Club) to include 10 additional sites along Terrigal Beach from the Terrigal Lagoon mouth to the Haven as well as sites at Forresters Beach to the north and North Avoca Beach to the south. Enterococci sampling was also undertaken at the major stormwater drain outlets discharging to Terrigal Beach and the Haven to assess their potential as sources of enterococci.

In February 2019, the NSW Government committed $500,000 to address water quality issues at Terrigal Beach and the Central Coast lagoons by undertaking a detailed, scientific audit and analysis of the microbial pollution sources to find solutions to improve water quality.

In April 2019, scientists from DPIE and the Central Coast Council developed a detailed work program to expand council's water quality audit. Specific objectives of the NSW Government and council's joint water quality audit were to:

- determine if microbial contamination in nearshore waters and stormwater outlets along Terrigal Beach and the Haven and in Terrigal Lagoon was from human sewage or other animal (e.g. bird, dog) faeces
- determine if microbial contamination of Terrigal Beach and the Haven nearshore waters extended into deeper waters of Terrigal Bay
- determine how long contaminated stormwater remained in the bay
- assess pollutants in sediments at Terrigal Beach and the Haven
- assess the spatial extent and temporal persistence of water quality issues in Central Coast lagoons
- identify and prioritise major microbial source locations in Terrigal Beach, the Haven, Terrigal Lagoon and Avoca Lagoon catchments.

Extensive field work has been done by the NSW Government and council in conjunction with University of Technology Sydney. This is Report #5 and is one of nine technical reports that describe the results of the NSW Government's Terrigal Water Quality Audit research. Additional reports will be provided by council on its components.

This research has led to the identification of the major biological sources of faecal bacteria and points in the sewage/stormwater drainage system where cross contamination occurs. Council can now focus on remediation of these priority areas, and has commenced works in Terrigal Beach, the Haven and lagoon catchments to improve water quality.

Due to the size and complexity of the task the entire work program could take up to six years to complete. If routine monitoring continues to detect unacceptable contamination, further investigation and remediation works may be required.

Introduction

In New South Wales, Australia a statewide beach water quality monitoring program (Beachwatch) rates swimming beaches according to safety for recreational use (DPIE 2019). In the most recent Beachwatch report, water quality at half of the 32 monitored beaches and coastal lagoons along the NSW Central Coast was rated as Poor (DPIE 2019). Stormwater inflows following rainfall were identified as the principal pathway of poor quality water reaching the swimming beaches. Among the most popular beaches on the Central Coast, Terrigal–Wamberal Beach and nearby Terrigal Lagoon, have been consistently characterised by poor water quality during the last several years, resulting in substantial community concern. DPIE is working with the local council to address water quality issues at Terrigal–Wamberal Beach and the surrounding lagoons.

In October 2019 DPIE, Central Coast Council and University of Technology Sydney did a source-tracking study to define the causes of poor water quality at Terrigal–Wamberal Beach with the results identifying sewage, rather than animal sources of faecal contamination, as the principal cause of poor water quality (Boehm & Sassoubre 2014). Three stormwater drains on Terrigal Beach were identified as the likely points of contamination. The sampling during a moderate rainfall event also demonstrated that the sewage signature in the nearshore of Terrigal Beach increased by up to 1000 times relative to dry weather conditions. Following the release of the report, the community raised key questions about the fate of the pollutants in the swimming beaches especially in the Terrigal Haven embayment (Figure 1), which is largely perceived by the community as a sheltered region.

Figure 1 **Satellite map of the central coast of NSW showing the study area and the relevant lagoons**

The insert is a closer view of the Terrigal–Wamberal Beach and swimming areas under consideration by this study. The (orange, semi-circular) outline indicates the Terrigal Haven embayment sheltered by Broken Head. The red solid circle indicates the ‘7 drains’ stormwater drain outlet. Images derived from Google Earth Pro 2020.

The study site of Terrigal Bay is located along the Central Coast of New South Wales (Figure 1). The Central Coast nearshore region, including Terrigal Bay, acts as a sink for a catchment that services a population exceeding 330,000. The bay receives discharge from two intermittently open coastal lagoons, with two others nearby. Discharges occur when lagoon berms breach often after large rainfall events. The lagoon berm can also be breached by coastal erosion of sand; however, this study examines the discharge of the lagoon and not the dynamics of the berm. The lagoons that discharge to Terrigal Bay are Terrigal Lagoon and Wamberal Lagoon; nearby lagoons are Cochrane Lagoon and Avoca Lake (Figure 1). Stormwater drains also discharge onto these beaches.

The nearshore parts of Terrigal Bay are influenced by large-scale synoptic drivers such as semi-diurnal tides (Mcpherson et al. 2013), wind (Monypenny & Middleton 1997), ocean swell (Lord & Kulmar 2000), alongshore flows (Kerry et al. 2019), as well as localised lagoon and stormwater discharges. The alongshore flow is not considered in this study. This consideration is made because observations at the offshore Sydney station, ORS65 station (at 65 m depth), show the mean depth-averaged speed is small, in the order of 0.08–0.09 metres per second (Ribbat et al. 2020). The East Australian Current (EAC) coastal model outputs show nearshore (depth <50 m) mean alongshore flows of 0.1 metres per second with a standard deviation of 0.1 metres per second (Ribbat et al. 2020).

Our report examines the Terrigal Bay hydrodynamics to understand the flushing timescale of contaminants in Terrigal Bay, and the spatial extent of the drain and lagoon discharges. The main objective of this project is to estimate the flushing timescale of pollutants in Terrigal Haven embayment and understand the circulation in Terrigal Bay. This is achieved by developing a calibrated hydrodynamic-wave coupled model to understand the circulation patterns for Terrigal Bay, New South Wales.

Methodology

Field campaigns

DPIE collected additional field data to verify the hydrodynamic-wave model. These field observations were complemented with data from the Terrigal Lagoon water level gauge and Sydney wave buoy maintained by Manly Hydraulics Laboratory (MHL), and climatology data from the Bureau of Meteorology (BoM).

The DPIE field campaign was between 27 September and 31 October 2019. An Acoustic Doppler Current Profiler (Teledyne Workhorse Sentinel ADCP 600 kHz upgraded with a directional wave array and built-in water pressure sensor) and three CTD (conductivity, temperature, depth) sensors (HOBO U26) were deployed along the Terrigal Beach and in Terrigal Haven embayment (Figure 2), as well as SonTek acoustic flowmeters in the largest drain network. In addition, wave statistics were used from the historic Wamberal nearshore wave rider buoy deployed by MHL from August 2011 to March 2012.

The ADCP was deployed in the sheltered Terrigal Haven embayment; however, the area was consequently later identified as an eddy zone. The highly transient property of eddies means the ADCP flow observations were only useful to verify the first order hydrodynamic circulation. In addition, the CTD sensors deployed were later assessed to have moderate sensor drift and missed recalibration after cleaning, causing the salinity and temperature to record higher than expected observations. For example, the surface salinity was observed as 35.6 grams per kilogram at the end of the first deployment period, but recorded as 37.6 grams per kilogram an hour later after redeployment. Thus, CTD observations were used to verify if the model was resolving the correct salinity trends, not the magnitude of change.

Figure 2 **Map of Terrigal Bay showing the locations of the deployed ADCP (yellow circle) and CTD instruments (red circle)**

CTD 4 was attached to a red navigation buoy. The red diamonds indicate the Terrigal Lagoon discharge location and the 7 drains stormwater discharge. Images derived from Google Earth Pro 2020.

The hydrodynamic-wave model domain

Although the study area of the DPIE campaign is focused in the nearshore Terrigal beaches and Bay, the hydrodynamic model domain covers a much larger area to minimise boundary effects at the observational sites. The model domain extends approximately 26 kilometres along the coast from Box Head (south) to The Entrance (north) and extends 12 kilometres offshore from Terrigal Bay (Figure 3). This puts the oceanic boundary at least 10 kilometres in each direction from Terrigal to prevent boundary numerical noise from reaching the study area. The Terrigal Bay region is modelled as a 2D (depth-averaged) model forced by offshore wave-spectra, tides, wind, and estimates of stormwater and lagoon discharges. The model is implemented using the TELEMAC modelling suite (Villaret et al. 2013). The 2D variant of TELEMAC resolves the Saint-Venant equations (shallow water equations), which assumes that horizontal velocity scales are much larger than the vertical velocity scales. The model bathymetry and model domain are shown in Figure 3. The bathymetry used in the model is a collation of bathymetric multi-beam and LiDAR surveys by DPIE referenced to WGS84 and AHD.

The grid size is 1000 metres at the offshore oceanic boundary, gradually decreasing to 30 metres (at ~700 m offshore) and to 10 metres along the coastline. The grid size is determined by the Delaunay Triangulation, which minimises sliver triangles based on the user-defined boundary spacings. The hydrodynamic time-step is 10 seconds to satisfy the Courant–Friedrichs–Lewy criterion to avoid instabilities. The coefficient of diffusion is governed by the grid size, time-step and flow; in our case this is set to 1.0 square metre per second which is in the range estimated in other studies for similar implementations (Shanahan 1992; Matsuzaki & Fujita 2017; Bennis et al. 2016). The hydrodynamic model is directly coupled to a TELEMAC coastal wave propagation model (TOMAWAC) and they run parallel to each other (using an MPI instruction set with 12 logic processors) at a time-step of 10 seconds with a factor of three internal reduction to resolve the nearshore breaking waves. The hydrodynamic model adds a wave-driven current (wave-setup and mean flow) by including the wave radiation stress resolved by the TOMAWAC module. The bottom drag in the wave model is set at 0.038 square metres per cubic second similar to other studies for this region (Cardno 2012); the same value is applied to the hydrodynamic model for consistency. The model is implemented and verified against field observations (see next section).

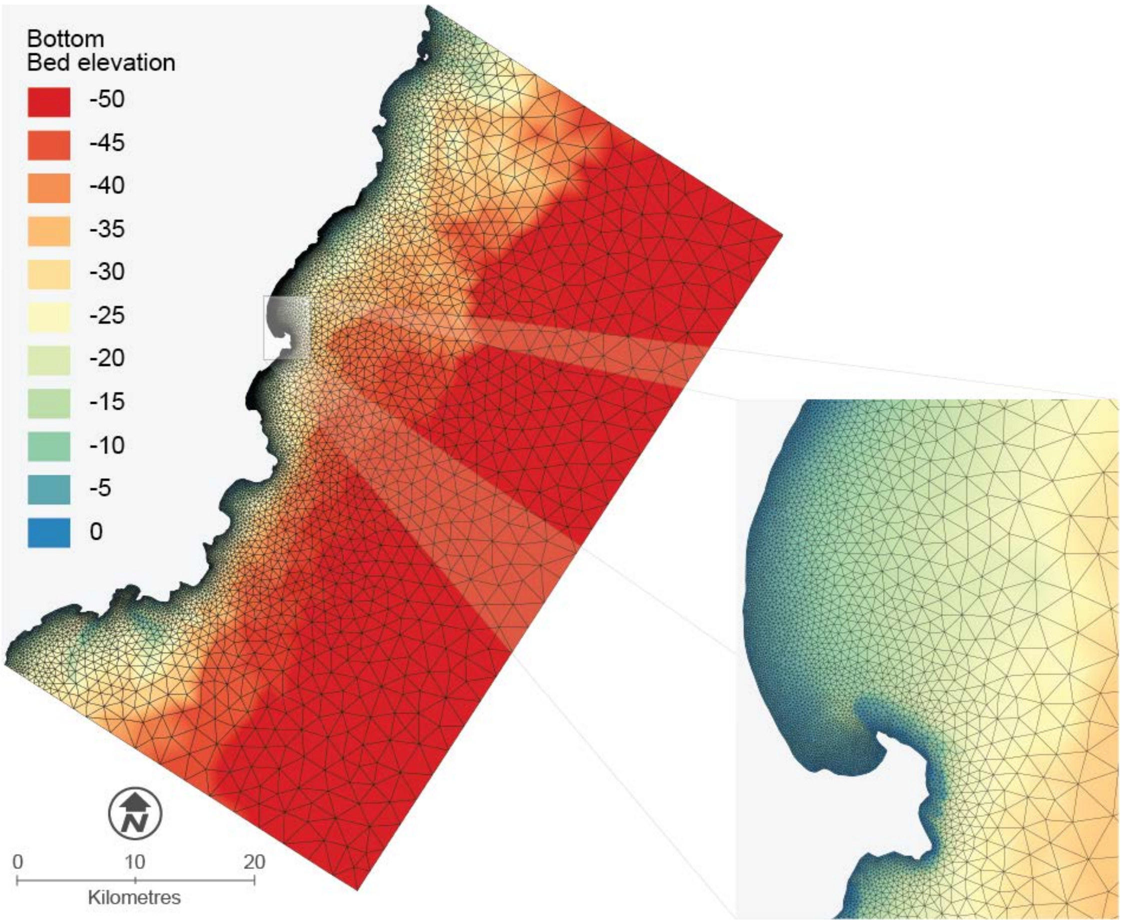

Figure 3 **Bathymetry of the model domain and the locations of the model grid nodes**

The tides in the model are forced using the TPXO7.2 global tide database (Egbert et al. 2002) along the model boundary. The waves are forced using the Sydney wave buoy observations; the water depth at the buoy is approximately 85 metres. The wind is from the Norah Head BoM weather station; station elevation is 18.8 metres. The stormwater is estimated from DPIE measurements of the primary discharge point (7 drains location). The lagoon discharge was estimated using the time-derivative MHL Terrigal Bridge water level time-series and the lagoon area.

The model simulation is for the period 14 September to 31 October 2019. This allows a two-week spin-up period for waves and currents. During this period: (i) the Terrigal Lagoon opened, and there was (ii) a rain event that resulted in stormwater discharge, (iii) a storm event that recorded large significant wave heights, and (iv) a full neap-spring tidal cycle. These events are individually significant drivers of nearshore water quality via direct source inflows or through resuspension and advection processes along the Terrigal–Wamberal Beach.

Model calibration and verification

Tides

The modelled water level was verified against the water level derived from the built-in pressure gauge of the ADCP (Figures 4 & 5). The model output is interpolated to observation time-stamps to carry out a correlation analysis. A correlation analysis between the modelled and observed time-series gives a correlation coefficient, r = 0.98 and a coefficient of determination, r^2 =0.96. This suggests the model can resolve the trends and variance in the observed tidal signal respectively. The tidal amplitude and phase for the major tidal constituents were derived and compared for the model and observations (Table 1).

Table 1 **Decomposition of the modelled and observed sea-level time-series into the tidal constituents**

The absolute difference (bold values) show that most modelled constituents are very similar to observations.

Tidal const.	Freq. [Hz]	Amp. (mod.) [m]	Amp. (obs.) [m]	Abs. diff. [m]	Phase (mod.) [°]	Phase (obs.) [°]	Abs. diff. [°]
M2	0.081	0.4843	0.4826	**0.00**	235.4	232.8	**2.6**
S2	0.083	0.1482	0.1500	**0.00**	251.0	245.9	**5.1**
N2	0.079	0.1075	0.1211	**0.01**	222.8	211.9	**10.9**
K1	0.042	0.1288	0.1061	**0.02**	101.7	102.8	**1.1**
O1	0.039	0.0986	0.0906	**0.01**	78.1	74.1	**4.0**

The results of the decomposition analysis show there are only small differences between the modelled and observed tidal constituents, suggesting the model can adequately resolve the amplitude and phase of each of the major tidal constituents.

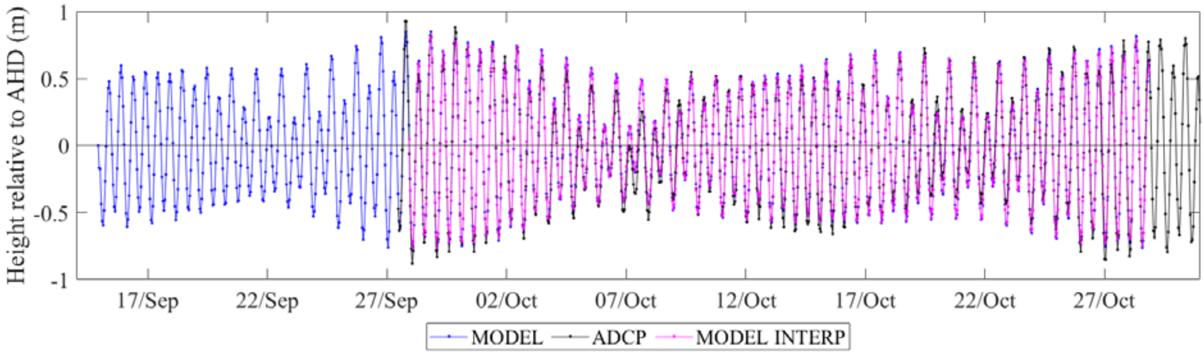

Figure 4 **Modelled and observed sea-level heights above AHD in metres at the location of the deployed ADCP for the period 14 September to 31 October 2019**

The observed sea-level (red line) is measured by a pressure sensor on the ADCP, the modelled sea-level (blue: model data) is interpolated to the same time stamps as the observations by the ADCP (green: interpolated model).

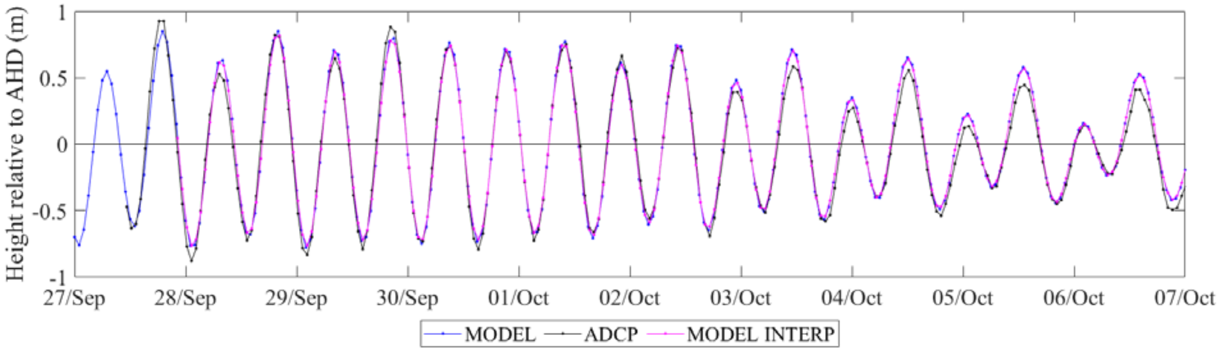

Figure 5 **Sea-level time-series for 11 days from 27 September to 7 October 2019 showing detail of model fit**

Waves

Wave action is a significant driver of the nearshore erosion (Mitchell et al. 2017). The wave model was forced using the observed wave statistics from the MHL Sydney wave buoy located offshore of Long Reef and Narrabeen beaches. This observational buoy is the closest offshore wave station available near the modelling domain. A time-series of the integrated wave parameters (significant wave height, mean wave direction, peak period and spread) from the wave buoy was derived (for the period 20 October to 19 November 2011) and applied uniformly along the oceanic boundary of the hydrodynamic model. The study area has a 10 kilometre offshore oceanic boundary, which is sufficiently far away that applying uniform integrated wave parameters along the boundary still allows the wave model to resolve the nearshore waves. The modelled wave statistics are compared to the historic Wamberal wave rider buoy dataset (Figures 6 & 7).

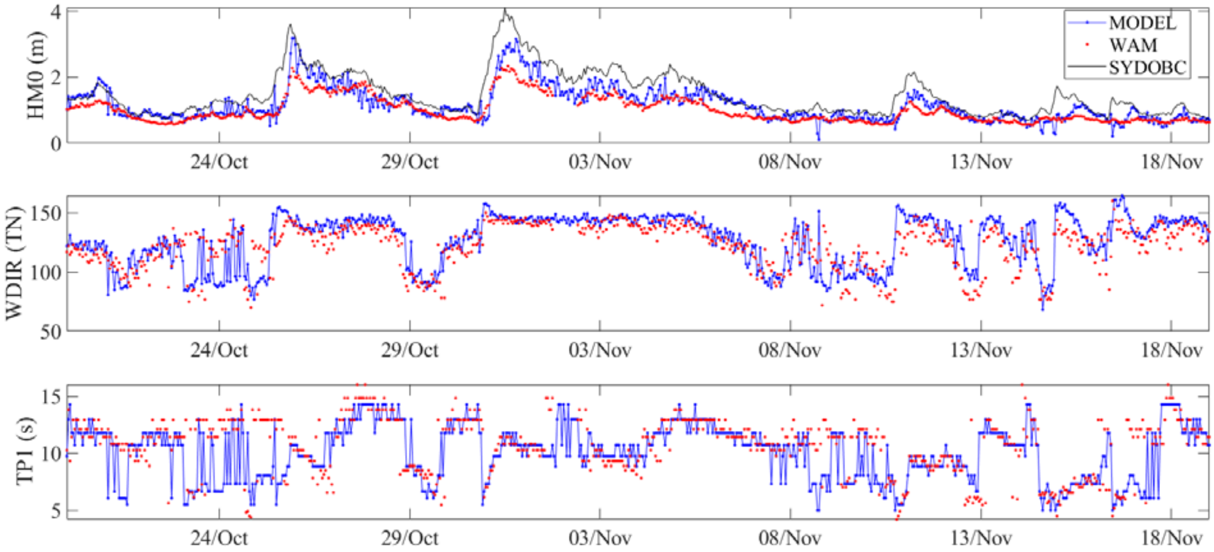

Figure 6 **Comparison between modelled and observed waves at the Wamberal wave rider buoy for 20 October to 19 November 2011**

The wave rider was deployed in a water depth of 11 m.

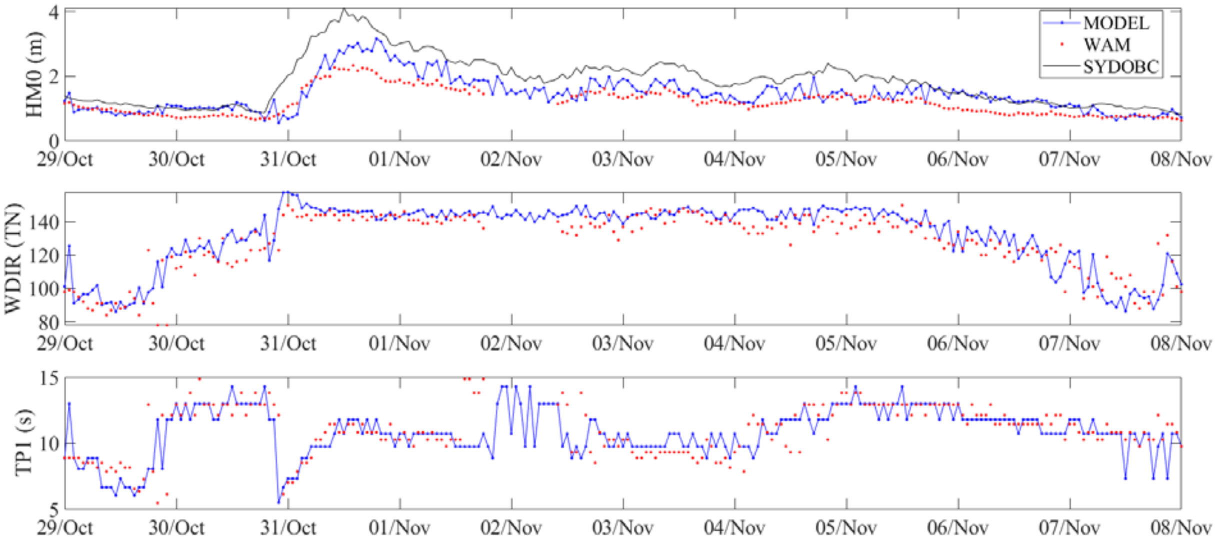

Figure 7 **Wave time-series for 11 days from 29 October to 8 November 2011 showing detail of model fit**

The observed significant wave height (HM0), peak period (TP1) and mean wave direction (MWD) at the Wamberal wave rider buoy were used to assess the model ability to resolve the waves. The wave model can predict the correct order of magnitude of the significant wave heights with reasonable error of RMSE (root-mean-square error)=0.29 metres, wave direction with an RMSE=15.6°, and TP1 with an RMSE=2.40 seconds; this is similar to other calibrated wave-modelling studies at the same location (e.g. Mortlock et al. (2013): 0.23 m, 11.91°, (Tm02) 1.90 s, respectively).

There are some limitations to the wave modelling in this study. Our wave model does not account for wind wave generation within the model domain, reflection from the coast, and diffraction at Terrigal Head and the reef; these processes become more important in the surf zone. The ADCP deployed during the DPIE field campaign is close to the surf zone on the edge of the sheltered Terrigal Haven embayment where the mean significant wave heights are roughly half of mean significant wave height just offshore of Wamberal (Mortlock et al. 2013). These limitations are such that the correlation between the modelled and observed significant wave height and directions (in the Haven) could not be reasonably calibrated in the surf zone; thus, these results have not been used.

Depth-averaged flows

The currents in the hydrodynamic model are compared to the depth-averaged currents measured by the ADCP in the Terrigal Haven. The ADCP location was chosen to protect the bottom-mounted ADCP from the large waves observed in Terrigal Bay during periods of storm activity; however, modelling of this region shows that the Haven often experienced multiple eddy circulations, driven by wave setup and mean flow (driven by wave radiation stresses) around Broken Head (Figures A1, A2, A3 in Appendix A). Due to the difficulty in resolving the magnitude of the instantaneous waves in the surf zone (as discussed in the previous section) and the transient nature of small-scale eddies, the modelled instantaneous currents cannot be reasonably calibrated using the ADCP observations in the Haven embayment (Figure 8A). The RMSE between the observed and modelled current magnitude is 0.06 metres per second and the coefficient of correlation between the model and observations was determined to be 0.298. This correlation coefficient is considered weak. We analysed the distribution of the current magnitude to assess other aspects of the model output.

The scatter plot of the current magnitudes (Figure 8B(i)) shows that there is a reasonable linear relationship between the modelled and observed datasets. A best fit line (fitted through [0,0]) has a slope of 0.70, which suggests that on average the model tends to underestimate the current magnitude. The quantile-quantile (QQ) plot shows that the distributions are similar for speeds <0.15 metres per second. For speeds >0.15 metres per second, the model tended to underestimate the current magnitudes. These higher speeds are related to the freshwater plume from the Terrigal Lagoon berm discharge arriving at the ADCP location (Figure 8A).

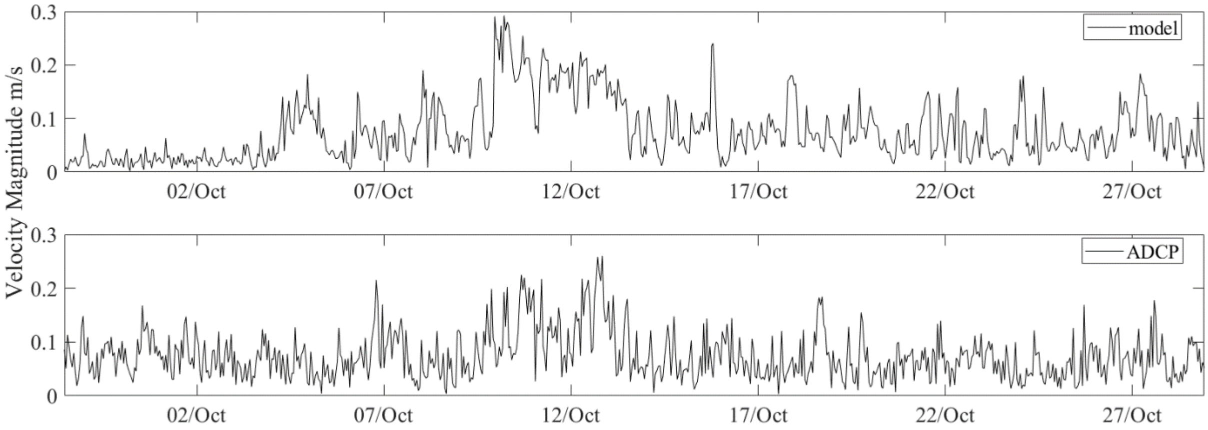

Figure 8A **Modelled and observed depth-averaged speed at the location of the ADCP in Terrigal Haven**

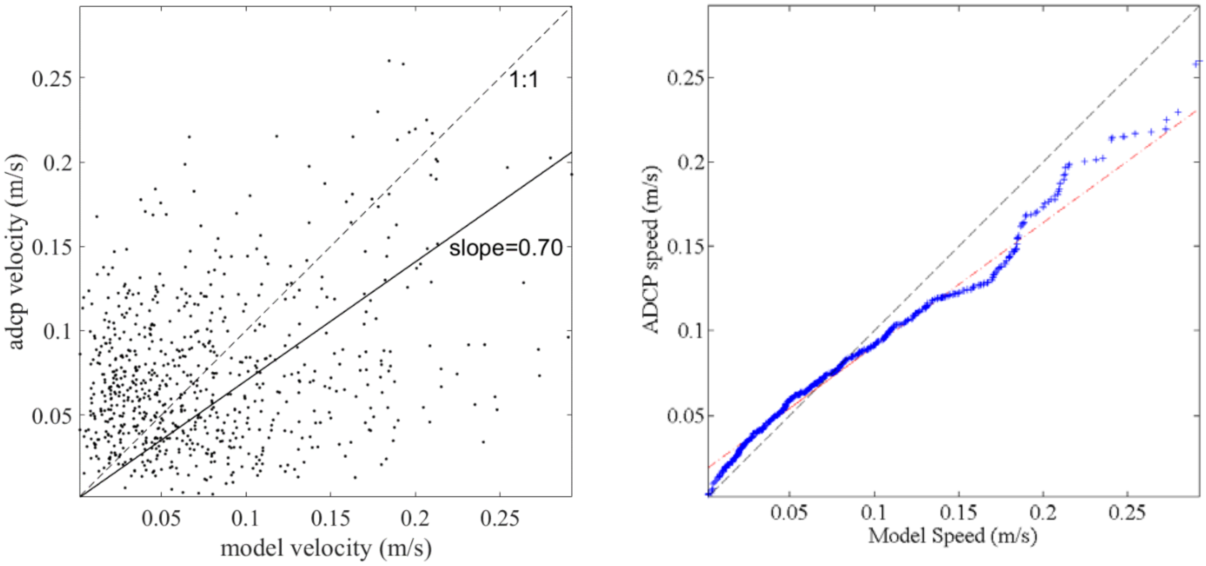

Figure 8B Statistical analysis of the modelled and observed current magnitudes at the ADCP location

(i) The scatter plot of the current magnitudes – the dashed line shows the 1:1 guide and the solid line shows the best fit slope. (ii) The quantile-quantile (QQ) plot – the dashed line shows the 1:1 guide and the red line is a line drawn through the 25th and 75th quantiles.

Lagoon and drain discharge and ocean salinity

During a berm breach on 18 September 2019, the Terrigal Lagoon outflow discharged at a mean rate of 20.8 cubic metres per second and sustained this rate for a few hours (volume lost = 300,000 m^3), followed by 17 days of weaker oceanic exchange fluxes decreasing over time. While the lagoon was open, the total volume of water released was estimated at 1.6 x 10^6 cubic metres (1.6 GL). In one of the largest rain events (375 mm cumulative total) measured at Terrigal, from 7–10 February 2020, the 7 drains outflow discharged at a mean rate of 0.5 cubic metres per second over two days (total volume = 86,000 m^3). The total volume discharged from the lagoon berm breach (considered typical) was 18.6 times the volume discharged through the primary drain during one of the largest rain events. During more typical rain events (44–63 mm cumulative total), the drain discharge volume is in the range of 2000–9000 cubic metres, giving a much larger difference in volume between drain and lagoon, with lagoon volume between 180 and 800 times greater.

During the DPIE campaign period, the observed lagoon discharge volume was 1.6 x 10^6 cubic metres over 17 days and observed drain discharge volume was 8000 cubic metres over 1.5 days. These values were used in the model forcing. The salinity in Terrigal Bay Haven is the result of the oceanic waters mixing with stormwater and lagoon discharges, but given the relative volumes discharged, the influence of the lagoon is dominant and the influence of the drains is relatively minor and confined to within 10s of metres of the drain discharge point.

During non-storm periods (2–3 days after storms), the salinity of the bay was observed to be oceanic in the range of 35–36 grams per kilogram (Figure 9) and the lagoon salinity was estimated at 17 grams per kilogram from the monthly lagoon monitoring by DPIE. The model is forced by (i) the stormwater discharge measured at the 7 drains outlet in the DPIE field campaign and (ii) the Terrigal Lagoon discharge derived from the time derivative of the lagoon volume during the berm breach (Figure 10).

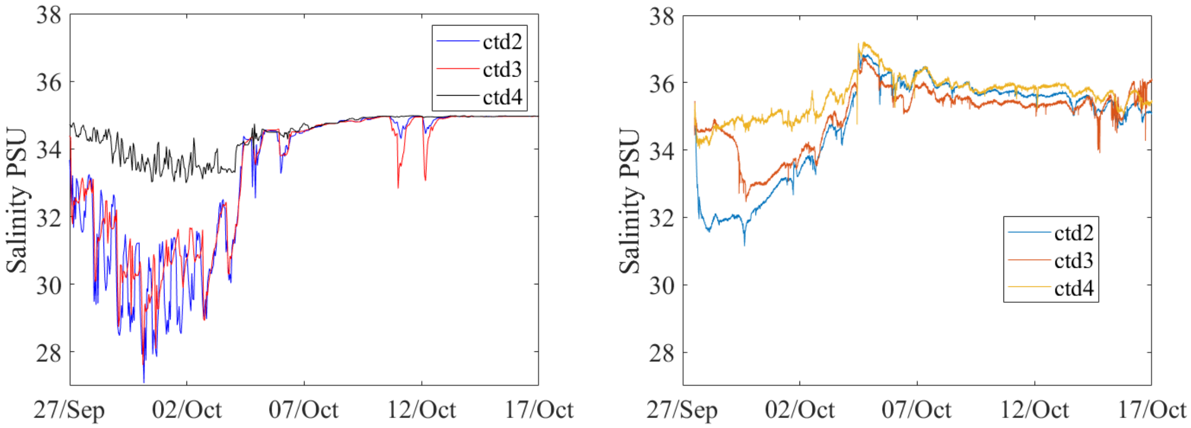

Figure 9 **Salinity at three locations in Terrigal Bay**

CTD2 is closest to the Terrigal Lagoon outlet, CTD3 is further south (in front of the Terrigal SLSC) and CTD4 is at the red buoy offshore (Figure 2). The left panel is the modelled depth-averaged salinity and the right panel is the surface salinity measured by CTD sensors deployed by DPIE.

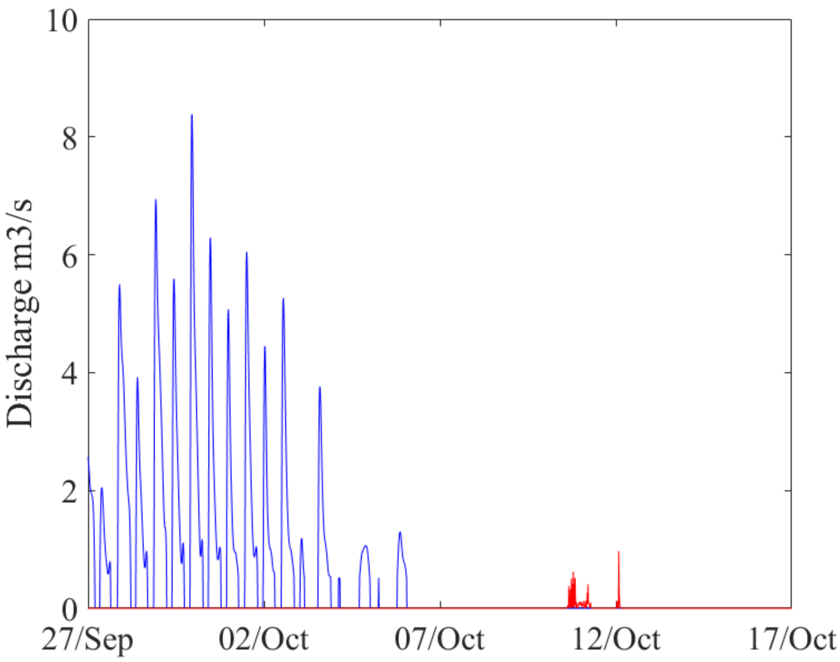

Figure 10 **Terrigal Lagoon discharge rate (blue) and the stormwater discharge at the 7 drains location (red)**

The modelled output shows a similar freshening and diluting trend as the observed surface salinity along the Terrigal beach sites (Figure 9). As the modelled lagoon plume reaches the three sensor locations, the response of the model salinity follows the observations (CTD2 and CTD3). Furthermore, the timescale to mix back to oceanic is also similar between the model and the observations.

The modelled salinity from 27 September to 5 October has a sinusoidal response superimposed on the lagoon-induced salinity drop in the bay. This is caused by the lagoon discharge being modelled as a series of discharges that occurs during the ebb tide, when the lagoon water level drops (Figure 10). The observations do not show a similar sinusoidal response, but peaks in lagoon discharge align with the drops in bay salinity at the CTD locations for both the model and observations.

Circulation

The calibration of the hydrodynamic-wave model shows the model can resolve the mean circulation for the study area. The model is next used to understand the influence of different swell and winds on the mean circulation of the bay. These conditions (scenarios) are derived from the commonly observed conditions along the NSW south-east coast. The conditions are kept constant during the simulation.

The aim of these scenarios is to address community concerns about the Terrigal embayment becoming a high retention zone under some weather conditions, i.e. trapping lagoon and stormwater outflows. As such, the swell scenarios were selected to cover the range of observed conditions. The wind directions were derived from the long-term wind observations from Norah Head automatic weather station (AWS); these are the commonly observed wind directions. The wind speed is derived from the maximum of the long-term monthly mean wind speeds from Norah Head AWS. This high speed is chosen to emphasise the effect of the sustained strong winds, as those observed during stormy conditions (the period of community concern). The swell wave height (HM0) was set as the temporal mean of the observed significant wave height during the DPIE campaign and swell directions were selected to cover the range of conditions observed (both rare and common occurrences). This allows us to gauge how the retention of the embayment changes with swell direction and to derive (if needed) an estimate of conditions between the scenarios.

The scenario set includes swells from the north-east, south-east, south and east directions (labelled as groups NE, SE, S & E respectively), and in each case a steady wind is applied in the westerly, southerly and north-easterly directions. The wind scenarios are labelled 1, 2, 3 respectively (Table 2). In all the scenarios, a lagoon discharge and stormwater drain discharge are included (Figure 11). The magnitude and duration of the releases are similar to observed conditions during the field campaign. The simulation is carried out for the tidal period starting 14 October and extending 14 days.

Table 2 **Significant wave height, mean wave direction and wind velocity used for the scenarios**

Scenario		West wind	South wind	North-east wind
		8 m/s @ 270°	8 m/s @ 180°	8 m/s @ 45°
North-east swell	**1.75 m @ 45°**	NE1	NE2	NE3
South-east swell	**1.75 m @ 135°**	SE1	SE2	SE3
South swell	**1.75 m @ 180°**	S1	S2	S3
East swell	**1.75 m @ 270°**	E1	E2	E3

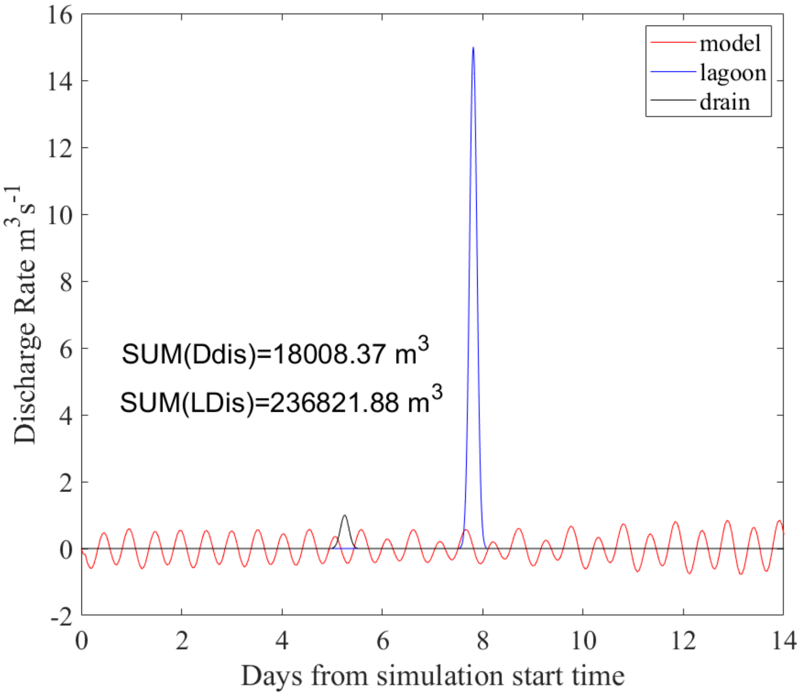

Figure 11 **Terrigal lagoon discharge (LDis) and stormwater drain discharge (Ddis) applied in each scenario**

The red line shows the model tidal level, the green peak is the stormwater discharge and the blue peak is the lagoon discharge. The total volume discharge from each source is also noted.

The results of the scenario variations in Table 2 show that the mean circulation in each group, i.e. NE, SE, E & S remained similar (see scenarios in Appendix A). Swells from the north-east and south-east drive similar circulation; a poleward nearshore flow, a weak equatorward return flow, a strong current at Broken Head driving two eddy zones, one in the Terrigal Haven embayment and the other between Terrigal and Wamberal (Figure 12a).

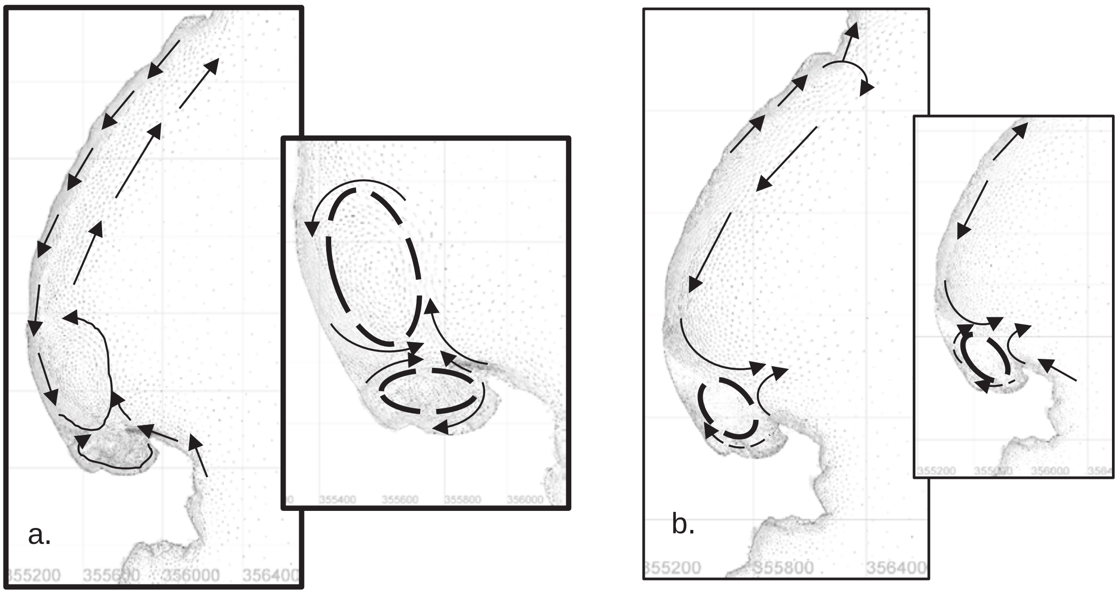

Figure 12 **Sketch of the general circulation induced by (a) NE swell, and (b) S swell**

Both include wind and tides. The inserts are a close view of the Terrigal Haven embayment. The solid arrows show the flow directions and the dashed circles show the eddy location and size.

Swell from the southern direction drives a different circulation (Figure 12b) because the Terrigal beaches are in the wave shadow of Broken Head. North of Broken Head, the current magnitude drops significantly causing a calmer zone from the Haven to the Terrigal Lagoon berm. Further, during the southern swell, there is no large eddy in front of Terrigal Beach compared to the north-eastern and south-eastern swells.

Flushing

In each of the scenarios, numerical particles are released inside the Haven embayment on the ebbing tide, on the 10th day of the simulations. These particles are tracked for two days (48 hours) and the fraction of particles remaining in the Haven is computed to estimate the flushing timescale (Figure 13). The results of the tracking suggest that the north-eastly and south-eastly swells have very similar particle flushing trends, i.e. a quick flush followed by stagnation followed by another quick flush. The southern swell particle tracking shows a more gradual release of particles. This is likely the result of the lower speeds observed in the Haven embayment due to Broken Head blocking wave energy. The e-folding timescale of flushing during the north-east and south-east swell is ~5 hours and the e-folding timescale during the southern swell is ~12 hours. This indicates that during storms with southern swells, pollutant inflow has a slower initial flushing phase; however, in all cases ~80% of the released particles are flushed out of the Haven in less than 24 hours. Recent observations by Central Coast Council officers and DPIE field scientists of mud plumes after heavy rain events have shown that the Haven clears up within 24 hours, which aligns with our modelling efforts.

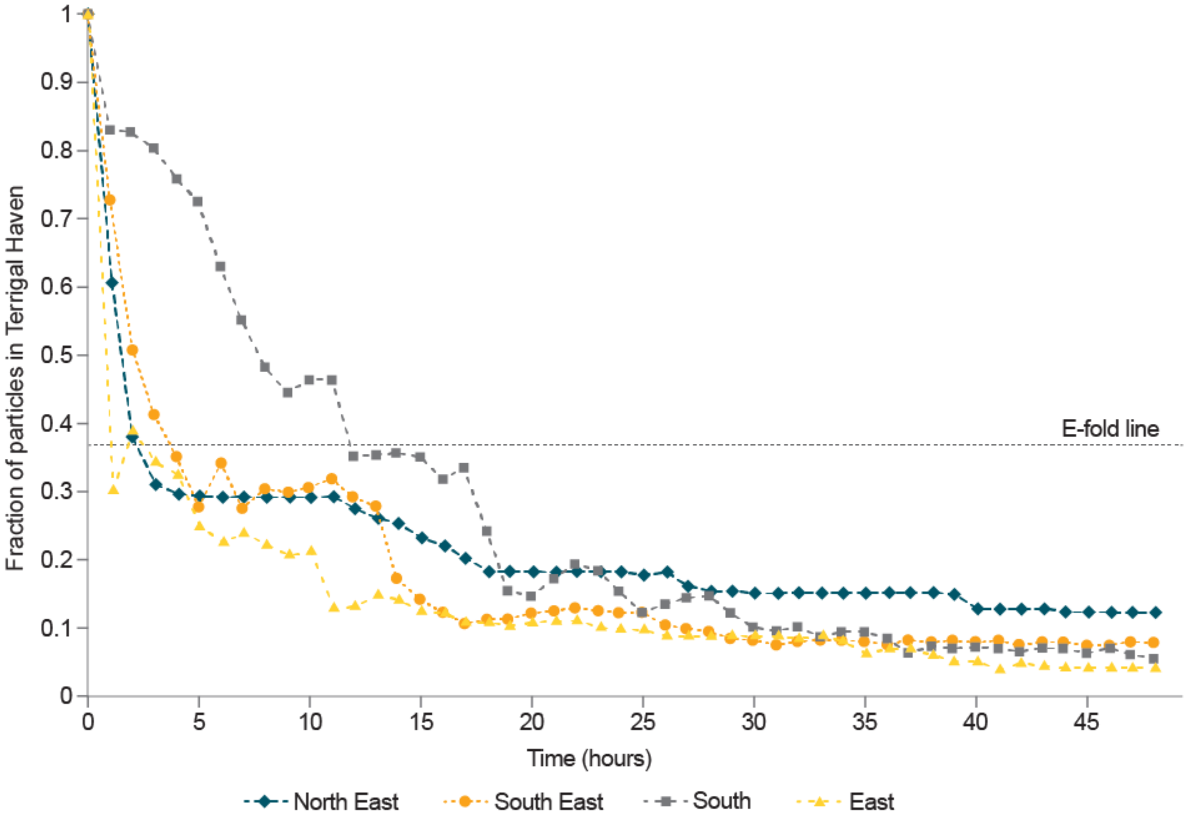

Figure 13 **Particle retention for numerical particles released inside the Terrigal Haven and advected for 48 hours under the forcing of a different swell direction**

The dashed line shows the e-folding timescale, i.e. the time taken for the fraction of particles to decrease to 1/e of initial.

Discussion and conclusion

A depth-averaged hydrodynamic-wave model was developed to understand the hydrodynamic characteristics for swimming spots in Terrigal after rainfall events. The model was calibrated to estimate the mean circulation in the study area.

Several weather scenario simulations were carried out to understand circulation and flushing. Swells from the north-east and south-east drive similar circulation: the poleward nearshore flow, a weak equatorward return flow, and two eddy zones. Swell from the southern direction drives a different circulation because the beach areas are in the wave shadow of Broken Head. North of Broken Head, the current magnitude drops significantly creating a calm zone from the Haven to the Terrigal Lagoon berm.

In each swell scenario, flushing timescales were estimated using numerical particle trajectories. In all scenarios, most of the particles (>80%) in the Haven were flushed out in a day. This suggests that the Terrigal Haven is not a backwater zone, and pollutants discharged into the bay after rainfall are likely diluted or advected away within 24 hours.

The magnitude of typical drain inflows is very small in relation to the volume of the sheltered Haven and the lagoon outflows (drains account for <5% of Haven embayment volume and <5% of total lagoon outflow). Drain flow in times of no rainfall is virtually zero, further reducing the potential for significant impacts of drains on the bay and Haven and confining any impacts to within 10s of metres of the drain outflow point.

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Appendix A: Circulation and flushing scenarios

Scenarios NE & E

The wave-driven currents are one of the primary drivers of circulation along nearshore Terrigal (Cardno 2012). These scenarios (see Table 2) deal with swell coming in from the (i) north-east, and (ii) east directions. In each scenario, the swell direction drives (Figure A1):

- a nearshore south-westly alongshore current along the Wamberal and Terrigal beaches
- a northward current around Broken Head that bifurcates into:
    - a south-westward current that flows along the Haven Beach
    - a north-westward current that flows towards the Terrigal Beach
- an offshore north-eastward return-current driven by the Haven jet.

The poleward flow along Terrigal Beach and the equatorward flow along the Terrigal Haven converge near the Terrigal SLSC before exiting the Haven by jetting in a north-eastly direction. The convergence of these currents creates an eddy flow in the Terrigal Haven basin. Further, the north-east jet from the Haven ('Haven jet') and the south-westly flow along Terrigal Beach create a large eddy circulation in front of the Terrigal Lagoon berm.

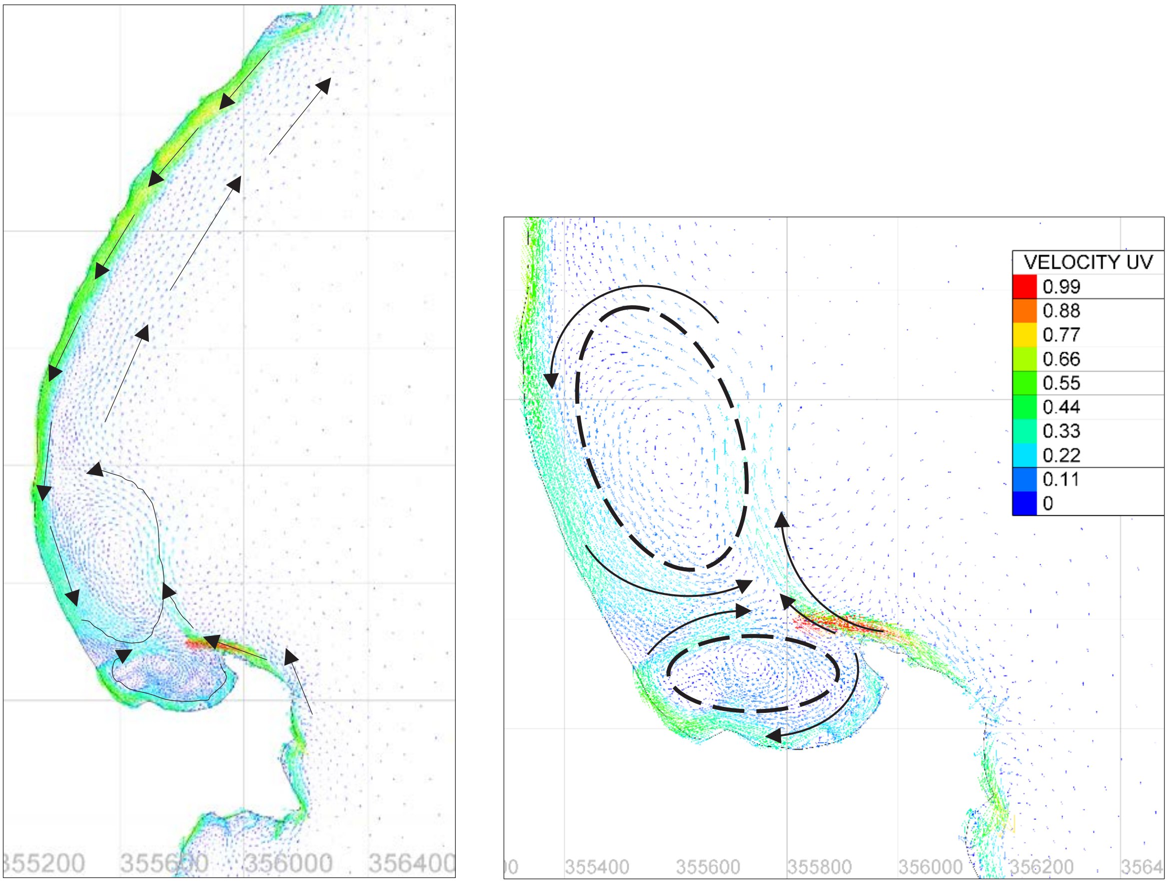

Figure A1 **Snapshot of the circulation induced by a north-eastern swell (east swell has similar circulation) with westerly winds**

The coloured shading under the arrows shows the speed in metres per second. Eddy circulations are highlighted by dashed ovals.

Scenario SE

This scenario (see Table 2) deals with swell coming in from the south-east direction. This swell direction drives (Figure A2):

- a nearshore south-westly alongshore current along the Terrigal and Wamberal beaches
- a northward current around Broken Head that bifurcates into:
  - a south-westward current that flows along the Haven Beach
  - a north-westward current that flows towards the Terrigal Beach
- a weak offshore north-eastward return-current driven by the Haven jet.

The circulation pattern is similar to the swell coming in from the north-eastly direction (Figure A1 & A2), for example the flows along the Terrigal beach, Haven beach and Broken Head, and the large eddy offshore of the Terrigal Lagoon. However, a key difference with the south-eastly swell is the Haven current retreats to Broken Head during high tide, this allows the south-westly alongshore Terrigal beach current to move into the Haven (red arrow in Figure A2). During low tide, in the centre of the Haven basin, the circulation is weak.

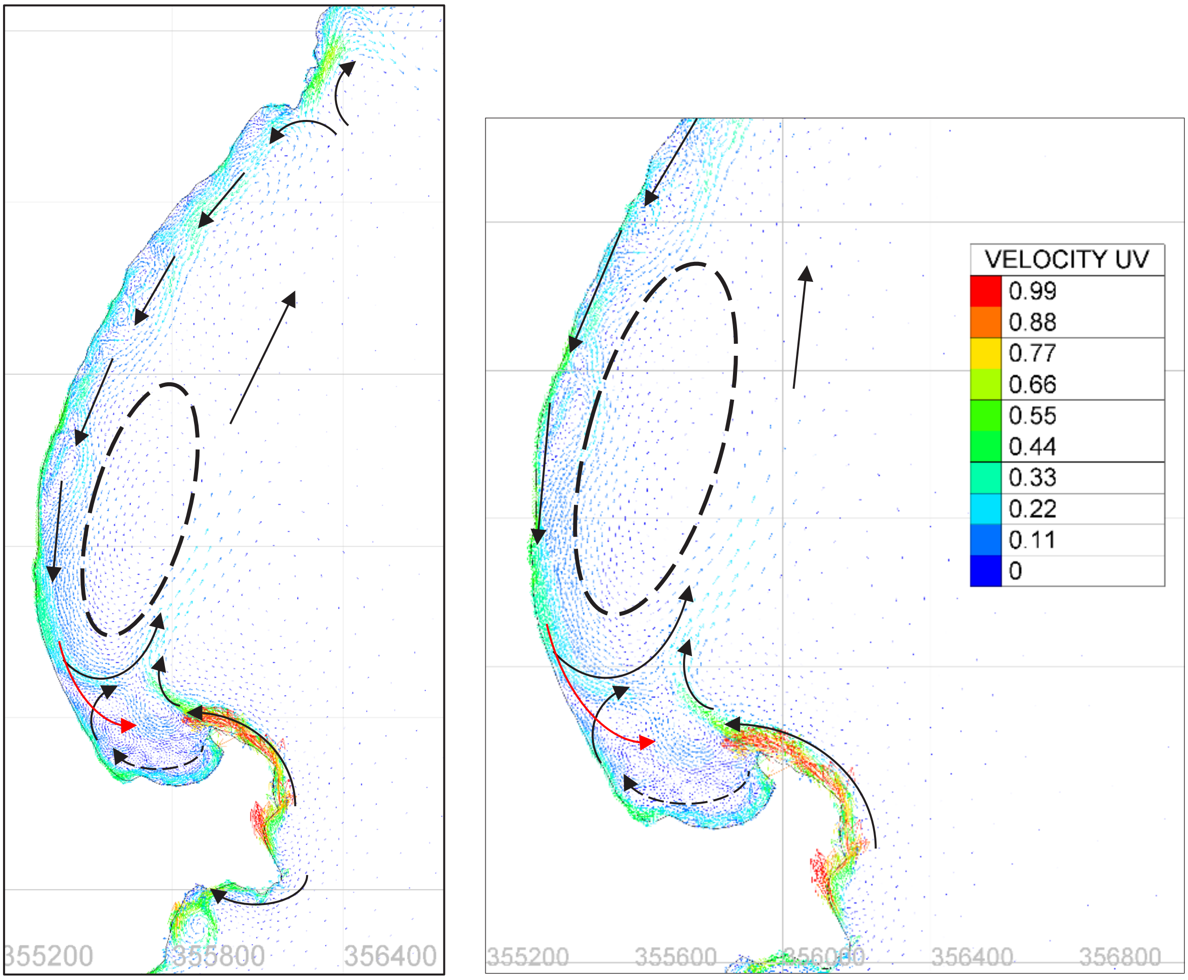

Figure A2 **Snapshot of the circulation induced by a south-eastern swell with westerly winds**

The coloured shading under the arrows shows the speed in metres per second. Eddy circulations are highlighted by dashed ovals. The dashed arrow shows the alongshore flow along the Haven Beach that flows during low tide and retreats during high tide. When the Haven current retreats the alongshore Terrigal Beach current flows into the Haven (red arrows).

Scenario S

This scenario deals with swell coming in from the south (see Table 2). The swell from this direction creates a circulation that is distinctly different when compared to the north-eastly and south-eastly swells. This swell direction is blocked by the Terrigal headland (Broken Head and Skillion). This creates a calm low significant wave height region from the Haven to the Wamberal Lagoon berm. North of the Wamberal Lagoon berm, the wave-driven currents are forced in the north-eastly direction by the southern swell (Figure A3). The flows created are:

- a nearshore north-eastly alongshore current along Wamberal Beach to north of Forresters Beach
- a weak offshore south-westward return-current driven by eddy back flow at each headland
- a northward current around Broken Head that bifurcates into:
  - a south-westward current that flows along the Haven Beach
  - a north-west current that flows towards the Terrigal Beach.

The Haven current creates an eddy circulation in the Haven. This eddy persists for extended periods, weakening and strengthening as the tides modulate the Haven current. The presence of the eddy causes the weak south-westward return-current and the north-westward current around Broken Head to converge and jet out of the Haven, a feature seen in all the previously discussed swell directions.

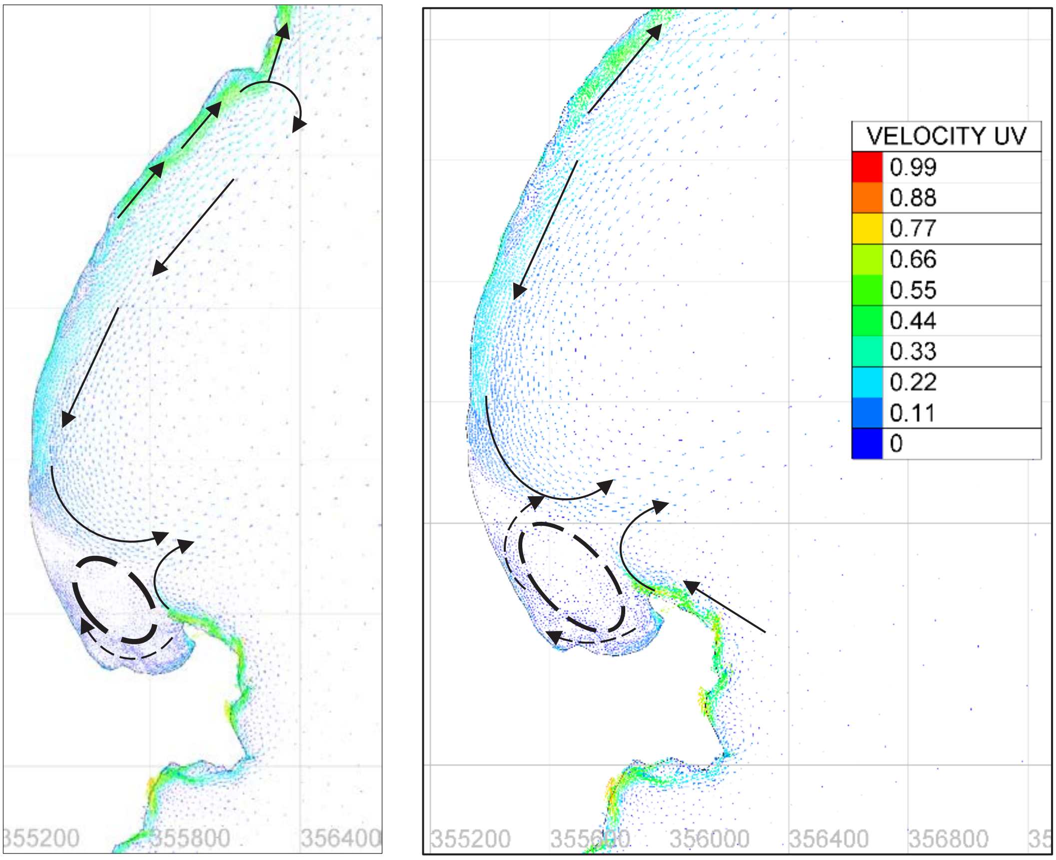

Figure A3 **Snapshot of the circulation induced by a southern swell with westerly winds**

The coloured shading under the arrows shows the speed in metres per second. Eddy circulations are highlighted by dashed ovals. The dashed arrow shows the alongshore flow along the Haven Beach that flows during low tide and retreats during high tide. During a southern swell, when the Haven current retreats, the Terrigal Beach current does not enter the Haven.