Stuarts Point Sewerage Scheme – Environmental Impact Statement

Appendix 8

Stuarts Point WWTP Marine and Estuarine Mixing Modelling

GHD (2025)

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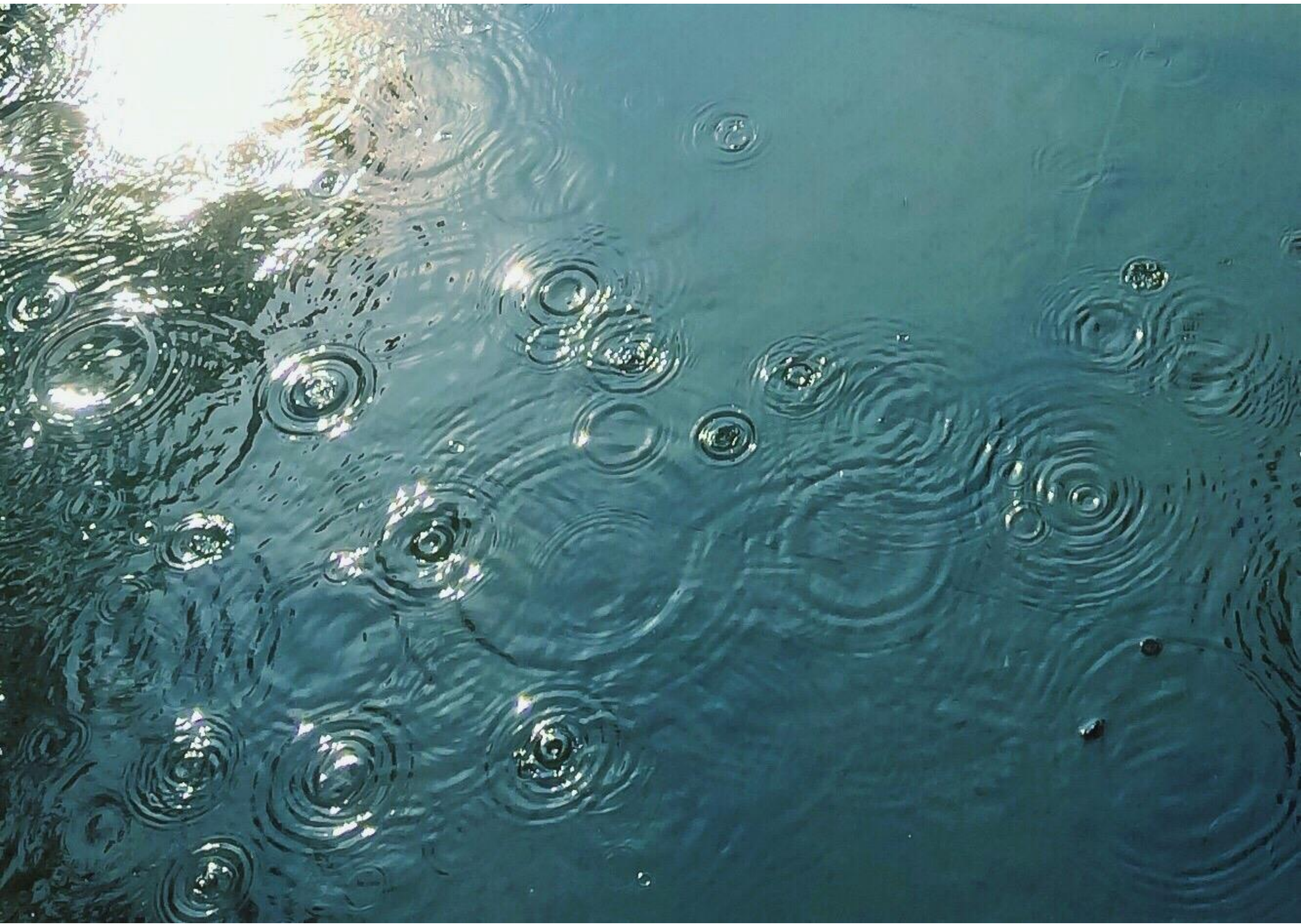
Stuarts Point WWTP

Marine and Estuarine Mixing Modelling

Kempsey Shire Council

23 September 2025

→ **The Power of Commitment**



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The Power of Commitment

Executive summary

Three-Dimensional (3D) hydrodynamic modelling was undertaken to predict the flushing rates of the Macleay Arm system and assess the relative improvement in water quality following decommissioning of septic tanks and replacement with a proposed Wastewater Treatment Plant (WWTP) into the dunal systems to east of the water body.

The 3D hydrodynamic model was configured to include the Macleay River from the upstream site at Kempsey to the ocean, the Macleay Arm and the near-shore coastal region. The model was calibrated and verified with water level measurements at two locations within the Macleay River. Good model performance was achieved in terms of the reproduction of measured water levels. Further, a qualitative comparison of simulated 2012 salinities with 2015-2019 measurements at Stuarts Point were similar.

Flushing rates of the entire Macleay Arm control volume, and the deeper northern portion of the Macleay Arm (referred to as the Stuarts Point control volume), were estimated as e-folding flushing timescales. Ten flushing simulations were run over a full year (2012) that spanned a range of tidal states and river flow conditions.

Dilution targets for proposed WWTP effluent via the groundwater pathway to the Macleay Arm were calculated for physical and chemical stressors (total nitrogen [TN], total phosphorous [TP] and salinity) on the basis of predicted concentrations of the groundwater, the ambient water quality, the default ANZECC & ARMCANZ (2000) TN guideline value and site-specific guideline values for TP and salinity. Similarly, ammonia and nitrate were assessed as toxicants using default guideline values from ANZG (2018). The most stringent dilution target for physical and chemical stressors was for TN, while for toxicants, ammonia was the most stringent for the septic effluent and nitrate was the most stringent for the dunal effluent. Therefore the dispersion and dilution of these parameters within the Macleay Arm (and Pacific Ocean) from groundwater WWTP effluent flows into both of these water bodies was simulated for the following scenarios:

– Scenario 1: the current (2024) off-peak septic discharge of 273 kL/d (25.2 kL/d from Grassy Head, 208.4 kL/d from Stuarts Point and 39.2 kL/d from Fishermans Reach) with a TN concentration of 41.25 mg/L, comprised entirely of ammonia.
– Scenario 2: the projected ultimate peak holiday effluent dune disposal of 1,030 kL/d with 515 kL/d each to the Macleay Arm and the Pacific Ocean with a TN concentration of 6 mg/L and a nitrate concentration of 4.5 mg/L.
– Scenario 3: the projected 2047 off-peak effluent dune disposal of 693 kL/d with 346.5 kL/d each to the Macleay Arm and the Pacific Ocean with a TN concentration of 6 mg/L and a nitrate concentration of 4.5 mg/L.

TN, ammonia and nitrate were simulated as conservative (non-decaying and non-transforming) numerical tracers. The ANZECC & ARMCANZ (2000) target water quality guideline of 0.3 mg/L for TN as a physical and chemical stressor was adopted, while the default guideline values for freshwater toxicants of 0.9 mg/L for ammonia and 1.1 mg/L for nitrate were adopted from ANZG (2018).

The conclusions from this study include:

– The flushing rates of the Macleay Arm control volume (as estimated by the e-folding timescale) are predicted to range between 10 to 28 days depending on tidal state and river flow events.
– The flushing rates of the Stuarts Point control volume were longer with flushing timescales of ~28-37 days due to the greater separation distance from the tidal exchange through the Macleay River opening with ocean.
– For the existing septic tank arrangement (scenario 1), TN greater than 0.3 mg/L is predicted to extend across nearly the entire 10 km length of the Macleay Arm with concentrations above 1 mg/L at times near the relatively poorly flushed areas of Grassy Head and Stuarts Point.

– Maximum predicted TN under the dune disposal scenarios was less than 0.4 mg/L. Exceedances of the 0.3 mg/L guideline is predicted to extend ~2 km under the ultimate peak holiday flow rate (scenario 2), and was localised to within 150 m westward distance from the discharge boundary for the 2047 off-peak effluent dune disposal (scenario 3).
– Minimal impacts to the Pacific Ocean are predicted following establishment of the dunal discharge system (scenarios 2 and 3).
– Ammonia exceeding toxic concentrations for the existing septic tank arrangement was only predicted to occur infrequently and in highly localised zones within the Macleay Arm at Grassy Head and Stuarts Point. The dunal discharge arrangement was predicted to be effective in mitigating any potential toxicity risks to the Macleay Arm related to either ammonia or nitrate via reduced loads of these constituents (relative to the septic effluent). Further, no toxicity impacts to the Pacific Ocean were predicted.

In summary, the Stuarts Point Wastewater Treatment and dunal disposal project is predicted to significantly reduce nutrient loading within the Macleay Arm following establishment of effluent treatment, and decommissioning of the existing septic tanks.

This report is subject to, and must be read in conjunction with, the limitations set out in Section 1.4 and the assumptions and qualifications contained throughout the Report.

Contents

Table index

Figure index

1. Introduction

The Stuarts Point area currently relies primarily on septic tanks for disposal of sewage effluent. The septic tanks drain to the groundwater system, much of which flows into the Macleay Arm. Elevated nutrient loads in the Macleay Arm have been a longstanding water quality issue, likely influenced by a combination of septic inflows and agricultural runoff.

Kempsey Shire Council (KSC) is investigating a preferred option for a Wastewater Treatment Plant (WWTP) to service the Stuarts Point township and surrounding areas including Grassy Head and Fishermans Reach. The proposed plant will dispose of treated wastewater to an infiltration trench system located in the dunal environment between the Macleay Arm and the ocean (see Figure 1.1 for indication of dunal disposal site). It is anticipated that the wastewater, after entering the groundwater system, will flow westward and eastward form the disposal site, and half of the discharged effluent will reach the Macleay Arm.

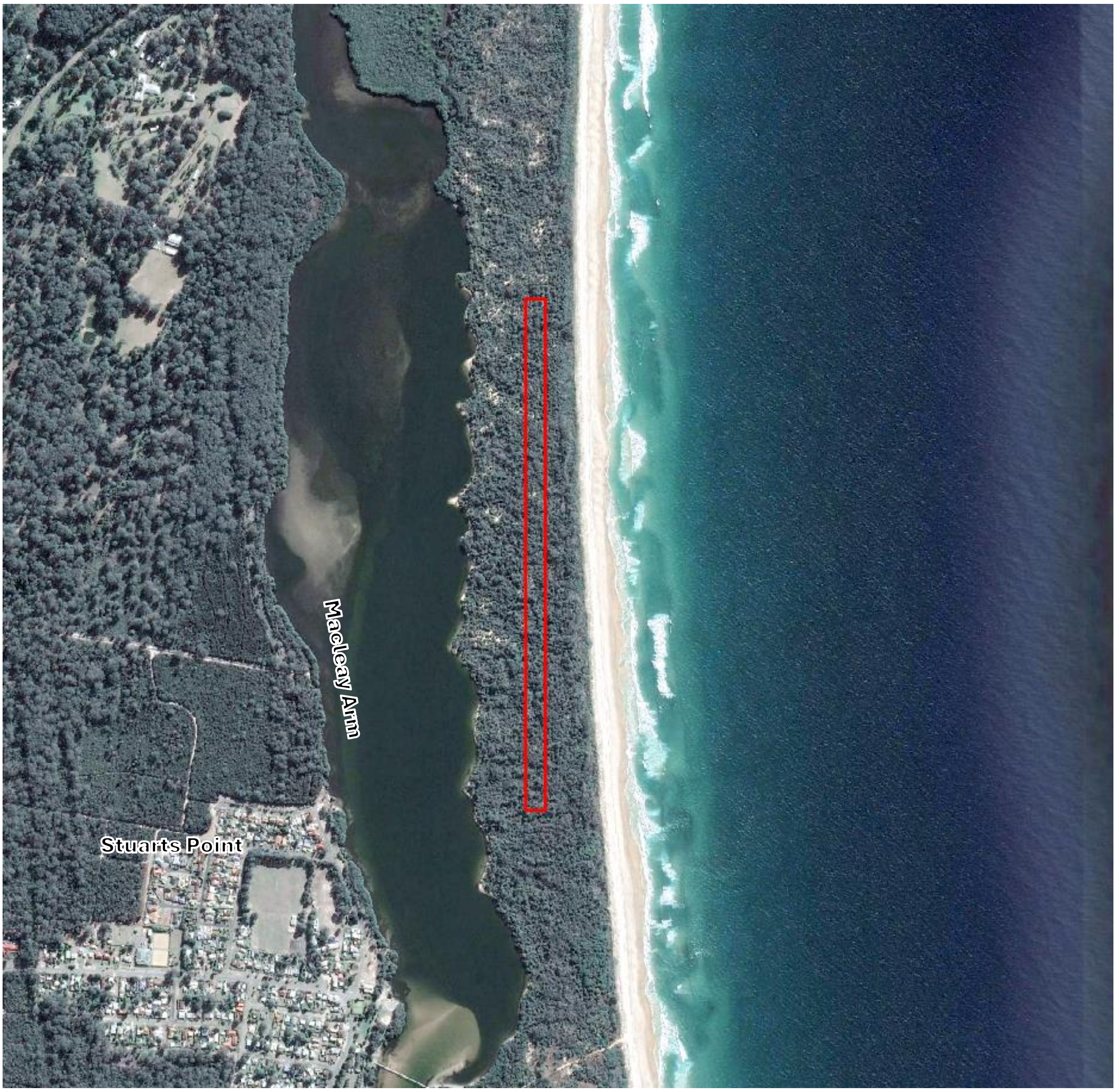


Figure 1.1 Proposed Stuarts Point WWTP dunal disposal location

KSC engaged GHD Pty Ltd (GHD) to undertake a mixing and flushing modelling study to predict the potential implications to water quality from nutrient enriched groundwater discharge into the Macleay Arm. This study is associated with the preparation of an Environmental Impact Statement (EIS) by KSC with the assistance of Beca HunterH2O.

1.1 Purpose of this report

Numerical modelling was carried out to assess whether the proposed groundwater discharge is likely to generate deleterious water quality within the estuarine regions of the Macleay River system, relative to the predicted impacts from the existing septic tank arrangement.

Specifically, the study aims to determine the following through three-Dimensional (3D) hydrodynamic modelling:

- The flushing rate of the Macleay Arm through estimation of the e-folding time. The e-folding time is the time taken for the Macleay Arm to exchange ~63% of its water with adjacent waters (i.e. connecting rivers and the Pacific Ocean) so that 1/e (~37%) of its original volume remains.
- The influence of nutrient-laden groundwater seepage into the Macleay Arm via:
  - The existing septic tanks at the Grassy Head, Stuarts Point and Fishermans Reach townships, are estimated to discharge 273 kL/d to the Macleay Arm.
  - The proposed dunal disposal system is forecast during ultimate peak holiday periods to discharge treated effluent at 1,030 kL/d with half assumed to flow to the Macleay Arm and the other half to the Pacific Ocean.
  - The proposed dunal disposal system is forecast in 2047 to have an off-peak treated effluent flow rate of 693 kL/d (again split 50/50 in the groundwater to the Macleay Arm and the Pacific Ocean).

  While the flow rates of effluent to the Macleay Arm are predicted to increase, the intent is that the wastewater treatment operation will significantly reduce the total nutrient loads that enter the system, thereby improving existing water quality.

This report details the methodology and outcomes of the hydrodynamic modelling assessment to inform preparation of the EIS.

1.2 Scope

The scope of work for this study includes the following:

- Determine the water quality objectives (WQOs) of the contaminants of concern (i.e. nutrients) in the groundwater discharge. WQOs establish the concentrations to be achieved that represent acceptable water quality.
- Establish a hydrodynamic model of the lower Macleay River, Macleay Arm and nearshore coastal Pacific Ocean.
- Calculate flushing rates (e-folding times) for the Macleay Arm under a range of conditions over a representative year.
- Simulate nutrient concentrations in the Macleay Arm over a representative calendar year and comparison of the outcomes between the existing and two future dunal discharge scenarios.

1.3 Assumptions

The following assumptions are adopted in this study:

- Macleay River discharge data was not available, however long-term continuous datasets of river water level measurements were supplied by Manly Hydraulics Laboratory (MHL) and KSC. The upstream Macleay River boundary in the 3D hydrodynamic model was simulated as a fluctuating water level, rather than a specified volumetric discharge. It is assumed that river flow is accurately simulated from the use of the water level model inputs at this upstream boundary. The model calculates the difference in the specified water level at the boundary compared to the model cell directly adjacent to the boundary to determine the direction and velocity of water flow. Incorporation of accurate bathymetry data at this location increases the level of confidence in the flow prediction on the basis of measured water levels at this upstream boundary.
- Several conservative assumptions regarding groundwater quality and the derivation of WQOs are adopted in this study as described in Section 4.
- The ambient nutrient concentrations are defined in this study on the basis of measurements during 2015 and 2016. It is likely that these measurements were influenced by high levels of nutrients that entered the Macleay Arm from groundwater that contained seepage from septic tanks. Hence, the adopted ambient conditions are likely influenced by septic seepage, and the simulated scenarios predict additional inflow from septics (and future dunal discharge) in addition to this. This approach provides a common set of assumptions across scenarios to allow a comparative analysis, However, the nutrient predictions are likely to be conservative (over-predict nutrient levels), particularly with respect to the future dunal discharge scenarios for which it is assumed the septic flows will have ceased, thereby further improving ambient water quality within Macleay Arm.

1.4 Limitations

This report: has been prepared by GHD for Kempsey Shire Council and may only be used and relied on by Kempsey Shire Council for the purpose agreed between GHD and Kempsey Shire Council as set out in Section 1.1 of this report.

GHD otherwise disclaims responsibility to any person other than Kempsey Shire Council arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report (refer Section 1.3 of this report). GHD disclaims liability arising from any of the assumptions being incorrect.

GHD has prepared the hydrodynamic model ("Model") for, and for the benefit and sole use of, Kempsey Shire Council to support preparation of the EIS and must not be used for any other purpose or by any other person.

The Model is a representation only and does not reflect reality in every aspect. The Model contains simplified assumptions to derive a modelled outcome. The actual variables will inevitably be different to those used to prepare the Model. Accordingly, the outputs of the Model cannot be relied upon to represent actual conditions without due consideration of the inherent and expected inaccuracies. Such considerations are beyond GHD's scope.

The information, data and assumptions ("Inputs") used as inputs into the Model are from publicly available sources or provided by or on behalf of the Kempsey Shire Council, (including possibly through stakeholder engagements). GHD has not independently verified or checked Inputs beyond its agreed scope of work. GHD's scope of work does not include review or update of the Model as further Inputs becomes available.

The Model is limited by the mathematical rules and assumptions that are set out in the Report or included in the Model and by the software environment in which the Model is developed.

The Model is a customised model and not intended to be amended in any form or extracted to other software for amending. Any change made to the Model, other than by GHD, is undertaken on the express understanding that GHD is not responsible, and has no liability, for the changed Model including any outputs.

GHD has prepared this report on the basis of information provided by Kempsey Shire Council and others who provided information to GHD (including Government authorities), which GHD has not independently verified or checked beyond the agreed scope of work. GHD does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information.

2. Methodology

2.1 Hydrodynamic model

2.1.1 MIKE 3 Flexible mesh

MIKE 3 Flexible Mesh (MIKE 3 FM) was used for this study. MIKE 3 FM was developed by the Danish Hydraulic Institute (DHI) and is an industry standard for 3D hydrodynamic modelling. The model domain in MIKE 3 FM is defined horizontally by an irregular network of triangles or quadrangles (the model 'cells') that are split into vertical 'layers' by either a z-level (defined layer thicknesses), sigma coordinate (fixed number of vertical layers throughout the model domain that vary in thickness according to the depth) or a combined sigma and z-level configuration. For each model cell, MIKE 3 FM simulates a range of hydrodynamic properties including, but not limited to, current speed, current direction, water level and salinity. MIKE 3 FM is driven by user-defined environmental inputs (e.g. tidal level variations at open boundaries, water levels or discharge of rivers, groundwater fluxes).

2.1.2 Model domain

The model domain, mesh and bathymetry are shown in Figure 2.1 and Figure 2.2 for the full domain and study area, respectively. Mesh element sizes range from ~1 km at the offshore boundaries to ~30 m in the upper stretches of the Macleay Arm, where fine resolution is necessary to characterise the geometry of the narrow stream channels, as well as to resolve the dispersion and dilution of the groundwater discharge into these areas. The model bathymetry was compiled from two sources:

– Digitised bathymetric survey data of Macleay River extending from the river mouth in the east to approximately 35 km upstream to Aldavilla. The lower reaches of the Macleay River were surveyed at high resolution (approximately 10 m spacing between data points). Portions of the Macleay Arm and the upstream sections of the Macleay River were surveyed at lower resolution with transects spaced approximately 100 m apart.
– Coastal bathymetry extracted from MIKE C-MAP bathymetrical database. MIKE C-MAP is a DHI product which uses the Global Electronic Chart database CM-93 Edition 3.0 provided by Jeppesen Norway.

The vertical domain in the 3D model was configured with a combined sigma/z-level coordinate system of 5 sigma layers to 5 m depth and 6 z-layers of 2, 3, 10, 20, 30 and 50 m thickness thereafter.

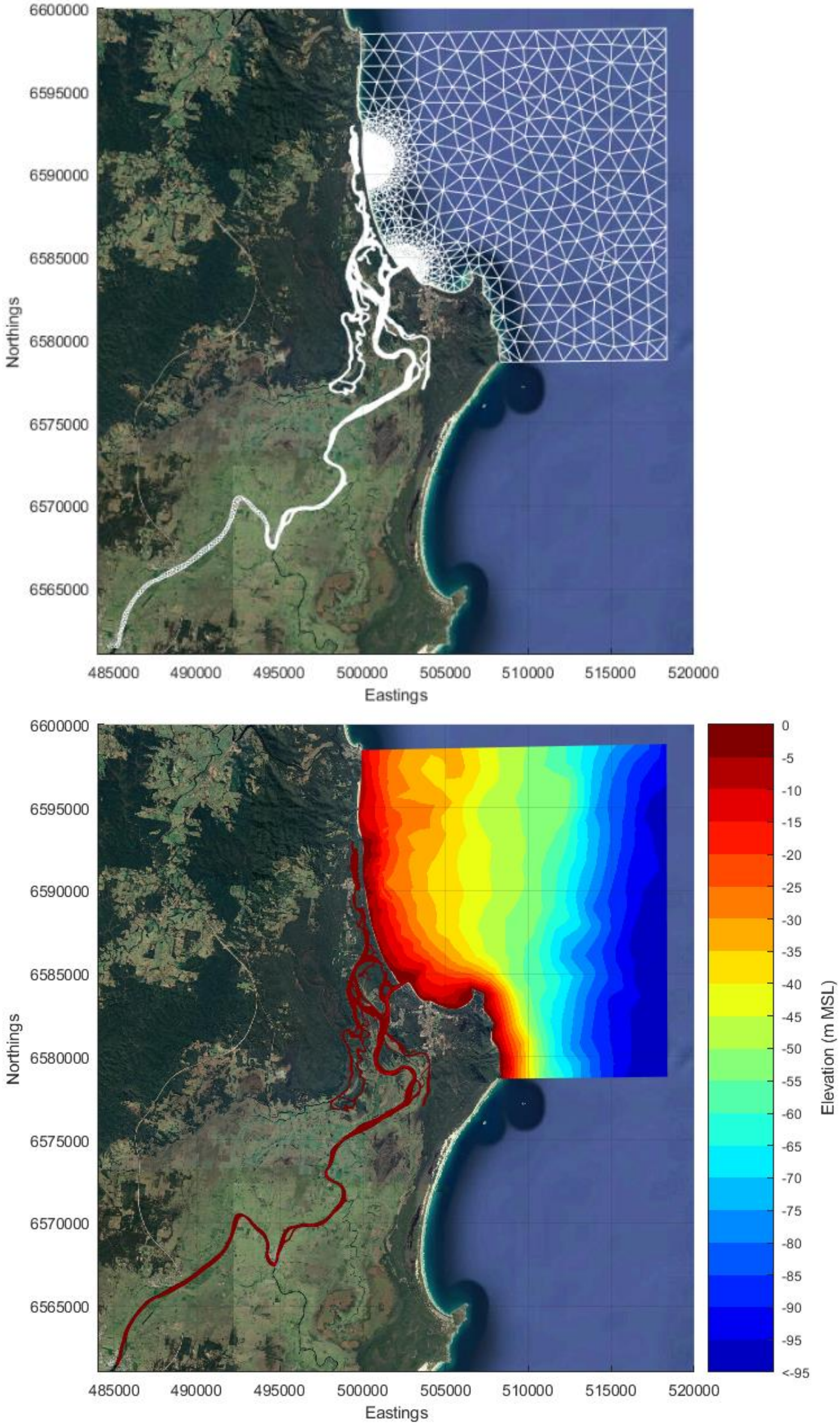


Figure 2.1 Model mesh (top) and bathymetry (bottom) – full domain

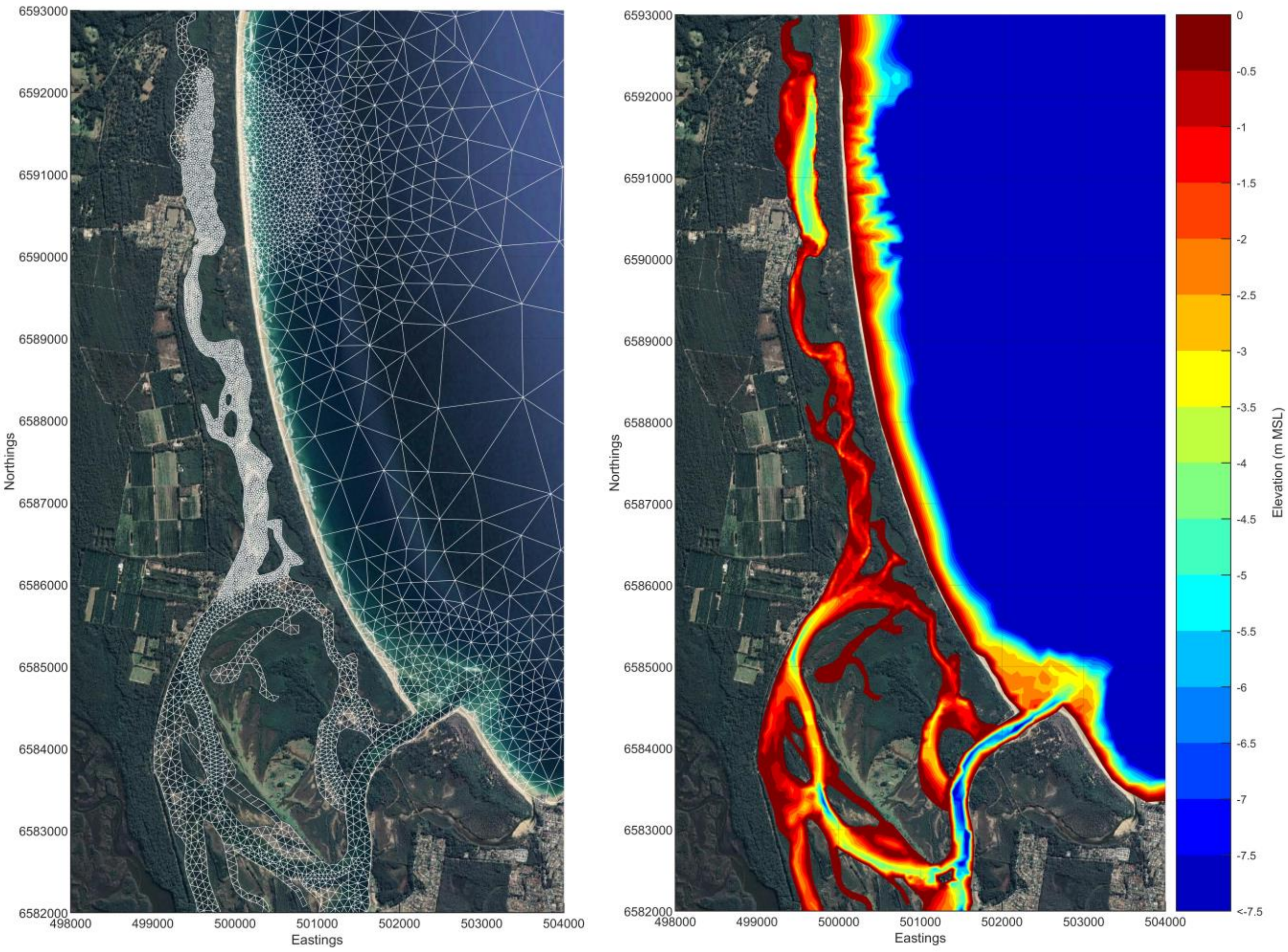


Figure 2.2 ***Model mesh (left) and bathymetry (right) – study area***

2.1.3 Modelling approach

DHI's Mike 3 three-dimensional (3D) hydrodynamic model was used to simulate the flushing of the Macleay Arm system and the dispersion and dilution of the simulated groundwater effluent plumes. This was carried out in the following manner:

– The bathymetry and the horizontal and vertical model grid were configured as specified in Section 2.1.2.
– Model inputs included water levels (Section 3.1) and salinity (Section 3.2) at the model domain boundaries, and ambient groundwater discharge into the Macleay Arm (Section 3.5).
– The flushing rates of the entire Macleay Arm and the deeper northern portion of the Macleay Arm were evaluated by seeding these areas with a conservative numerical tracer and calculating the e-folding time via the methods described in Section 2.3 for ten start dates spread over a one year period with varying tidal conditions (Section 2.5).
– The elevated total nitrogen concentrations of the groundwater were simulated with conservative (i.e. non-decaying, non-transforming) numerical tracers to track the influence of the groundwater plume on nutrient levels within the Macleay Arm for the various scenarios (Section 2.4). Additionally, for the dunal discharge scenarios, nutrients flowing to the Pacific Ocean were also simulated.
– The hydrodynamic model was run over the entire year of 2012 as justified in Section 3.1.

2.2 Model verification

Verification of the hydrodynamic model was based on measurements of water levels (Section 3.2), with a secondary qualitative check on measured salinity data (Section 3.2). No measurements of current speeds were available for validation purposes at any sites in the vicinity of the study area.

Model verification for water levels utilised the following quantitative indices to compare the simulation with the measurements:

– **Percentile probability distributions.** This is a graphical comparison of the statistical spread of a parameter between the simulation and measurements. This comparison quantifies the percentage of time that the model under- or over-predicts the measurements.

– **Mean Absolute Error (MAE).** A quantitative measure of the absolute differences between the simulation and measurements. Low values of MAE represent good model performance. This metric is easily interpretable and a more natural measure than the commonly used root-mean-squared error, as it is less influenced by extreme values (i.e. outliers or 'noise' in the measured data) (Willmott 1982). The **MAE** is calculated as:

$$\boldsymbol{MAE} = \frac{\sum_{i=1}^{n} |P_i - O_i|}{n}$$

where:

P_i = Predicted value at comparison time i

O_i = Observed value at comparison time i

n = Number of comparison measurements

– **Index of Agreement (IOA).** IOA is a quantitative measure of the average differences between predicted and observed values relative to the range of values in the observation data (Willmott 1982). It is bounded between the values of 0 and 1, with values close to 0 describing large relative differences (i.e. poor validation) and values close to 1 describing small relative differences (i.e. good validation). Willmott et al. (1985) suggests that IOA values meaningfully >0.5 represent good model validation, with values approaching 1 representing excellent validation. Here, IOA values greater than 0.8 are deemed to represent very good model agreement. The **IOA** is calculated as:

$$\boldsymbol{IOA} = 1 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (|P_i - \bar{O}| + |O_i - \bar{O}|)^2}$$

where, further to the definitions for MAE:

$\bar{O}$ = Mean of the observations during the comparison period.

2.3 Flushing

The flushing rates of the Macleay Arm were evaluated through calculation of the e-folding flushing time. The e-folding flushing time is the duration for ~63% of a water body's volume to be exchanged with adjacent ambient waters until ~37% (1/e) of the original volume remains. Numerically, this is estimated by fitting an exponential curve of the form $C_t = C_0\, e^{-kt}$ to the conservative tracer concentration (C_t) over time (t). The inverse of the fitted exponent (1/k) is the e-folding flushing time scale.

Two 'control volumes' were assessed for flushing rates in this study. Flushing time-scales were evaluated by seeding the control volume with a uniformly distributed conservative (i.e. non-decaying) numerical tracer. The change in the tracer concentration over time is tracked by the model, and the e-folding time is estimated from this data via post-processing calculations as described above.

The control volumes assessed were the Macleay Arm (as depicted in Figure 2.3, left) and the more isolated, deeper northern portion of the Macleay Arm (as depicted in Figure 2.3, right), referred to as the Stuarts Point control volume.

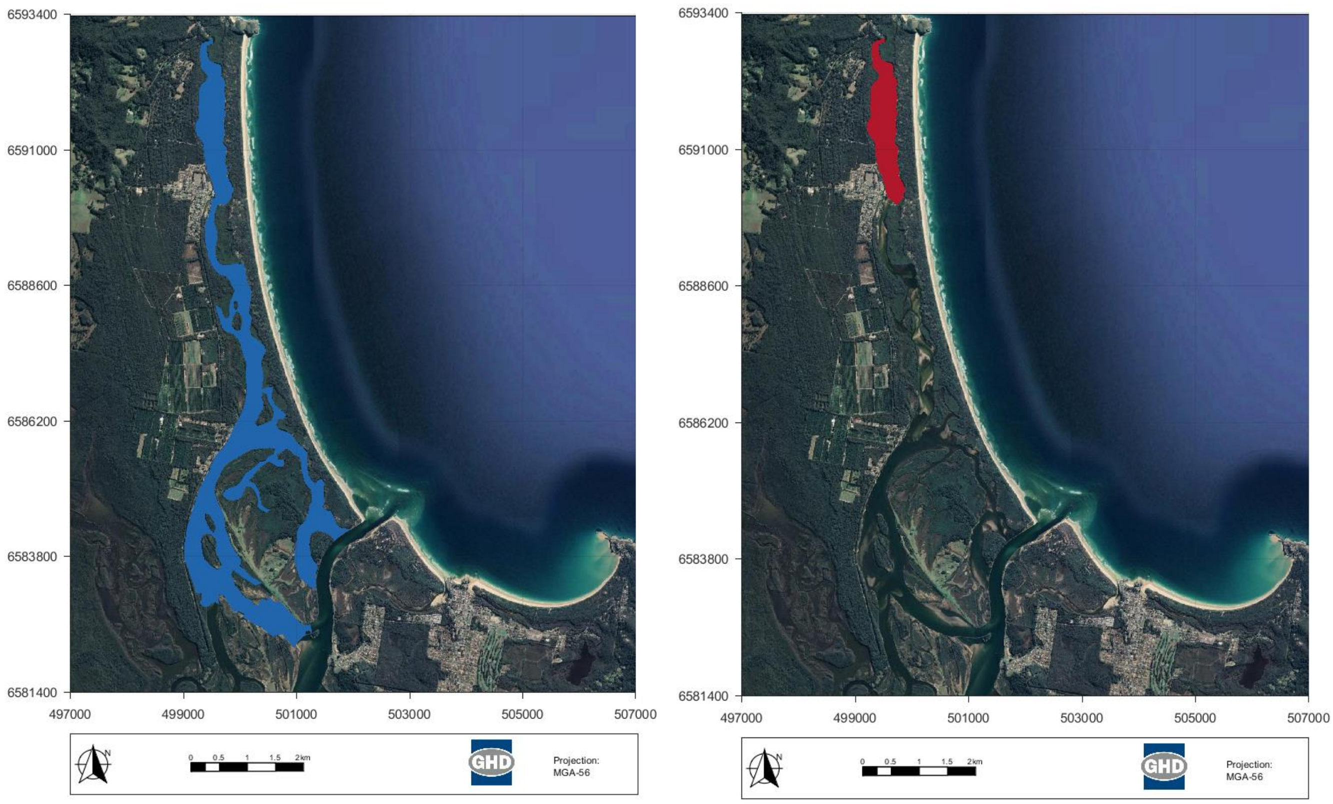


Figure 2.3 Macleay Arm control volume (left) and Stuarts Point control volume (right)

2.4 Simulation of groundwater effluent

Groundwater discharge was simulated in two components; ambient groundwater flow and groundwater effluent plumes.

The data informing the model inputs for ambient groundwater flow are detailed in Section 3.5. Ambient groundwater quality was assumed to be equivalent to the ambient Macleay Arm water quality (Section 4.2), since the Macleay Arm is likely highly influenced by groundwater inflows.

Simulated groundwater effluent quality is detailed in Section 4.1, while the flow rates are summarised in the next sections.

2.4.1 Groundwater effluent from existing septic tanks (Scenario 1)

The existing sewage arrangement for the Stuarts Point region consists of septic tanks that seep to groundwater and flow to Macleay Arm. Scenario 1 of this modelling assessment represents the current arrangement.

Effluent groundwater flow rates and locations of inflow were defined by Beca Hunter H2O (BHH2O). The specified boundaries of groundwater discharge carrying septic tank effluent into the Macleay Arm are shown in Figure 2.4 and Figure 2.5, from the populated areas of Grassy Head, Stuarts Point and Fishermans Reach.

Figure 2.4 *Location of septic tank discharge (via groundwater) from Grassy Head to Macleay Arm*

Figure 2.5 *Location of septic tank discharges (via groundwater) from Stuarts Point (left) and Fishermans Reach (right) to Macleay Arm*

The total groundwater effluent flowrates defined by BHH2O are 25.2, 208.4 and 39.2 kL/d from Grassy Head, Stuarts Point and Fishermans Reach, respectively, totalling 273 kL/d. These represent typical existing (2024) off-peak flow rates.

2.4.2 Groundwater effluent from dunal disposal site (Scenarios 2 and 3)

The location of the effluent discharge into the dunal disposal site is shown in Figure 2.6. The total effluent discharge is assumed to be split evenly eastwards to the Pacific Ocean and westwards to the Macleay Arm. The simulated length of the effluent discharge boundary into the marine and estuarine regions of the model was configured to be equal to the north-south length of the proposed dunal discharge site (~1,300 m).

The two scenarios that were simulated under this proposed arrangement include:

– Scenario 2: the projected ultimate peak holiday effluent dune disposal of 1,030 kL/d with 515 kL/d to each to the Macleay Arm and the Pacific Ocean.
– Scenario 3: the projected 2047 off-peak effluent dune disposal of 693 kL/d with 346.5 kL/d each to the Macleay Arm and the Pacific Ocean.

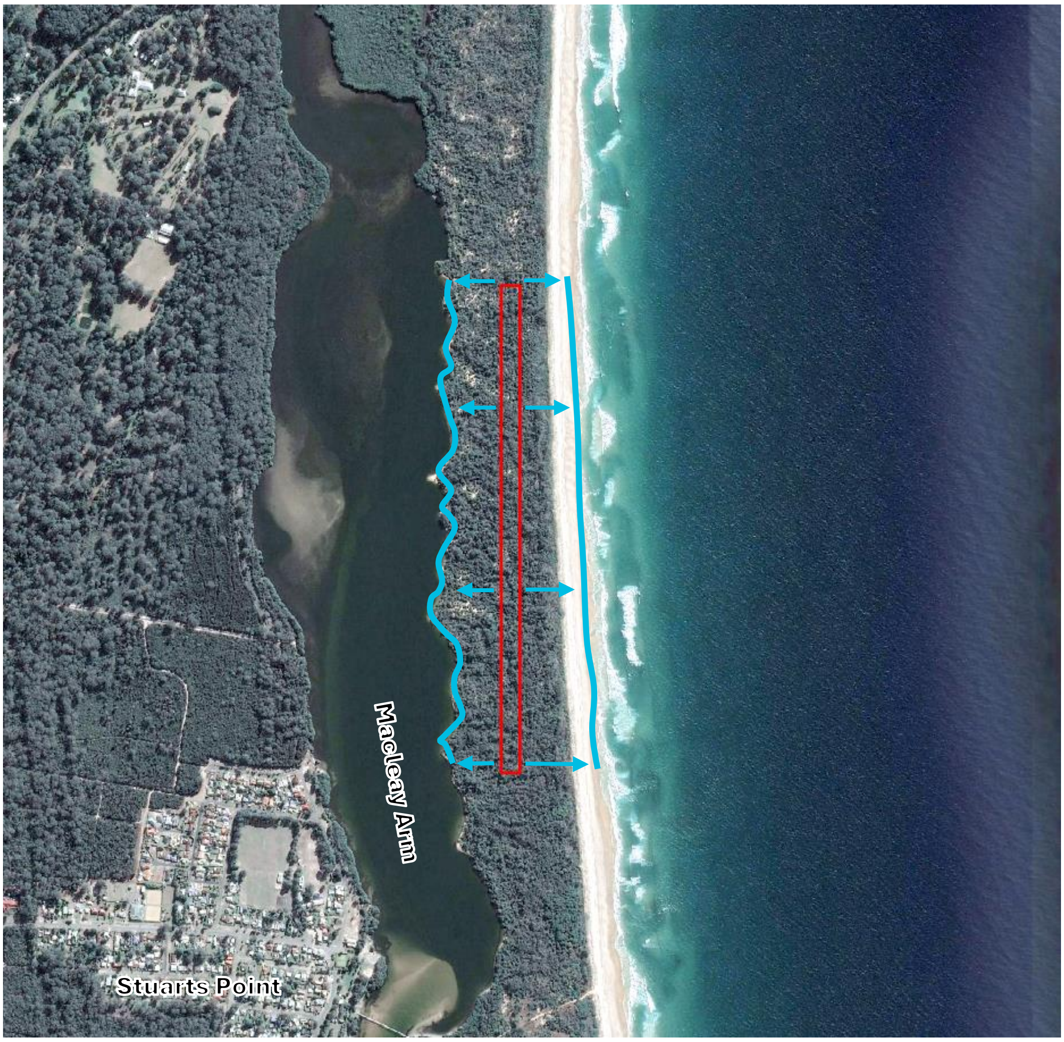


Figure 2.6 ***Dunal disposal site (red) from which simulated groundwater effluent enters the Macleay Arm and Pacific Ocean through the boundaries indicated by the blue borders***

2.5 Modelling scenarios

The hydrodynamic model was initialised with spatially varying salinity, water levels at mean sea level (MSL) across the domain, and no water currents. To ensure salinity gradients in the model domain achieved realistic dynamic conditions, the model was 'hot started' with spatially varying salinity that was extracted from a previous model run of ~3 months duration.

In order to include a range of site conditions in the flushing assessment, a total of ten simulations were run with start dates spaced 20-40 days apart over a one-year period. The simulation start dates were selected to target varying tidal states (neap/spring and flooding/ebbing or high/low tide). Further, the first flushing simulation coincides with the start of a large river flow event (beginning 25 January 2012) that allows assessment under high river flows. A summary of the flushing simulations is provided in Table 2.1.

Table 2.1 Summary of flushing scenarios

Assessment	Simulation Start Date	Simulation End Date	Tidal State at Start of Flushing Assessment
Flushing (total of 10 simulations)	25-01-2012	25-03-2012	Spring, ebbing[1]
	28-02-2012	28-04-2012	Neap, high tide
	03-04-2012	02-06-2012	Mid neap/spring, flooding
	01-05-2012	30-06-2012	Neap, flooding
	05-06-2012	04-08-2012	Spring, ebbing
	15-07-2012	13-09-2012	Neap, low tide
	19-08-2012	18-10-2012	Spring, ebbing
	18-09-2012	17-11-2012	Mid spring/neap, ebbing
	08-10-2012	07-12-2012	Neap, flooding
	01-11-2012	31-12-2012	Spring, ebbing

The groundwater discharge simulations spanned the entirety of 2012 in order to predict conditions within the Macleay Arm over a long-term period. A summary of the groundwater discharge scenarios include:

– Scenario 1: the current (2024) off-peak septic discharge of 273 kL/d (25.2 kL/d from Grassy Head, 208.4 kL/d from Stuarts Point and 39.2 kL/d from Fishermans Reach).
– Scenario 2: the projected ultimate peak holiday effluent dune disposal of 1,030 kL/d with 515 kL/d each to the Macleay Arm and the Pacific Ocean.
– Scenario 3: the projected 2047 off-peak effluent dune disposal of 693 kL/d with 346.5 kL/d each to the Macleay Arm and the Pacific Ocean.

The selection of 2012 as the simulation year was on the basis of water levels as justified in Section 3.1.

[1] This simulation aligns with the start of a large river flow event (see Section 3.1)

3. Data

3.1 Water levels

Water levels in the Macleay River are affected by tidal elevations and river flows. These factors are also the primary flushing mechanisms of the Macleay Arm.

A summary of tidal elevations at South West Rocks from MHL (2012) is presented in Table 3.1.

Table 3.1 Tidal planes for South West Rocks

Tidal Datum	Tide Level (m above Australian Height Datum)
Mean High Water Springs (MHWS)	0.591
Mean Sea Level (MSL)	0.065
Mean Low Water Springs (MLWS)	-0.461
Mean Tidal Range	0.841

Source: MHL (2012)

Measured riverine water levels were supplied by MHL for sites located at Kempsey, Smithtown and South West Rocks (Figure 3.1). The available data is plotted in Figure 3.2 to Figure 3.4 with the 2012 model period highlighted.

Water levels at the upstream site of Kempsey are tidally influenced during base flow conditions with typical water levels between -0.5 to 1 m AHD. Several large flood events occurred over the 31 year record with peak water levels between 1.5 and 7.0 m AHD. These flood events are expected to have a short-term influence on flushing times of the Macleay Arm. A summary of the frequency of such flood events on an annual basis is presented in Table 3.2. The average occurrence of flood events exceeding water levels of 1.5 m AHD is 2.2 per year. On the basis of this information, 2012 was selected as the representative year for modelling because:

– Three flood events occurred with water levels greater than 1.5 m AHD, which is slightly above the yearly average of 2.2, though two of these events with peak water levels of 3.5-4.0 m and 5.5-6.0 m were only separated by eight days during late January/early February 2012.
– The highest river level recorded during 2012 was approximately 5.5 m, which is a good representation of a typical large flood event (33 of the 68 flood events in the record had associated peak water levels of 3.0-7.0 m).
– 2012 is the second most recent year within the available water level record, which is closer in time to the available 2015-2016 ambient Macleay Arm water quality data (Section 4.2).

Table 3.2 Yearly summary of significant river flow events at Kempsey where darker shading indicates larger numbers

Year	River flow event peak water level category (m)											TOTAL
	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	6.0-6.5	>6.5	
1983	0	0	0	0	0	0	0	0	0	0	0	0
1984	1	1	0	0	0	0	0	0	0	0	0	2
1985	0	0	0	0	0	0	0	0	0	1	0	1
1986	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	2	0	0	0	0	1	1	0	0	0	4
1989	1	0	0	0	0	1	0	0	0	2	0	4
1990	5	2	0	0	1	0	2	0	0	0	0	10
1991	1	0	0	0	0	0	0	0	0	0	0	1
1992	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	1	0	0	0	0	0	0	0	1
1996	0	1	0	1	1	0	1	0	1	0	0	5
1997	1	1	0	0	0	0	0	0	1	0	0	3
1998	1	0	0	0	0	0	0	0	0	0	0	1
1999	0	0	0	0	0	0	1	0	0	0	0	1
2000	1	0	0	0	0	0	0	0	0	0	0	1
2001	0	0	0	0	0	0	0	0	0	0	1	1
2002	0	0	0	0	0	0	0	0	0	0	0	0
2003	1	0	0	0	0	0	0	0	0	0	0	1
2004	0	1	1	0	0	0	0	0	0	0	0	2
2005	0	0	0	0	0	0	0	0	0	0	0	0
2006	0	0	0	0	0	0	0	0	0	0	0	0
2007	1	1	0	0	0	0	0	0	0	0	0	2
2008	2	1	1	0	1	0	0	0	0	0	0	5
2009	4	0	0	0	0	0	0	1	1	0	0	6
2010	1	0	0	0	0	0	0	0	0	0	0	1
2011	0	0	0	2	0	0	1	1	0	0	1	5
2012	1	0	0	0	1	0	0	0	1	0	0	3
2013	2	0	0	0	0	0	1	0	3	0	2	8
AVERAGE												**2.2**

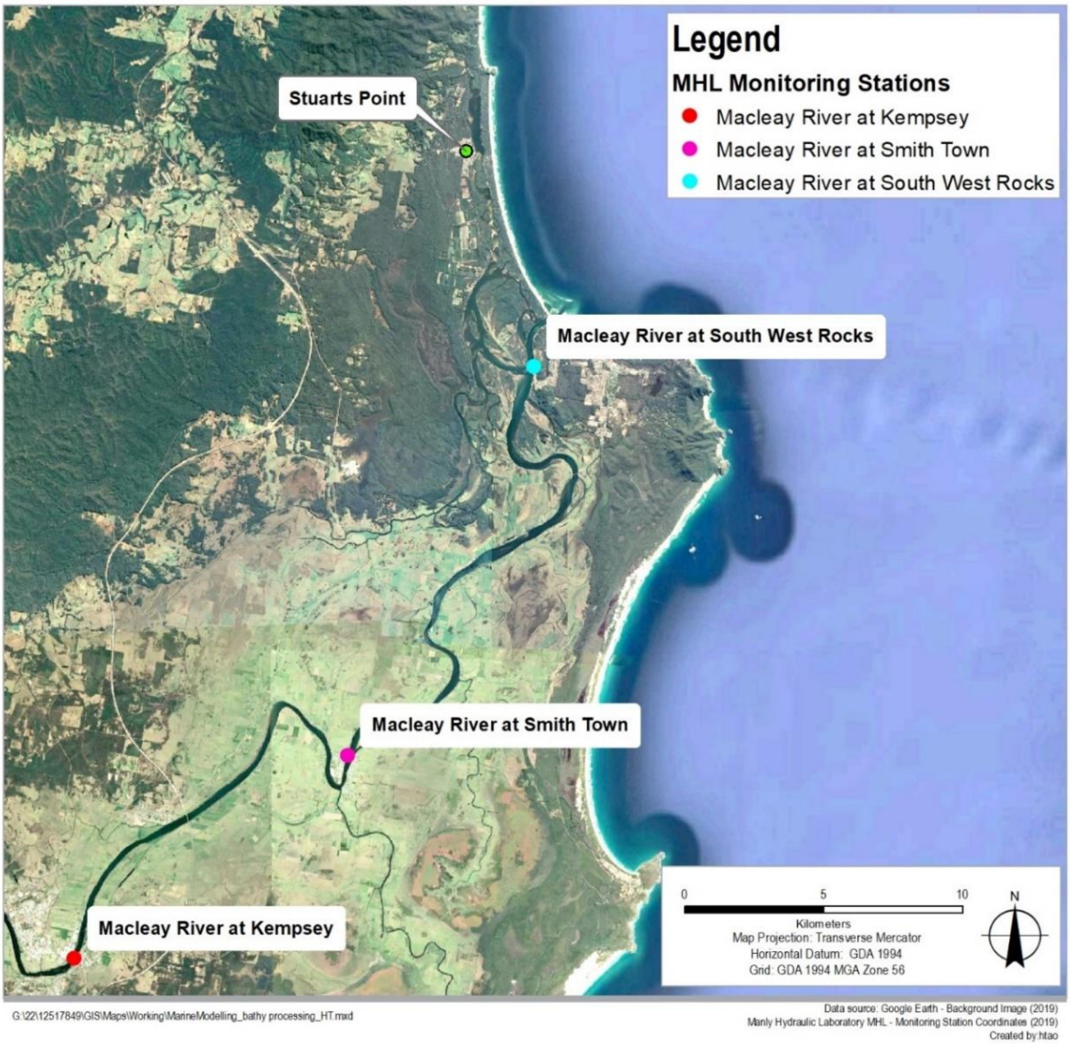


Figure 3.1 Water level measurement and proposed groundwater discharge sites

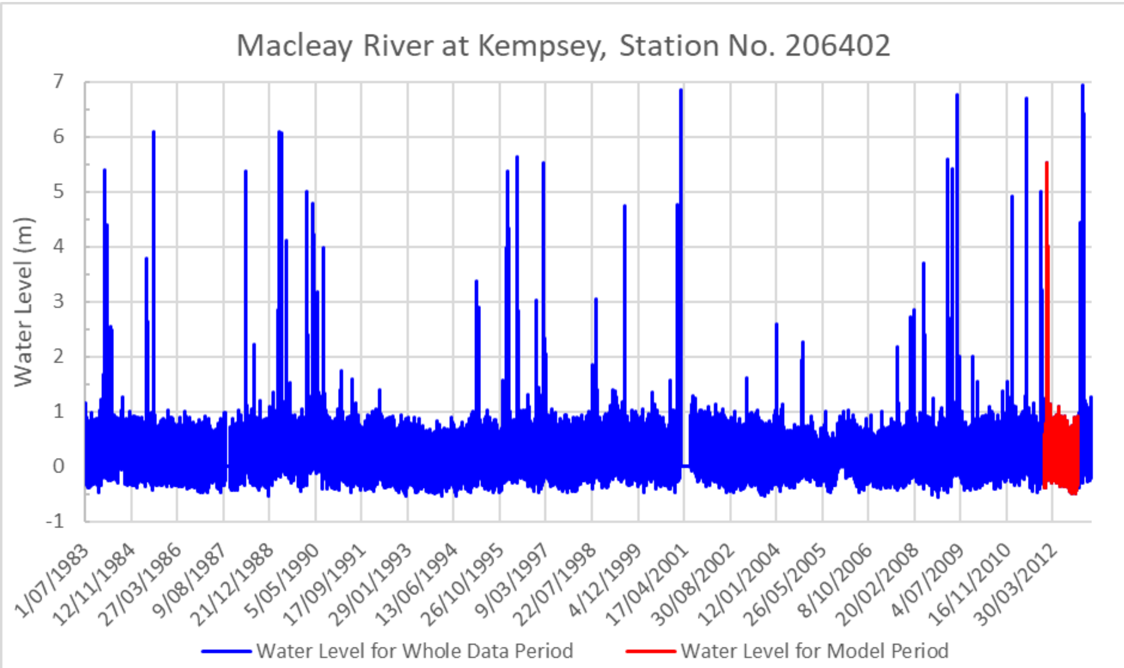


Figure 3.2 Measured water levels at Kempsey (Station No. 206402) relative to AHD (data provided by MHL)

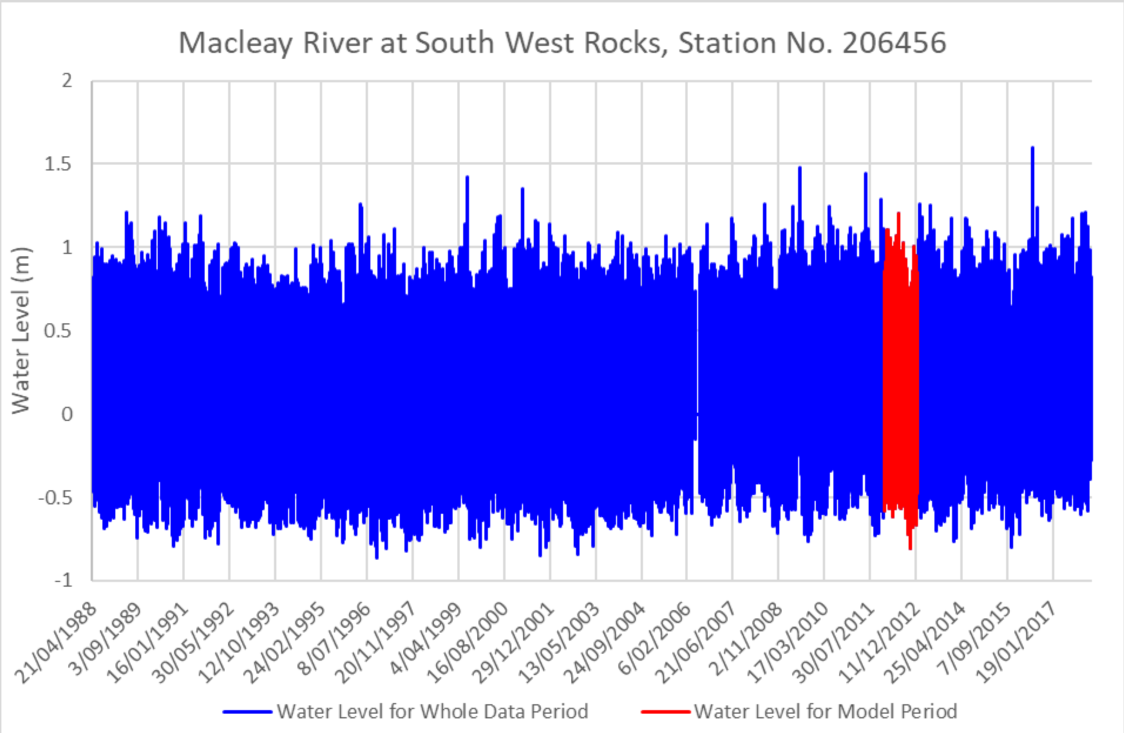


Figure 3.3 Measured water level at South West Rocks (station No. 206456) relative to AHD (data provided by MHL)

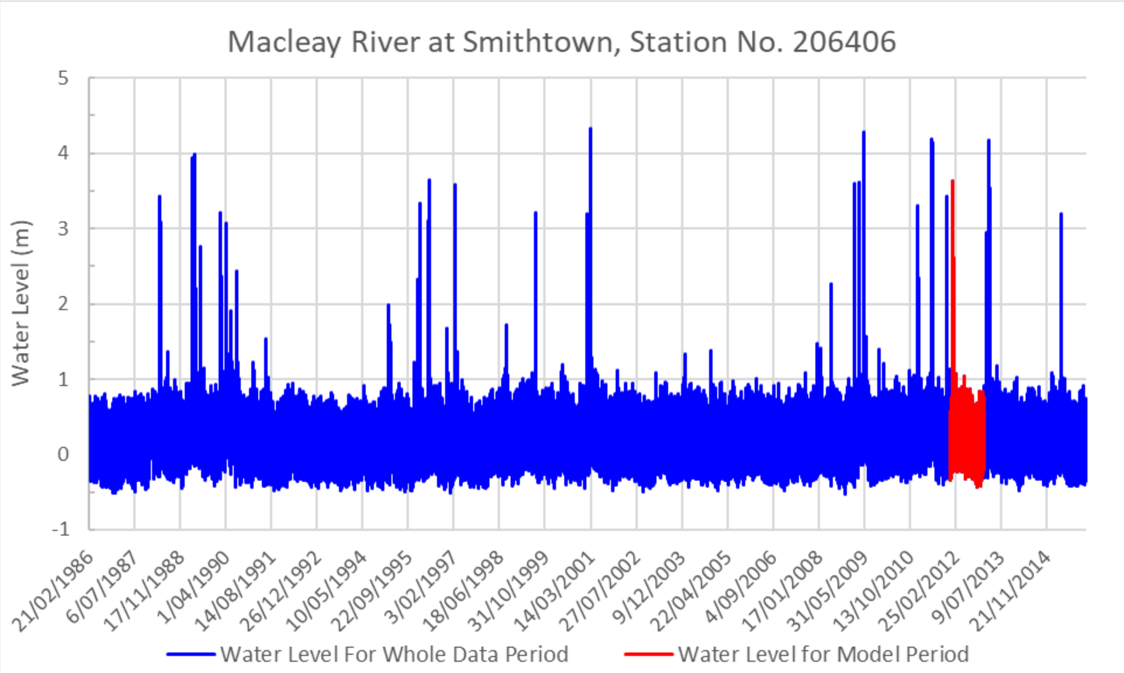


Figure 3.4 Measured water level at Smithtown (station No. 206406) relative to AHD (data provided by MHL)

3.2 Wind

Wind data was sourced from the National Centre for Environmental Prediction (NCEP) Climate Forecast System (CFSv2) (Kalnay et al. 1996; Kistler et al. 2001) to serve as temporally (hourly) and spatially (0.2°) varying model inputs for wind speed and wind direction. The wind data was applied across the surface of the model domain. Time-series wind speeds and directions extracted from a location within the centre of the model domain are presented in Figure 3.5 for the simulation period of 2012.

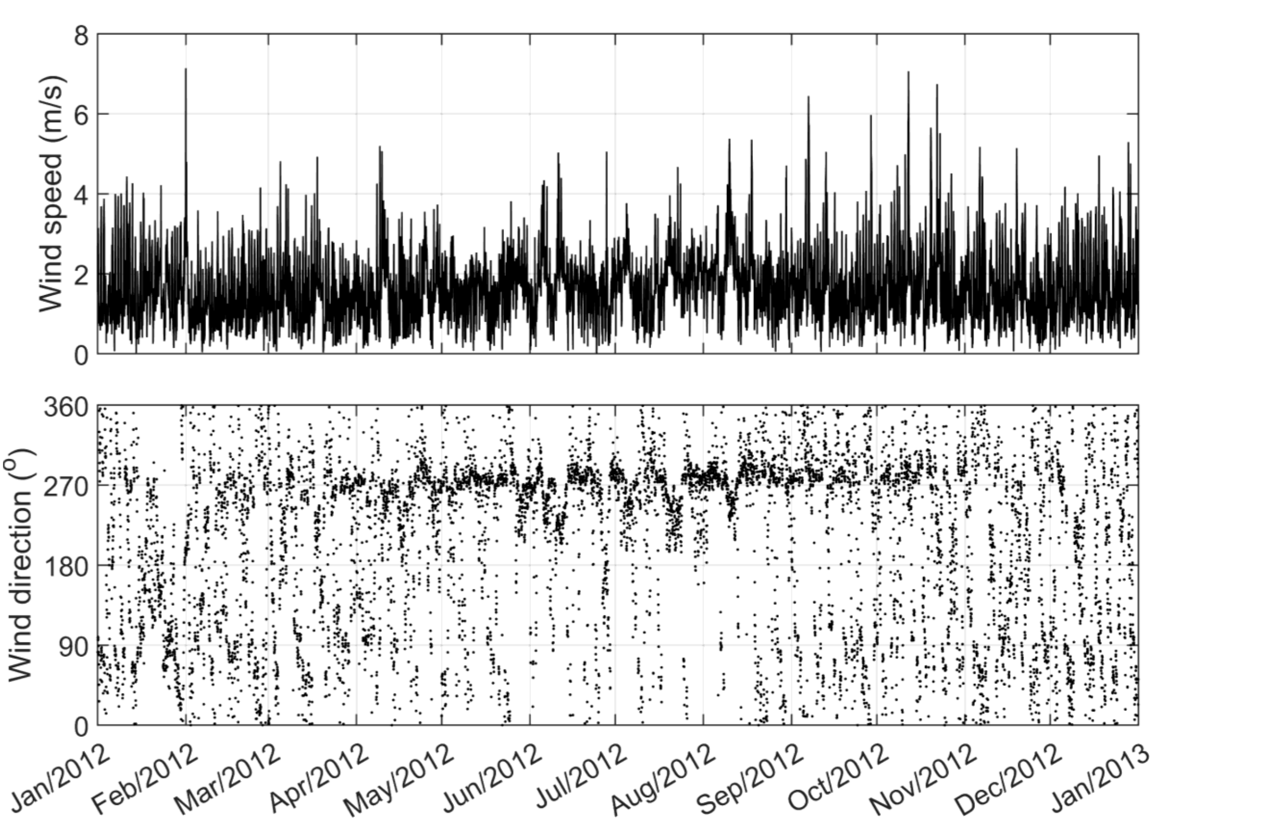


Figure 3.5 ***Time series inputs of wind speed (top) and direction (bottom) from CFSv2 with wind direction defined as the direction the wind is coming from***

3.3 Precipitation

Precipitation was also simulated to account for the effect of large rainfall events on the flushing of the Macleay Arm. The Bureau of Meteorology (BOM) daily rainfall data from South West Rocks (station number 59030) served as the model inputs.

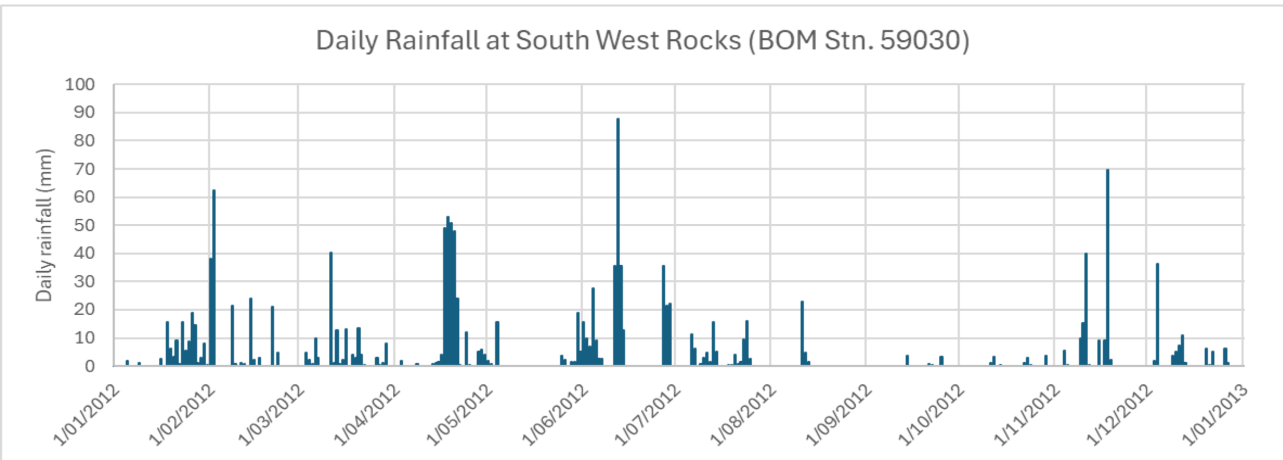


Figure 3.6 ***Daily rainfall from BOM station 59030 at South West Rocks***

3.4 Salinity

Weekly measurements of salinity spanning 2015-2019 were supplied by KSC. Salinity data for the measurement sites near Kempsey and Stuarts point are presented in Figure 3.7 and Figure 3.8, respectively.

The Kempsey site is a freshwater site with typical salinities of 0.1-0.3 ppt, and peak salinities of ~0.8-1.6 ppt. Though water levels at this site appear to be tidally influenced (Section 3.1), the salinity data indicates the estuarine 'salt wedge' does not extend upstream to this location.

The Stuarts Point site is an estuarine environment which experiences large salinity fluctuations throughout the year typically ranging between 10 to 35 ppt. A period of very high salinities of 35-50 ppt was recorded during March 2016, the cause of which is unknown. The salinity readings during this period exceed typical ocean salinities (generally 34-36 ppt), suggesting poor logger calibration.

Salinity data from Kempsey were used to define the salinity at the upstream model boundary, while salinity at Stuarts Point were qualitatively compared to the predicted model salinity as a means of qualitative model verification.

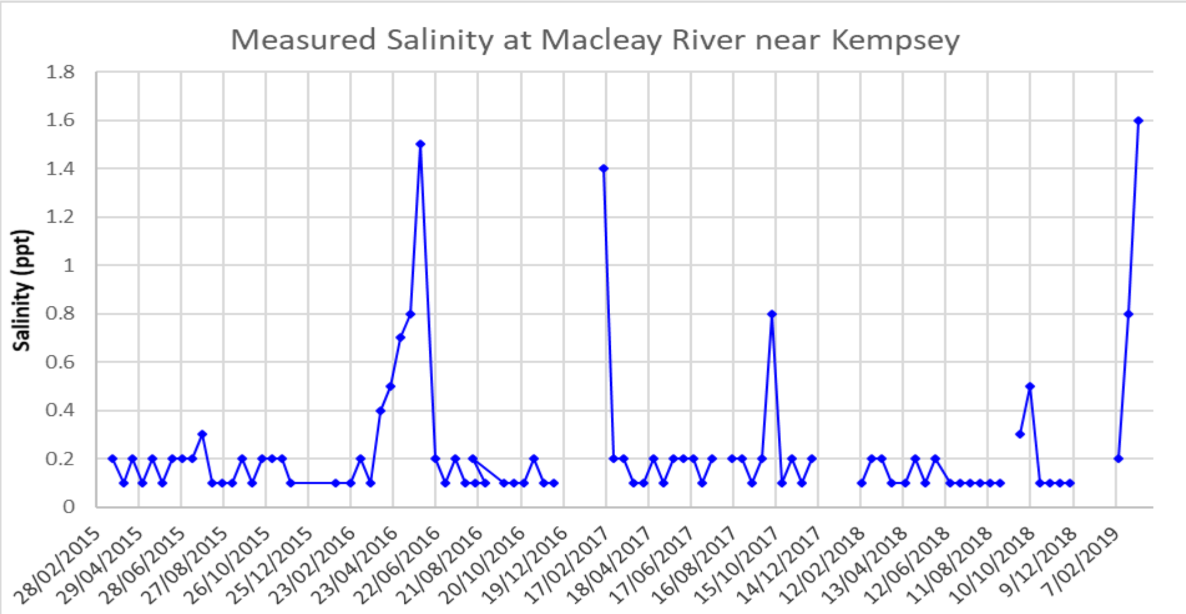


Figure 3.7 **Measured salinity at Macleay River near Kempsey**

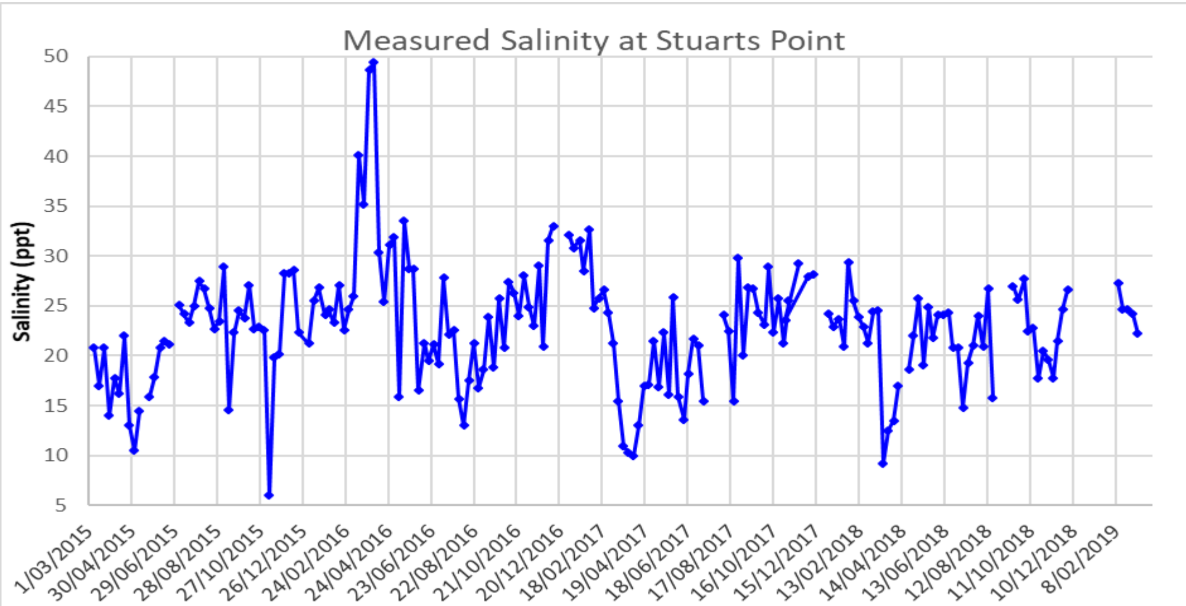


Figure 3.8 **Measured salinity at Stuarts Point**

3.5 Ambient groundwater discharge

The Stuarts Point region is characterised by shallow groundwater, which drains into the deeper sections of the Macleay Arm. Ambient groundwater flow rates into Macleay Arm were estimated via the following approach:

– A hydraulic conductivity of 0.1225 m/d was adopted as the average groundwater discharge rate. This value was calculated as the mid-point of the stated range in GHD (2019) of 0.035-0.21 m/d based on monitoring across the Stuarts Point region.
– The length of the Macleay Arm boundary whereby ambient groundwater was assumed to flow into the estuary was calculated as 55.5 km.
– A typical groundwater elevation of 1 m AHD was assumed from GHD (2019).
– The characteristic elevation of the deepest points of the Macleay Arm channels was estimated to be -1.5 m AHD through interrogation of the model bathymetry. In many locations the Macleay Arm is deeper than this, so this represents a conservative estimate on the depth of the estuary.
– The total ambient groundwater influx rate to the Macleay Arm was therefore estimated by multiplying the following:
  - The hydraulic conductivity (0.1225 m/d)
  - The length of the groundwater interface (55,500 m)
  - The characteristic depth of the groundwater interface (1 m AHD minus -1.5 m AHD = 2.5 m)

  Resulting in an estimated ambient groundwater discharge flux of ~17,000 m^3/d (0.196 m^3/s).

The groundwater flux of 0.196 m^3/s was applied to the length of the Macleay Arm boundary in MIKE 3 as a discharge boundary, meaning the flow was evenly distributed across the entire boundary. The only exceptions were the locations where groundwater effluent was simulated either from septic flows or the dunal discharge.

4. Mixing zone criteria

4.1 Groundwater effluent quality

Assessment of the quality of groundwater effluent focused on Total Nitrogen (TN) and Total Phosphorous (TP) as the primary nutrient constituents, as they can be assumed to behave in relatively conservative manner within groundwater. Other nutrient analytes such as nitrate, ammonium, filterable inorganic phosphorus and organic forms of nitrogen and phosphorus are more likely to undergo substantive fate transformations during groundwater transport and subsequently upon discharge into the Macleay Arm, thereby making estimation of their concentrations problematic. Other parameters such as Biological Oxygen Demand (BOD) and pathogen concentrations face similar issues, and are not the focus of this study. Finally, suspended solids are assumed to be largely filtered out by the natural substrate as the groundwater moves from the point of discharge towards the Macleay Arm.

Nevertheless, nitrate and ammonia were further assessed as potential toxicants in this study to predict the potential extent of more severe ecological impacts (beyond physical and chemical stress) for the scenarios assessed. Additionally, reductions in salinity were considered as a potential physical and chemical stressor, since the proposed dunal discharge may increase the flow of groundwater to the Macleay Arm and thereby reduce the salinity of the system.

BHH2O defined the groundwater quality as follows:

– Effluent from septic tanks:
  - TN = 41.25 mg/L (reduced from a concentration of 55.0 mg/L through biological and physiochemical action in the soils assuming these processes account for 25% loss). TN is assumed to be entirely comprised on ammonia, as nitrates are not expected to be present in septic effluent, while particulate N is assumed to be filtered out within the soil.
  - TP = 9.37 mg/L (reduced from 12.5 mg/L after 25% losses).

– Effluent entering the dunal discharge system following treatment:
  - TN = 6 mg/L.
  - TP = 0.6 mg/L.
  - Ammonia = 1.5 mg/L.
  - Nitrate = 4.5 mg/L.

No losses or transformations of TN or TP were assumed to occur within the groundwater effluent plume from the dunal discharge.

The salinity of the septic effluent and dunal discharge effluent was assumed to be 1 PSU.

4.2 Ambient Macleay Arm water quality

Ambient water quality sampling was undertaken in the Macleay Arm for the Macleay Ecohealth Project 2015-2016 (Ryder et al., 2016). KSC provided this raw water quality data. Six water quality samples were collected during this project from April 2015 to February 2016. The nearest site to the proposed Stuarts Point dunal discharge site is designated as site ID NAMR2 (Ryder et al., 2016), which is located approximately 340 m to the south. Summary water quality statistics from this site for TN and TP are presented in Table 4.1. Furthermore, the summary salinity statistics for Stuarts Point from the KSC weekly sampling data (Section 3.4) are included. Ambient measurements of ammonia in the Macleay Arm were not available.

Table 4.1 Summary statistics of nutrients from the Macleay Ecohealth Project 2015-2016 and salinity from the KSC weekly sampling data

Parameter	Min	20th Percentile	Median	80th Percentile	Max
TN (µg/L)	146.4	164.1	247.9	313.6	1,398.3
TP (µg/L)	20.9	29.2	52.4	78.8	79.7
NOx (µg/L)	13.6	25.1	98.6	119.0	266.9
Salinity (PSU)	6.0	17.9	22.9	26.7	33.7

4.3 Water quality guidelines

4.3.1 Default trigger values – physical and chemical stressors

ANZECC & ARMCANZ (2000) defines default trigger values for physical and chemical stressors for south-east Australian estuaries. These values are presented in Table 4.2. Comparison to the ambient water quality data (Table 4.1) indicates that the default trigger values are frequently exceeded within the Macleay Arm in approximately 20% of the TN samples and approximately 80% of the TP samples.

In these instances, where pre-existing conditions frequently exceed the default guidelines, it is necessary to define site-specific trigger values in order to derive water quality objectives that maintain the existing ecosystem condition without placing further stress on the system.

It is noted that the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZG, 2018) does not include updated default guideline values for TN and TP and therefore defers to ANZECC & ARMCANZ (2000).

Table 4.2 Default trigger values for nutrients as physical/chemical stressors

Parameter	ANZECC & ARMCANZ (2000) default trigger value	Trigger value basis (from ANZECC & ARMCANZ [2000])
TN (mg/L)	0.30	Physical and chemical stressors – south east Australian estuaries
TP (mg/L)	0.03	Physical and chemical stressors – south east Australian estuaries

4.3.2 Default guideline values – toxicants

ANZG (2018) defines default guidelines values (DGVs) for ammonia and nitrate as toxicants in both marine and freshwater for ammonia, and freshwater for nitrate. Due to the estuarine nature of the Macleay Arm, the freshwater values were adopted in both cases, being the most conservative value available for ammonia and the only option available for nitrate. The 95% level of species protection values were adopted as an appropriate assessment level due to the moderately disturbed nature of the Macleay Arm. The toxicant DGVs are outlined in Table 4.3.

Table 4.3 Default trigger values for nutrients as physical/chemical stressors

Parameter	ANZG (2018) DGV	DGV basis from ANZG (2018)
Ammonia (mg/L)	0.9	Freshwater toxicant DGV for 95% level of species protection recommended for slightly to moderately disturbed ecosystems
Nitrate (mg/L)	1.1 [2]	Freshwater toxicant DGV for 95% level of species protection recommended for slightly to moderately disturbed ecosystems

[2] Assuming soft water (<30 mg/L $CaCO_3$), which yields the most conservative DGV

4.3.3 Site-specific guideline values

ANZG (2018) provide guidance on the derivation of site-specific guideline values ('reference-site approach') on the basis of natural statistical variability. For discrete measurements, ANZG (2018) specifies data collected over 2 years of monthly sampling are sufficient to indicate ecosystem variability. The six samples collected for the Macleay Ecohealth Project do not satisfy this criterion, though the span of the samples from April 2015 to February 2016 does incorporate a degree of seasonality. In the absence of further available data, and noting that many of the values already exceed the default trigger values, these data are adopted as baseline data for deriving site-specific guideline values.

ANZG (2018) defines a default site specific guideline value as the 80th percentile of background water quality for slightly or moderately disturbed ecosystems. The 80th percentile concentrations of TN and TP from the Macleay Ecohealth Project (Table 4.1) were considered as alternatives to the default trigger values.

The same approach is applied for the salinity data (Section 3.4), which includes weekly samples over ~5 years of monitoring (satisfying the ANZG [2018] data requirements). For the low salinity groundwater discharge, a salinity decrease (rather than increase) in the Macleay Arm is the potential impact of concern. As such, the 20th percentile ambient salinity is adopted as the site-specific trigger value (rather than the 80th used for the nutrients).

4.3.4 Final selected guideline values

The final selected guideline values were:

– Physical and chemical stressors:
  - **0.30 mg/L for TN** from ANZECC & ARMCANZ (2000), which was only marginally lower than the calculated site-specific guideline value of 0.31 mg/L and was therefore considered a reasonable value.
  - **0.08 mg/L for TP** as a site-specific guideline value, given the significant difference to the default trigger value of 0.03 mg/L the default value is not considered appropriate for this particular system.
  - **17.9 PSU for salinity** as a site-specific guideline value representing the lower range (20th percentile) of ambient salinity in Macleay Arm.

– Toxicants:
  - **0.9 mg/L for ammonia** as a freshwater toxicant from ANZG (2018).
  - **1.1 mg/L for nitrate** as a freshwater toxicant from ANZG (2018).

4.4 Effluent dilution requirements

The level of dilution of the groundwater effluent required to meet the water quality guidelines was initially assessed in order to understand:

– The differing dilution requirements of the septic seepage relative to the proposed treated wastewater effluent to the dunal system.

– Which physical and chemical stressor (TN, TP or salinity), requires the highest level of dilution and is therefore the focus of the assessment of physical and chemical stress.

– Similarly, which toxicant (ammonia or nitrate) requires the highest level of dilution to define the toxicity mixing zone.

The dilution at the edge of the mixing zone (D_{MZ}) required to achieve a water quality trigger values (C_{TV}) is calculated as:

$$D_{MZ} = \frac{C_{GW} - C_{AMB}}{C_{TV} - C_{AMB}}$$

Where C_{GW} is the representative groundwater effluent concentration and C_{AMB} is the median ambient receiving waters concentration.

Dilution targets in Table 4.4 were calculated from the above equation, where inputs for:

– C_{GW} are the projected groundwater effluent quality in Section 4.1.

– C_A are the median ambient water quality in Section 4.2.

– C_{MZ} are the adopted trigger values based in Section 4.3.4.

For seepage from septic tanks and effluent from the dunal discharge, TN requires greater dilution to meet the water quality guideline for physical and chemical stressors. Therefore, this modelling assessment focuses on TN to assess the extent of the zone of physical and chemical stressors. Further, as expected, the septic tank seepage requires a much greater dilution to meet the water quality guideline (786 dilutions for TN) compared to the treated effluent from the dunal discharge (111 dilutions for TN), which has a significantly reduced discharge concentration.

It is important to recognise that the adopted TN trigger value adopted does not represent acute or chronic toxic effects, but rather the potential for increased biological productivity that poses a eutrophication risk if exceeded for extended periods of time. Therefore, the adopted dilution target is not a 'mixing zone' criterion in the typical sense (i.e. acute of chronic effects on estuarine organisms), but rather a trigger value for stimulated ecosystem productivity (e.g. increased algal concentrations). The toxicity mixing zone is defined by ammonia for the septic tank effluent that requires 55 dilutions to meet the toxicant DGV, and nitrate for the dunal discharge that requires only 4 dilutions to meet the toxicant DGV.

Table 4.4 Dilution requirements at the edge of the mixing zone

Parameter	Impact category	Groundwater Quality (C_{GW})	Ambient Quality (C_A)	Mixing Zone Criteria (C_{MZ})	Dilution Required at MZ Edge (D_{MZ})
Septic tank groundwater effluent					
TN (mg/L)	Physical & chemical stressors	41.25	0.25	0.30	**788.5**
TP (mg/L)		9.37	0.05	0.08	345.3
Salinity (PSU)		1	22.9	17.9	4.4
Ammonia (mg/L)	Toxicants	41.25	0.15 [3]	0.9	**54.7**
Nitrate (mg/L)		0	0.1	1.1	0
Dunal discharge groundwater effluent					
TN (mg/L)	Physical & chemical stressors	6	0.25	0.30	**110.6**
TP (mg/L)		0.6	0.05	0.08	20.3
Salinity (PSU)		1	22.9	17.9	4.4
Ammonia (mg/L)	Toxicants	1.5	0.15 [3]	0.9	1.8
Nitrate (mg/L)		4.5	0.1	1.1	**4.4**
Colour Legend:					
Median of water quality data					
Default trigger values from ANZECC & ARMCANZ (2000)					
Site-specific guideline values					
Toxicant DGV from ANZG (2018)					

[3] Ambient measurements of ammonia not available, so assumed to be equivalent to TN minus nitrate

5. Results

5.1 Model verification

The model performance was assessed via comparison of simulated and predicted water levels at South West Rocks (Figure 5.2) and Smithtown (Figure 5.3) as described in Section 2.2. Generally, the model performance was good whereby:

– The model performance as indicated by the IOA was excellent for both sites, with values exceeding 0.9.

– The MAE was 0.15 m and South West Rocks and 0.21 m at Smithtown. Simulated water levels were typically higher than the measurements, however the statistical range of the simulated water levels (as indicated by the percentile distribution plots) is similar to the measurements in both cases indicating the model is representing the tidal amplitude well (the primary factor influencing flushing of the Macleay Arm).

No measurements of salinity were available during 2012 for direct comparison to the model, however a qualitative comparison of the simulated salinity at Stuarts Point (Figure 5.1) indicates the simulated range (~12-23 PSU) is within the typical range of measured salinity during 2015-2019 of 10-35 PSU (Section 3.2). The influence of the flooding event during late January and February is evident in the simulated salinity time-series (salinity reduces over this period and slowly increases for the remainder of the year), indicating that these events are likely to have some influence on the flushing rates of the Macleay Arm.

Table 5.1 Calibration statistics for water level (WL) at Macleay River near South West Rocks and Smithtown

Model Performance Statistic	WL at Macleay River near South West Rocks	WL at Macleay River Smithtown
MAE (m)	0.15	0.21
IOA	0.93	0.91

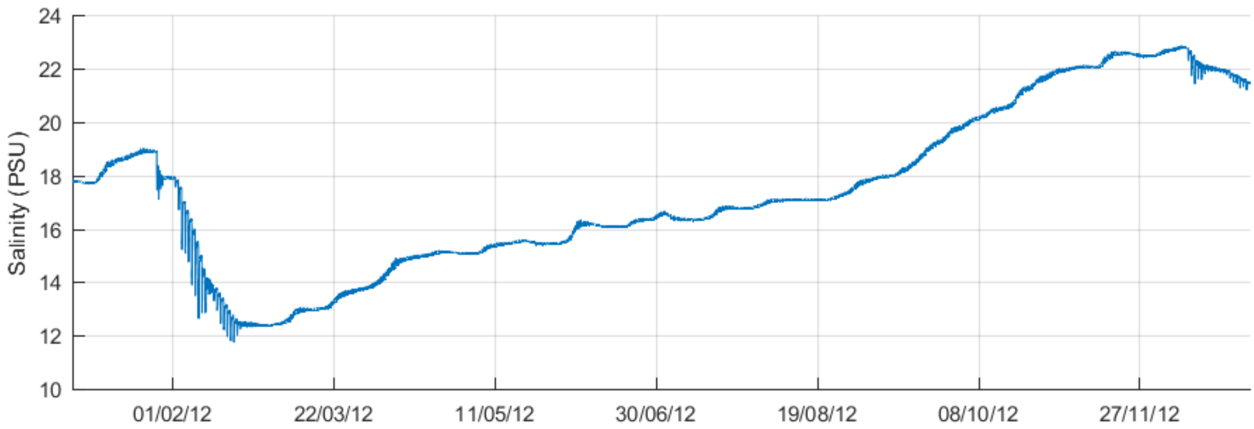


Figure 5.1 Simulated salinity at Stuarts Point

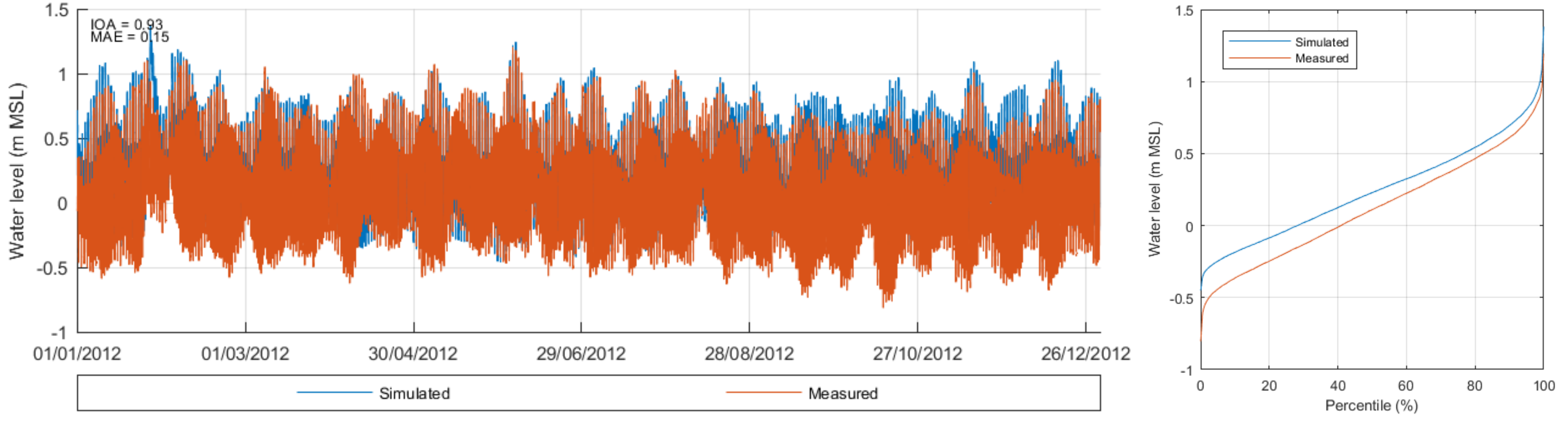


Figure 5.2 ***Simulated and measured water level at Macleay River near South West Rocks (left panels: time-series, right panels: percentile distributions)***

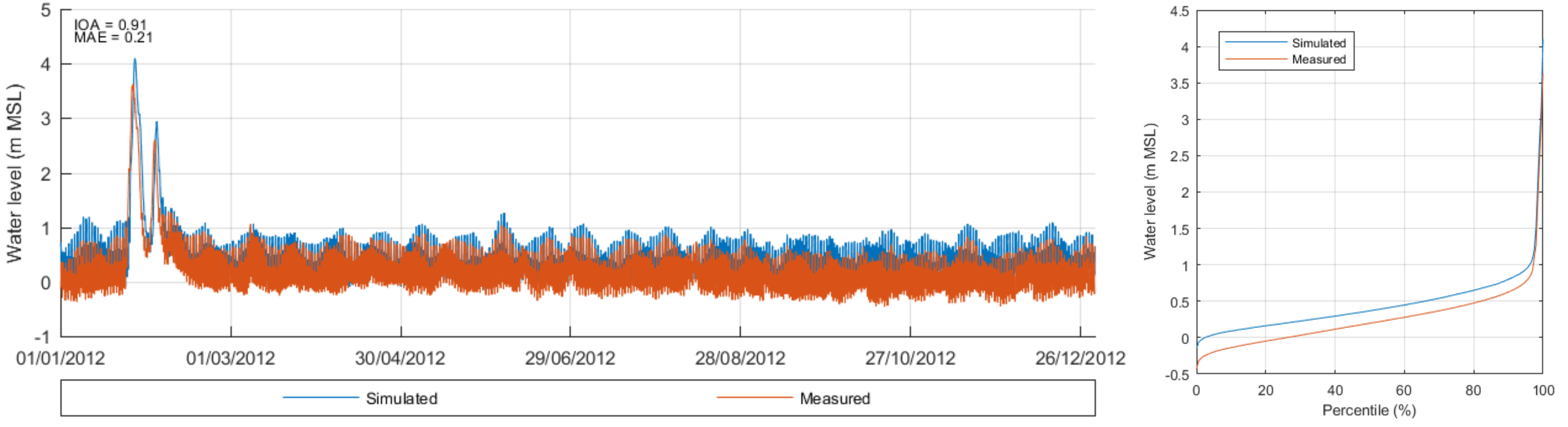


Figure 5.3 ***Simulated and measured water level at Macleay River near Smithtown (left panels: time-series, right panels: percentile distributions)***

5.2 Flushing

Flushing rates were evaluated for ten different simulations with start dates spread throughout the simulated year as described in Section 2.3. The e-folding flushing timescale was calculated for the control volumes of Stuarts Point and the Macleay Arm for each of the simulations. An example of this calculation process is presented in Figure 5.4 for the Stuarts Point control volume during the flushing simulation beginning 5 June 2012.

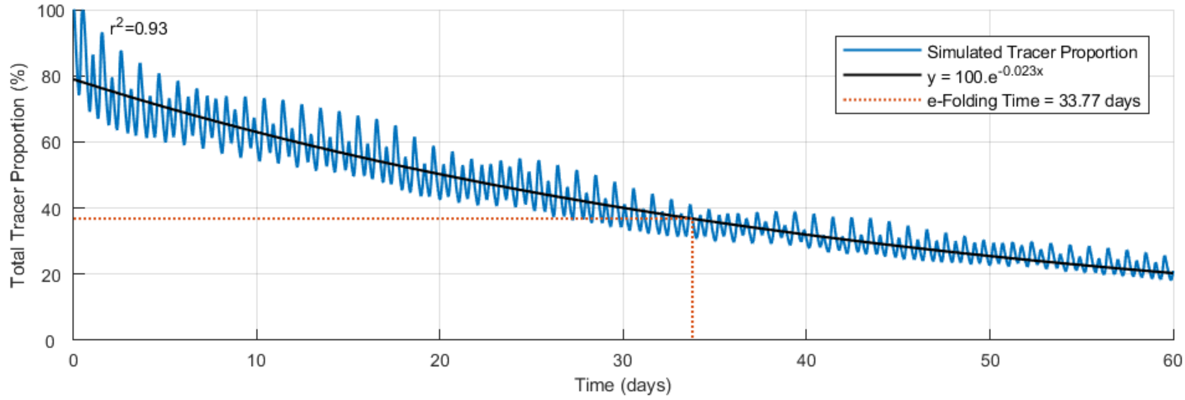


Figure 5.4 Example e-folding calculation for Stuarts Point

The full range of flushing times for the Macleay Arm and Stuarts Point control volumes are presented graphically in Figure 5.5. Indications of the tidal state (spring, neap, neap tide transitioning to spring tide [neap/spring] or spring tide transitioning to neap tide [spring/neap]) and the flood event beginning in late January are also marked on the figure.

For both control volumes, the first flushing simulation aligning with spring tides and the river flood event produced the shortest e-folding flushing times. During the remainder of the year, flushing rates are driven by tidal exchange.

The Macleay Arm is predicted to have e-folding flushing timescales ranging from ~10 days to ~28 days. The tidal state at the start of the simulation has a strong influence on the flushing rate of this control volume, with spring tides resulting in e-folding times of ~10-12 days and the weaker neap tides resulting in e-folding times of ~23-28 days.

The Stuarts Point control volume located at the north of the Macleay Arm had longer predicted e-folding flushing timescales of ~28 days during the flood event, and 34-37 days for all other simulations. The tidal state has less of an influence on this control volume which is further removed geographically from the point of tidal exchange at the Macleay River outlet to the ocean.

The flushing timescales of weeks to months for the two control volumes indicate relatively long residence times of the water within the Macleay Arm system. This suggests the potential for poor water quality to arise if groundwater (or any other source) loading rates of pollutants or chemical stressors are greater than the low rates of simulated flushing to transport these constituents to the ocean.

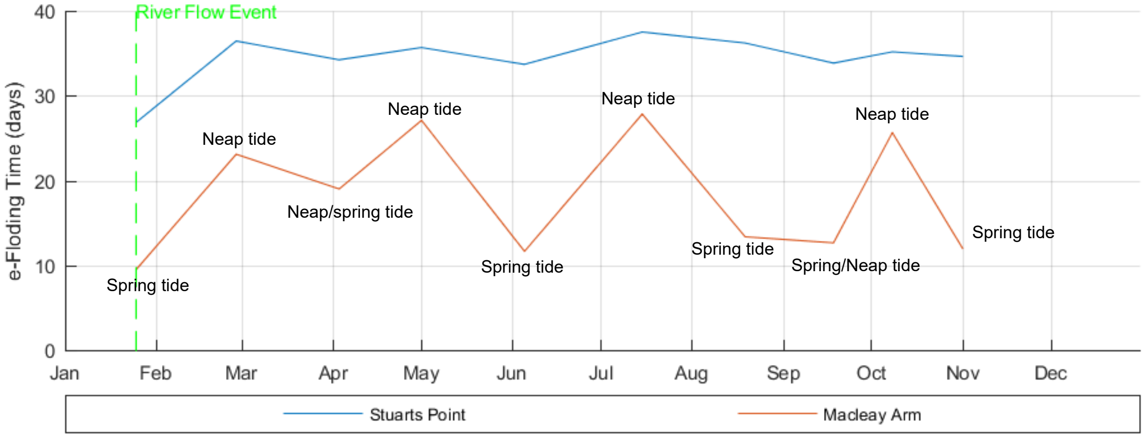


Figure 5.5 e-folding flushing time-scales (x-axis represents flushing simulation start date). Tidal state at the start of the simulation is indicated on the figure

An example figure of the spatial variability of e-folding times is presented in Figure 5.6. This output is calculated in the same manner as previously described, but is done for every cell individually within the control volume. Similar spatial patterns are observed for all scenarios, so only one example is provided. This output indicates that the deeper portions of the Macleay Arm extending from Fishermans Reach to the confluence with the Macleay River in the south are much more rapidly flushed (5-10 days) compared to the remaining stretches of the Macleay Arm with flushing rates in the range of 10-60 days. This is due to the greater connectivity of this southern portion to the Macleay River, through which the tidal exchange is driven.

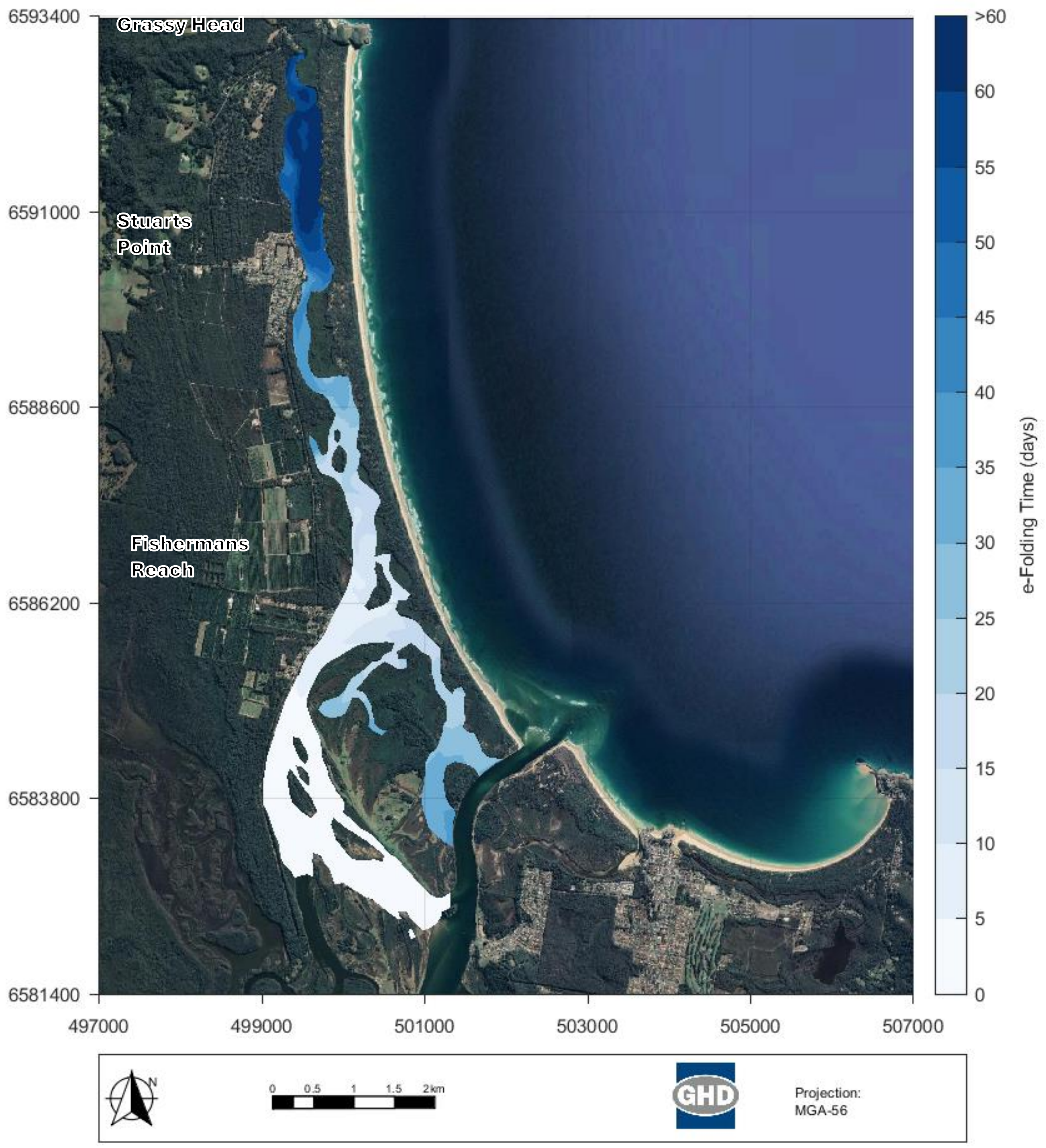


Figure 5.6 Spatial variability of e-folding times for the Macleay Arm control volume, simulation beginning 3 April 2012

5.3 Groundwater effluent scenarios

To recap, the discharge of groundwater effluent into the Macleay Arm has been simulated for three scenarios:

– Scenario 1: the current (2024) off-peak septic discharge of 273 kL/d (25.2 kL/d from Grassy Head, 208.4 kL/d from Stuarts Point and 39.2 kL/d from Fishermans Reach) with a TN concentration of 41.25 mg/L (assumed to be comprised entirely of ammonia).
– Scenario 2: the projected ultimate peak holiday effluent dune disposal of 1,030 kL/d with 515 kL/d each to the Macleay Arm and the Pacific Ocean and a TN concentration of 6 mg/L and nitrate concentration of 4.5 mg/L.
– Scenario 3: the projected 2047 off-peak effluent dune disposal of 693 kL/d with 346.5 kL/d each to the Macleay Arm and the Pacific Ocean and a TN concentration of 6 mg/L and nitrate concentration of 4.5 mg/L.

For the two future scenarios, it is assumed that the WWTP will replace the need for septic tanks, so the septic flows are inactive. Nevertheless, the ambient water quality within the model domain, which is informed by measurements from the Macleay EcoHealth Program that are influenced by nutrient loads from septic inflows, is assumed to remain unchanged.

TN dispersion was modelled for the entire year of 2012 with a conservative numerical tracer with effluent concentrations as described above, and an ambient concentration of 0.25 mg/L. The adopted water quality guideline to be achieved for TN is 0.3 mg/L.

Additionally, ammonia as a toxicant was modelled for scenario 1, while nitrate as a toxicant was modelled for scenarios 2 and 3, as these parameters require the greatest levels of dilution in the respective scenarios to achieve the toxicant DGVs. For scenario 1, ammonia was simulated at an effluent concentration of 41.25 mg/L, ambient concentration of 0.15 mg/L and a target DGV of 0.9 mg/L. For scenarios 2 and 3, nitrate was simulated at an effluent concentration of 4.5 mg/L, ambient concentration of 0.1 mg/L and a target DGV of 1.1 mg/L.

5.3.1 Outcomes at Macleay Arm

5.3.1.1 Zone of physical and chemical stress

Spatial plots of the statistical median and maximum predicted TN concentrations (assessed as a physical and chemical stressor) throughout Macleay Arm are presented in Figure 5.7 and Figure 5.8, respectively, for all three scenarios. To aid the interpretation of these figures, the median contours represent the values that are predicted to be exceeded at any particular location for 50% of the time, while they are lower for the other 50% of the time. The maximum contours simply present the highest concentration that occurred at any location throughout the one-year simulation.

The results clearly demonstrate that the future scenarios with the dunal effluent discharge result in a significant reduction in nutrient loads (modelled as TN) to the Macleay Arm relative to the existing septic tank seepage scenario:

– For the existing septic tank arrangement (scenario 1), predicted TN exceeds 0.3 mg/L across nearly the entire 10 km length of Macleay Arm with the following specific outcomes:
  - At the poorly flushed, northern-most reaches of the Macleay Arm where the Grassy Head septic tank seepage source enters the model domain, median and maximum TN concentrations exceeded 1 mg/L.
  - At the boundary of Stuarts Point, median and maximum TN concentrations were ~0.5 mg/L and >1 mg/L, respectively.
  - At Fishermans Reach, which is situated within a much more rapidly flushed region of the Macleay Arm (see Figure 5.6), the effect of the septic tank seepage on Macleay Arm water quality is much less pronounced with predicted median TN concentrations below the 0.3 mg/L guideline, and maxima of ~0.35-0.4 mg/L.
– For the ultimate peak holiday effluent dune disposal (scenario 2), the median extent of TN exceeding 0.3 mg/L was confined to within the upper ~2 km of Macleay Arm and was not predicted to exceed 0.4 mg/L. The maximum predicted concentrations were also predicted to be less than 0.4 mg/L, and extended approximately 5 km southward before reducing below 0.3 mg/L.

– For the 2047 off-peak effluent dune disposal (scenario 3), which represents more likely future flows for the majority of the time, the median TN concentration was not predicted to exceed 0.3 mg/L anywhere within the model domain. In effect, this means that the dilution required to reduce the TN concentration to below 0.3 mg/L occurred within the spatial scale of one model cell (~30 m) from the groundwater effluent discharge boundary. The maximum predicted concentrations were 0.3-0.35 mg/L and confined to within ~150 m westward distance from the discharge boundary.

In summary, significant reductions in TN concentrations are predicted following the decommissioning of the septic tanks and replacement with the wastewater treatment and dunal discharge strategy. Further, the spatial extents of TN concentrations exceeding the guideline value of 0.3 mg/L are predicted to be significantly reduced.

5.3.1.2 Toxicity mixing zone

The toxicity mixing zone is defined by ammonia for scenario 1 and nitrate for scenarios 2 and 3. The spatial extent of this zone is conservatively assessed based on the maximum predicted concentration throughout the one-year simulation, as shown in Figure 5.9.

Only scenario 1, with highly elevated ammonia concentrations in the septic effluent, was predicted to produce exceedances of the toxicity DGVs within Macleay Arm, although these occurred only in highly localised areas along the groundwater interface near Grassy Head and Stuarts Point. Since no exceedances were modelled for scenarios 2 and 3, the nitrate toxicity DGV was predicted to be achieved within the spatial scale of one model cell (<30 m) from groundwater effluent discharge at Grassy Head, Stuarts Point and Fishermans Reach.

In short, the reduced nutrient load within the dunal discharge is predicted to effectively mitigate potential toxic impacts within Macleay Arm, even though these are only predicted to occur infrequently and in highly localised areas at Grassy Head and Stuarts Point under the current septic tank arrangement.

	Scenario 1 - Current (2024) off-peak septic discharge – 273 kL/d	Scenario 2 - Ultimate peak holiday effluent dune disposal– 1,030 kL/d [4]	Scenario 3 - 2047 off-peak effluent dune disposal – 693 kL/d [4]

Median TN concentrations

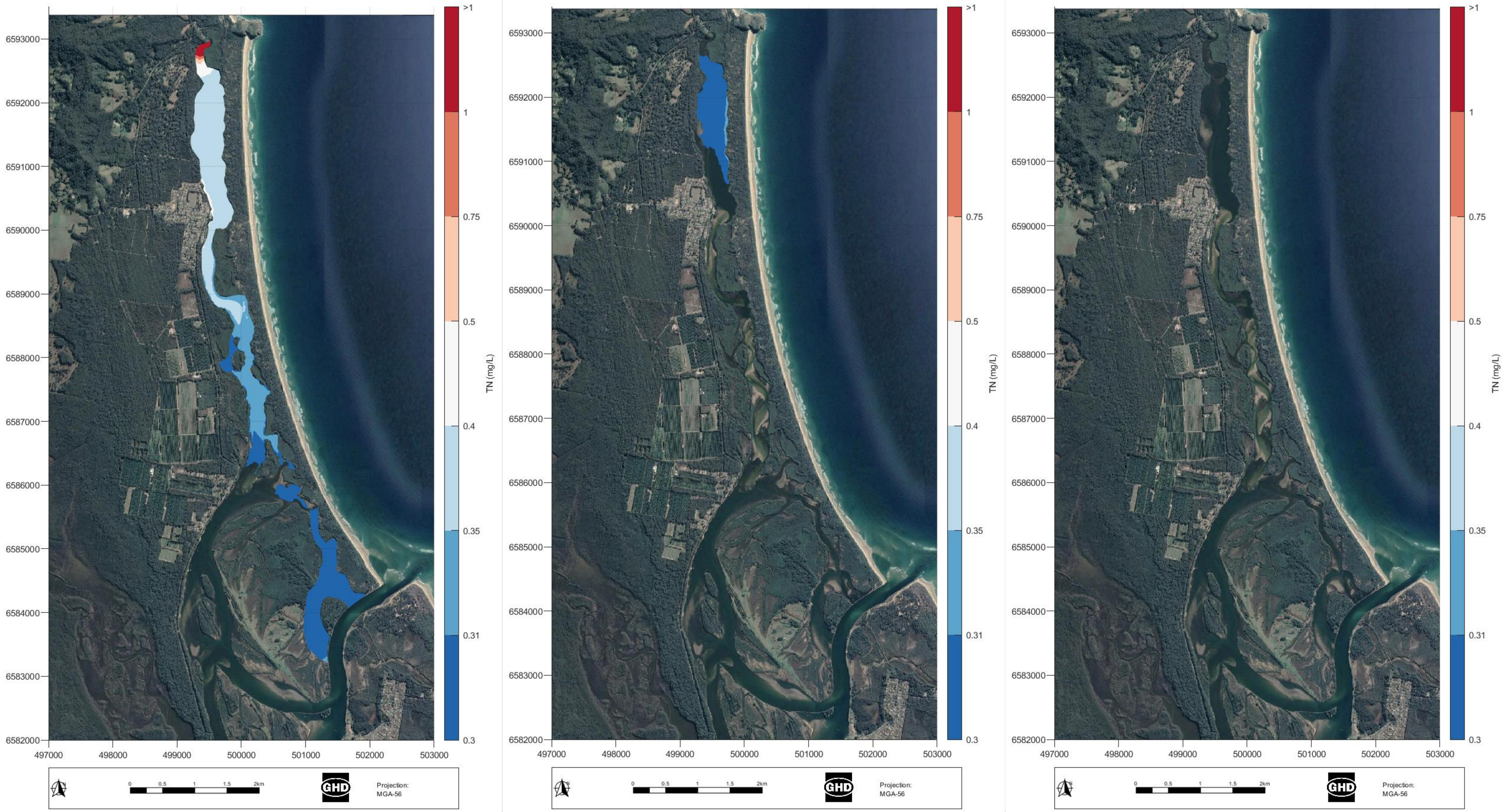


Figure 5.7 Spatial plots of the statistical median of predicted TN concentrations within Macleay Arm from scenario 1 (left), scenario 2 (middle) and scenario 3 (right). The blank contours for scenario 3 indicate the median predicted concentrations were always below 0.3 mg/L

[4] Only 50% of the flow is simulated to reach Macleay Arm, while the other 50% flows to the ocean

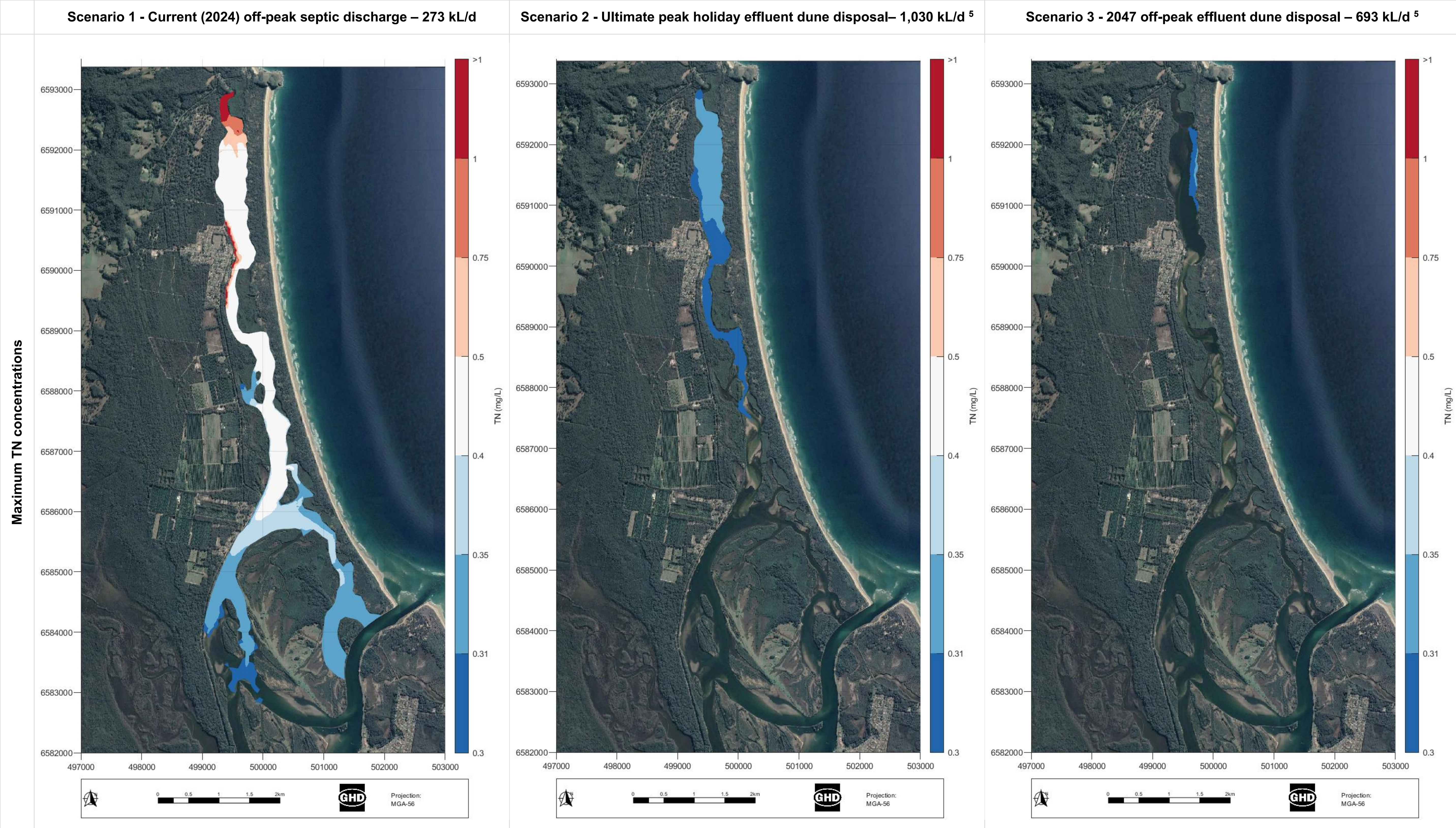


Figure 5.8 ***Spatial plots of the statistical maximum of predicted TN concentrations within Macleay Arm from scenario 1 (left), scenario 2 (middle) and scenario 3 (right)***

[5] Only 50% of the flow is simulated to reach Macleay Arm, while the other 50% flows to the ocean

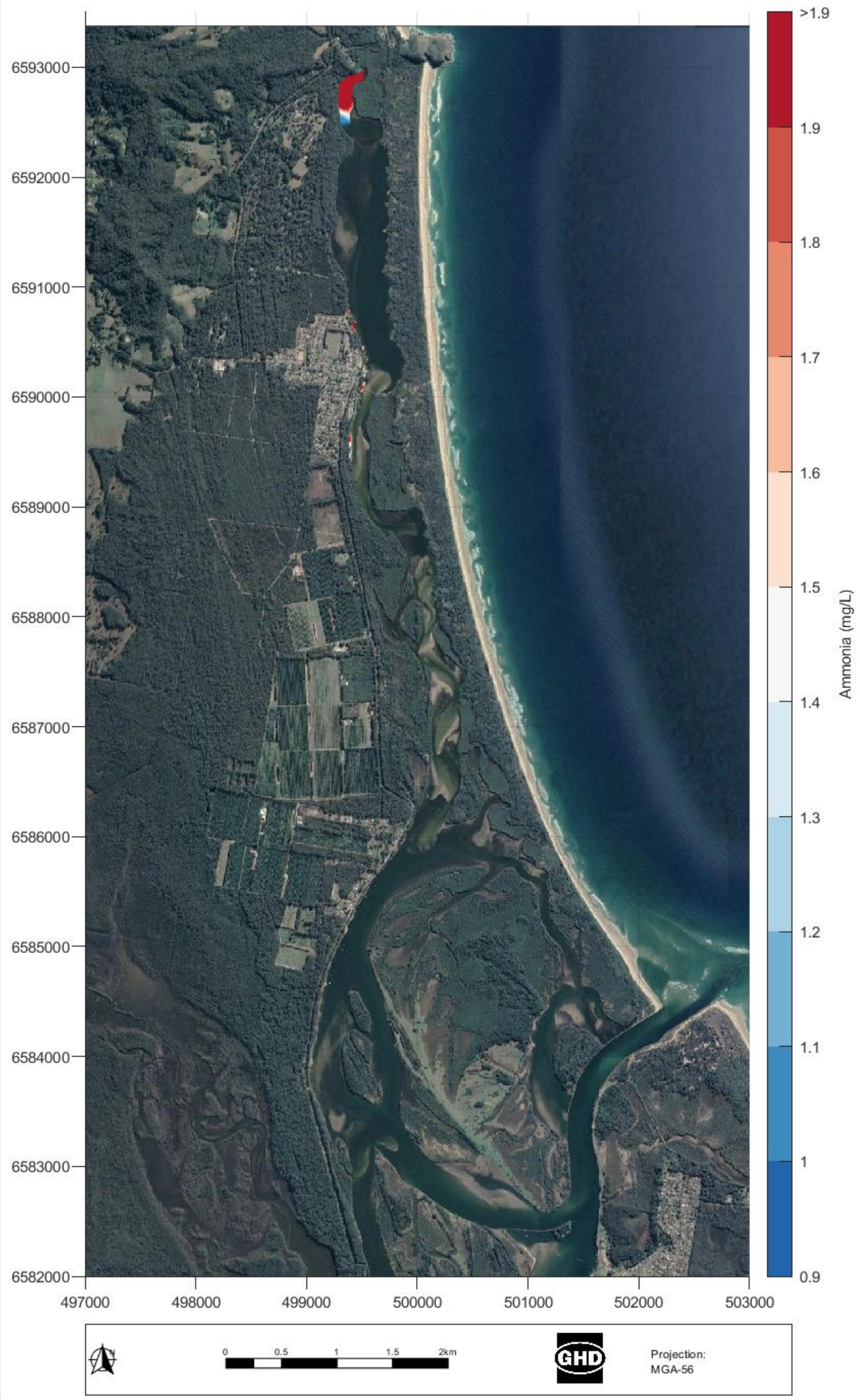
	Scenario 1 - Current (2024) off-peak septic discharge – 273 kL/d	Scenario 2 - Ultimate peak holiday effluent dune disposal– 1,030 kL/d [6]	Scenario 3 - 2047 off-peak effluent dune disposal – 693 kL/d [5]
Maximum toxicant concentrations		No predicted exceedance of the toxicity DGVs	No predicted exceedance of the toxicity DGVs

Figure 5.9 Spatial plots of the statistical maximum of predicted toxicant concentrations, namely ammonia for scenario 1 (left) and nitrate for scenarios 2 and 3 (no predicted toxicity, as shown middle and right)

[6] Only 50% of the flow is simulated to reach Macleay Arm, while the other 50% flows to the ocean

5.3.2 Outcomes at the Pacific Ocean

5.3.2.1 Zone of physical and chemical stress

Scenarios 2 and 3 for the proposed dunal effluent discharge strategy will likely result in groundwater effluent flows to the ocean. The flushing of the coastal waters east of the dunal discharge is significantly more rapid than that of the Macleay Arm. Hence, it is only necessary to evaluate the maximum TN concentration to determine the outcome of these scenarios.

The maximum predicted TN concentration for scenario 2 is presented in Figure 5.10, which shows exceedances of the guideline value only within a few localised model cells along the coast. These exceedances were not present on the 95th percentile output (not shown), indicating they occurred for less than 5% of the time in this simulation.

There was no predicted exceedance of the guideline value within the Pacific Ocean as a result of the dunal discharge for scenario 3 (not shown).

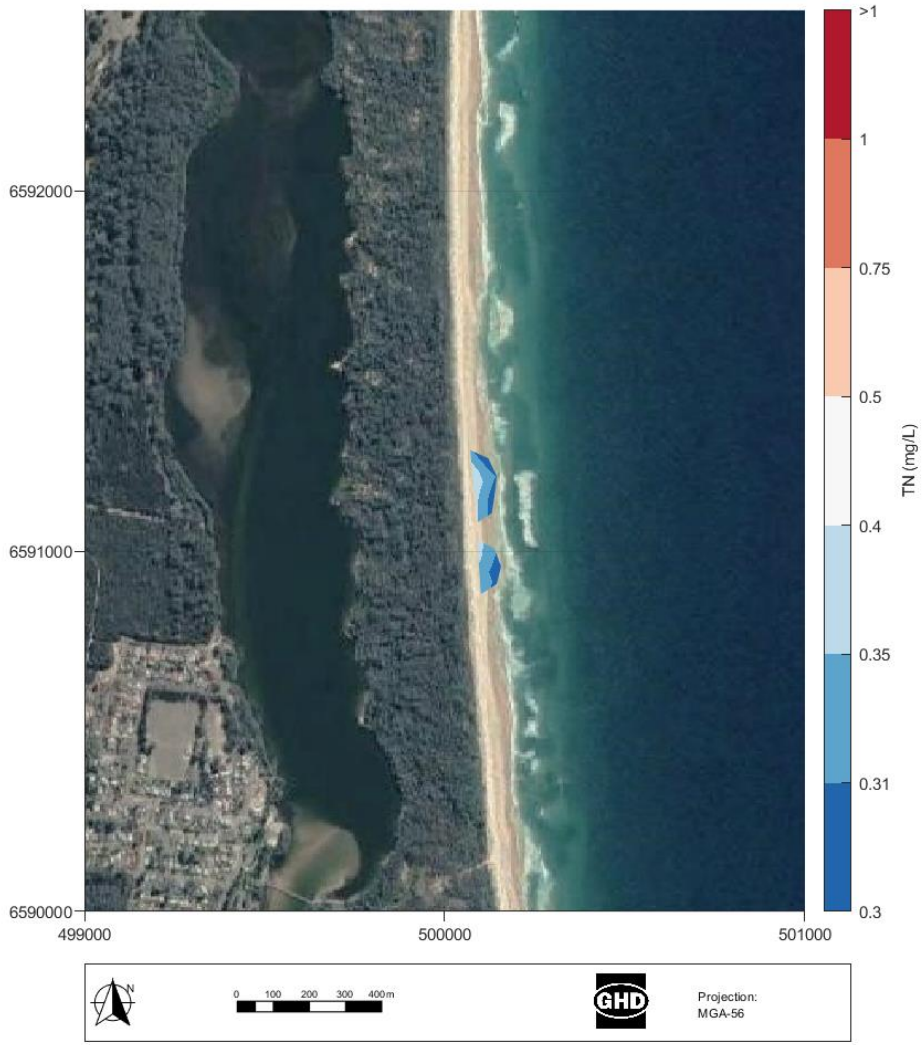


Figure 5.10 Spatial plot of the statistical maximum of predicted TN concentrations at the Pacific Ocean from Scenario 2

5.3.2.2 Toxicity mixing zone

No toxicity mixing zone resulting from ammonia or nitrate within the groundwater effluent flowing to the Pacific Ocean was predicted for either scenario 2 or 3, due to the low dilution target to meet the toxicity DGV (4 dilutions) and the rapid flushing rate of the coastal environment.

6. Conclusions

Flushing rates of the Macleay Arm system and the dispersion of groundwater effluent comprising TN as a physical and chemical stressor, and ammonia and nitrate as toxicants, were assessed via 3D hydrodynamic modelling.

The following conclusions resulted from this study:

- The flushing rates of the Macleay Arm control volume (as estimated by the e-folding timescale) are predicted to range between 10 to 28 days depending on tidal state and river flow events. The deeper portions of the Macleay Arm extending from Fishermans Reach to the confluence with the Macleay River are much more rapidly flushed compared to the remaining stretches of the Macleay Arm that have a greater separation distance from the tidal exchange through the Macleay River opening with the ocean.
- The flushing rates of the Stuarts Point control volume were less influenced by tides and river flow events as this portion of the estuary is further removed geographically from the Macleay River estuarine region. As such, longer flushing timescales of ~28-37 days were predicted for this control volume.
- For the existing septic tank arrangement (scenario 1), TN greater than 0.3 mg/L is predicted to extend across nearly the entire 10 km length of the Macleay Arm with concentrations above 1 mg/L at times near the relatively poorly flushed areas of Grassy Head and Stuarts Point.
- Significant TN reductions are predicted following the decommissioning of the septic tanks and replacement with the wastewater treatment and dunal discharge strategy. Maximum predicted TN under this arrangement was less than 0.4 mg/L, and extended only ~2 km under the ultimate peak holiday flow rate (scenario 2), and was localised to within 150 m westward distance from the discharge boundary for the 2047 off-peak effluent dune disposal (scenario 3), which represents more likely future flows for the majority of the time.
- Minimal impacts to the Pacific Ocean are predicted following establishment of the dunal discharge system, with only within a few localised model cells along the coast predicted to exceed 0.3 mg/L TN under ultimate peak holiday flow rates, and this occurred less than 5% of the time.
- Ammonia exceeding toxic concentrations for the existing septic tank arrangement was only predicted to occur infrequently and in highly localised zones within the Macleay Arm at Grassy Head and Stuarts Point. The dunal discharge arrangement was predicted to be effective in mitigating any potential toxicity risks to the Macleay Arm related to either ammonia or nitrate via reduced loads of these constituents (relative to the septic effluent). Further, no toxicity impacts to the Pacific Ocean were predicted.

In summary, the Stuarts Point Wastewater Treatment and dunal disposal project is predicted to result in significant reductions in nutrient loading within the Macleay Arm following establishment of effluent treatment and decommissioning of the existing septic tanks.

7. References

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