DEPARTMENT OF PLANNING, INDUSTRY & ENVIRONMENT

Towards safer swimming – Terrigal region

Terrigal Bay, Terrigal Lagoon and Avoca Lagoon stormwater catchment audit

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Authorship and citation

This document was prepared by Colin Johnson.

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Contents

List of tables

List of figures

Summary

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 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.

To identify and prioritise the locations of the major potential sources of sewer inputs to receiving water via the stormwater networks, we measured enterococci concentrations throughout stormwater networks of the major sub-catchments during multiple wet weather events. Major drain outlets and their upstream stormwater networks were identified and prioritised according to their estimated enterococci loads.

The swimming waters of Terrigal Bay and Terrigal and Avoca lagoons are heavily impacted by sewage contamination following rainfall. This has been the primary driver of poor recreational water quality ratings reported by statewide swimming risk monitoring. Sewage is being delivered indirectly to the bay and lagoons via the stormwater network. This report provides maps showing the parts of the drain network that are the highest priority for remediation by council.

The very large enterococci concentrations and proportions of raw sewage estimated suggest that even in moderate flows there is substantial contribution of sewage that can be best explained by a significant input from sewerage overflow points or substantial system failure, rather than small-scale leaks and infiltration. Remediation must focus on identification of potential sources of large-scale inputs in addition to small-scale cross connections, leaks and breakages.

This research has led to the identification of the major biological sources of faecal bacteria and indicates regions in the sewage/stormwater drainage system where likely 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.

Background

Central Coast Council, in partnership with Beachwatch, monitors and reports 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. 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, 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 the NSW Department of Planning, Industry and Environment (DPIE) and 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 Central Coast Council in conjunction with University of Technology Sydney. This is Report #9 and is one of nine technical reports that describe the results of the NSW Government's Terrigal Water Quality Audit research.

Objectives

Human sewage from public or private sources entering the network of stormwater drains during wet weather is the main source of faecal contamination and the principal cause of poor recreational water quality at Terrigal Beach, the Haven and Terrigal and Avoca lagoons (Reports 1, 2 and 5). However, the areas in the drainage network where sewage contaminates stormwater are unknown. This information is needed to focus investigation and remediation efforts in the catchment and to implement cost and time efficient management strategies to resolve water quality issues at the beach and lagoons.

The objectives of this report are to:

- identify specific stormwater networks within sub-catchments of Terrigal Beach, the Haven, Terrigal Lagoon and Avoca Lagoon that produce the greatest microbial loads to their respective receiving waters
- produce maps locating priority areas for further investigation of sewerage and stormwater infrastructure to implement remedial actions.

Methodology

Previous work (Reports 1, 2 and 5) has demonstrated that most faecal contamination of waters near the drains that were sampled on the Central Coast was human, and human sewage markers and enterococci levels were strongly correlated. Although enterococci can potentially survive and proliferate in the environment without faecal inputs (Byappanahalli et al. 2012), because they are easily culturable they are considered valuable indicators of faecal contamination around the world. In our case, the demonstrated strong link between enterococci and human sewage markers validates the use of enterococci concentrations to trace likely sewer infiltration in this study. We acknowledge that potential environmental reservoirs of enterococci may contribute to measured concentrations in some instances, but evidence from the previous work would suggest that this is a small source of uncertainty.

To identify and prioritise the locations of the major potential sources of sewer inputs to receiving water via the stormwater networks, we measured enterococci concentrations throughout stormwater networks of the major sub-catchments during multiple wet weather events. Major drain outlets and their upstream stormwater networks were identified and prioritised according to their estimated enterococci loads. This was calculated by multiplying the mean enterococci concentration during a rainfall event by the volume of water discharged into receiving waters. Prioritised major drain outlets and their upstream stormwater networks were further sampled at accessible locations on the network's upstream branches. Branches within the network were then prioritised in order of branches with the highest enterococci concentrations.

Site selection

At Terrigal Beach and the Haven there are six stormwater outlets discharging directly into bay waters. In Terrigal and Avoca lagoons there are 34 and 36 stormwater outlets (respectively) discharging directly into their waters. All six stormwater outlets discharging into Terrigal Bay, and a subset of 23 and 20 outlets in Terrigal Lagoon and Avoca Lagoon respectively were assessed as potential sources of microbial pollutants.

Selection of major stormwater outlets to be assessed was based primarily on their catchment size as well as their proximity to swimming locations and sewerage infrastructure. Upstream sites in the Terrigal Bay catchment were located where there was access to network junctions within the catchments of selected drains. Within lagoon catchments, additional upstream sites were focused on network junctions within the catchments of drains that had persistently high enterococci concentrations or loads in the first three sampling rounds (ALD6, ALD16, TLD4, TLD5, TLD6, TLD10, TLD19 and TLD20).

Due to the steep topography and relatively small sub-catchments of the stormwater systems assessed at all locations, sampling was only possible in wet weather as there was little to no base flow in most of the assessed drains.

Rainfall event sampling

Six major drain outlets and 41 upstream catchment locations in Terrigal Bay, 22 drain outlets in Terrigal Lagoon and 20 drain outlets in Avoca Lagoon were sampled by DPIE staff and Central Coast Council staff during rain events on 12 October 2019 (30.5 mm), 18 January 2020 (44 mm) and 7 February 2020 (152 mm) (Figures 1 and 2). A further 25 upstream locations in the Terrigal Lagoon catchment were sampled on 30 April (5.5 mm) and 14 (44.5 mm), 22 (5 mm) and 26 (12.5 mm) May 2020. Drain outlets and five upstream sites in the Avoca Lagoon catchment were also sampled on 14, 22 and 26 May 2020 (Figures 1 and 2). During sampling, estimates of instantaneous flow rates were obtained by measuring stream dimensions and current velocity.

From November 2019, flow loggers (Sontek IQ, Xylem Inc.) were installed on the three incoming branches at the stormwater junction adjacent to the sewer pump station at Ash Street, the largest stormwater sub-catchment in Terrigal Bay draining about 53% of the land area of Terrigal CBD and the Haven (Figure 2B). Flow loggers in the two major arms (TSD and TBD2) at this junction were run in tandem with automated water samplers (SCU Smart Auto Sampler) that collected discrete water samples each time drain water level changed by 2 centimetres throughout a rainfall event. The autosamplers are equipped to keep enterococci samples chilled until collection. Flow loggers and autosamplers were installed in January 2020 and were operational during wet weather events on 18 January and 7 February 2020.

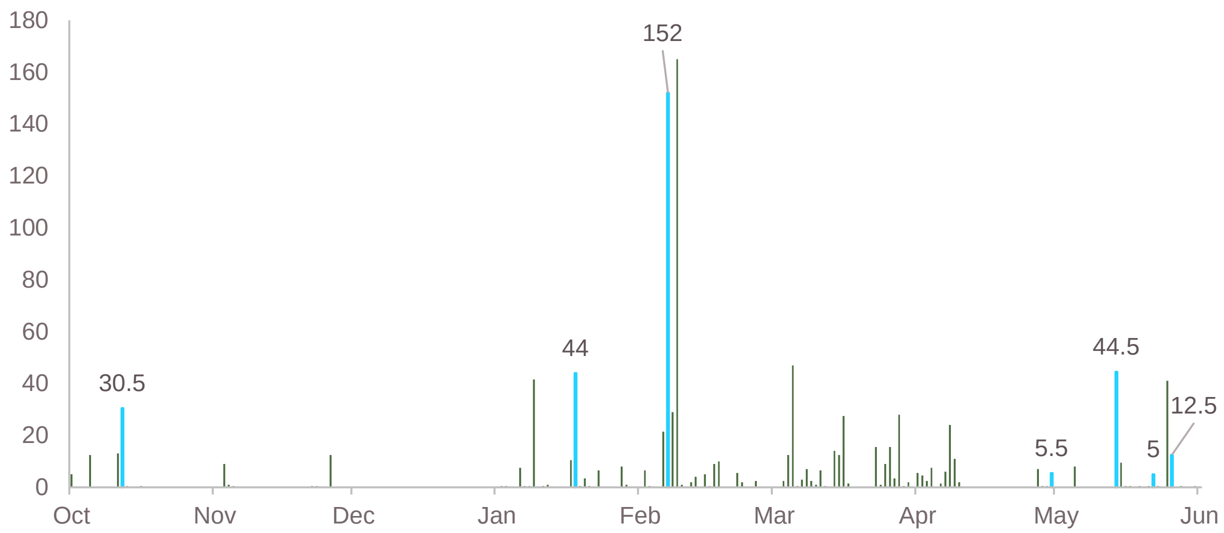

Figure 1 **Daily rainfall at Kincumber, sampling days are shown in blue with daily rainfall (mm) above**

Autosamplers at Terrigal, upstream on seven drains. Photo: DPIE

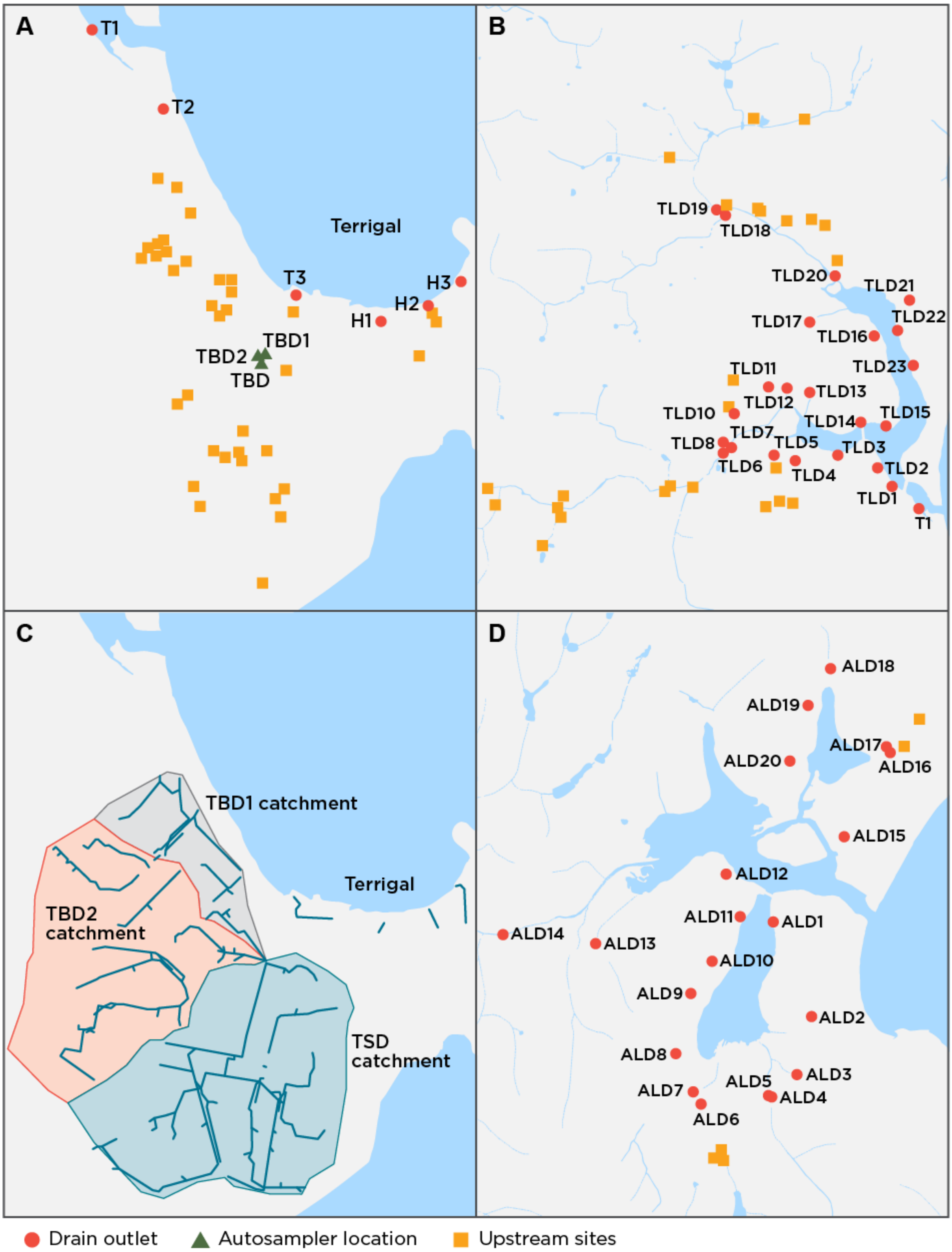

Figure 2 Maps of A: Terrigal Bay, ~~B: Major sub-catchments of Terrigal CBD, C~~B: Terrigal Lagoon, C: Major sub-catchments of Terrigal CBD, D: Avoca Lagoon, showing stormwater catchment sampling sites assessed during the 2019–20 sampling campaigns

Enterococci sample collection and analysis

Enterococci samples were collected in sterile polypropylene jars using aseptic techniques during hand sampling at drain outlets and when transferred from autosamplers. Between uses, autosampler tubing and sample bottles were sterilised in 10% bleach for 20 minutes, rinsed in milliQ water and air dried. All water samples for enterococci enumeration were stored on ice after sampling and were delivered to laboratories for analysis within eight hours of collection. Enterococci levels were obtained using Enterolert™ (ISO 7899-1) testing, assessed in a laboratory under the ISM-Quality Assurance for Microbiology program at Charmhaven and Kincumber wastewater treatment plants.

Catchment prioritisation

Outlets were ranked based on both enterococci loads and enterococci concentrations. Loads are indicative of the magnitude of contamination and concentrations can be used to determine sites with the greatest impact on enterococci load and proximity of contamination source to the sampling point.

All assessed stormwater outlets were ranked according to average wet weather enterococci loads across all sampled events (Table 1). Equivalence of raw sewage is estimated based on an indicative enterococci count of 524,000 cfu/100 mL[1] in raw sewage (Srinivasan et al. 2011).

Table 1 Enterococci load criteria for determining stormwater outlet priority ranks, and equivalent raw sewage flow rates

Priority rank	Enterococci load (‘000,000 cfu/s)	Equivalent flow of raw sewage *
1	>100	>20 L/s
2	10–100	2–20 L/s
3	5–10	1–2 L/s
4	1–5	0.2–1 L/s
5	0.5–1	0.1–0.2 L/s
6	<0.5	<0.1 L/s

* assuming all enterococci inputs are from sewage

Outlets and upstream sites throughout the Terrigal Bay and lagoon catchments were then ranked according to mean wet weather enterococci concentrations during sampling from October 2019 to May 2020 during moderate (5–45 mm) rainfall events. Due to the unusually heavy rainfall during the 7 February wet weather event (152 mm over 24 hours), enterococci concentrations during this one in 30-year flood event were excluded from mean enterococci concentration calculations for priority ratings. Sub-catchments have been rated separately for this extreme rainfall event. Only on occasions when flow was present were enterococci concentrations used to calculate averages across events, with nil flow not counted rather than being assessed as zero.

Based on these average enterococci concentrations, stormwater sub-catchments were assigned priority rankings describing their degree of likely sewage infiltration of stormwater (Table 2), and consequently the order in which associated sewerage catchments require investigation and remediation.

[1] Enterococci are measured in colony forming units per 100 millilitres of sample (cfu/100 mL).

Table 2 Stormwater sub-catchment priority ranks, associated enterococci concentrations, equivalent raw sewage contribution to flow (assuming all enterococci are derived from sewage), equivalent wet weather overflow contribution to flow (1:4 ratio) and potential enterococci source

Priority rank	Enterococci (‘000 cfu/100 mL)	Equivalent raw sewage contribution	Equivalent wet weather overflow contribution	Likely cause
1	>25	>5%	>25%	Nearby overflows/ system failure
2	20–25	4–5%	20–25%	Nearby overflow
3	15–20	3–4%	15–20%	Distant overflow/ major infiltration
4	10–15	2–3%	10–15%	Distant overflow/ minor infiltration
5	5–10	1–2%	5–10%	Surface runoff/ minor infiltration
6	<5	<1%	<5%	Surface runoff

A consequence of the sub-catchment mapping process was that all portions of a stormwater network within a catchment upstream of a sampling point were ranked according to the average enterococci concentration estimated across events at that sampling location, unless there was another sample further upstream within that sub-catchment. Sewerage infrastructure within a sub-catchment has been assigned the same ranking as the stormwater sub-catchment containing it.

Results

Drain outlet flow rates

Flow rates for stormwater outlets to Terrigal Bay, and Terrigal and Avoca lagoons were highly variable among locations (Figure 3) and throughout rainfall events at very short time scales (e.g. Figure 4). The greatest measured stormwater flow rates into Terrigal Lagoon were at the lagoon’s two natural tributaries (Figure 3): South Arm Creek (TLD6) ($\bar{x}$ = 1234±666 L/s) and North Arm Creek (TLD20) ($\bar{x}$ = 1127±257 L/s). Greatest stormwater flow rates in drain outlets were measured at TLD4 ($\bar{x}$ = 460±457 L/s) discharging into the lagoon’s southern arm and TLD 21 ($\bar{x}$ = 150±143 L/s) discharging into the northern arm. Greatest stormwater flow rates into Avoca Lagoon were from the lagoons major tributary, Saltwater Creek (ALD14) ($\bar{x}$ = 148±97 L/s), and from the three stormwater drain outlets in the north: ALD18 ($\bar{x}$ = 175±85 L/s) and the west: ALD19 ($\bar{x}$ = 181±165 L/s) and ALD20 ($\bar{x}$ = 151±137 L/s) of the northern arm. Of the drains discharging into Terrigal Bay, the most significant was the seven-drain complex (T3) at the southern end of Terrigal Beach. Within the catchment of this drain, the branch draining the southern and eastern sub-catchments of the Terrigal Bowl (TSD: $\bar{x}$ = 159±93 L/s) has the greatest flow, followed by the north-western branch (TBD2: $\bar{x}$ = 66±28 L/s), with the northern branch having the lowest flow (TBD1: $\bar{x}$ = 24±13 L/s).

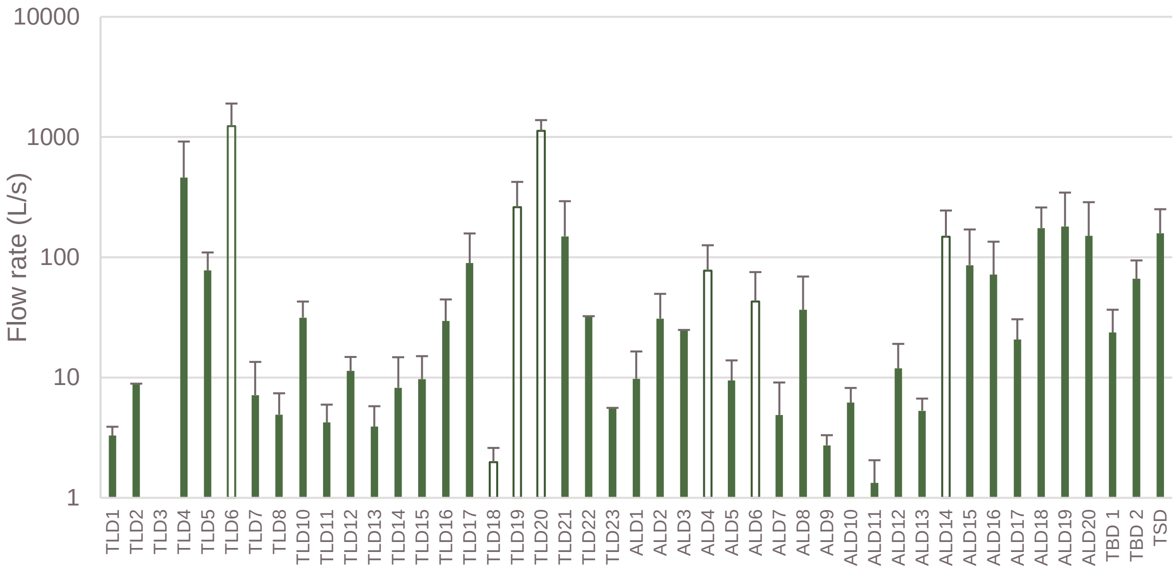

Figure 3 **Mean (±SE) wet weather stormwater flow rates discharging into Terrigal Bay (TBD-, TSD), Terrigal Lagoon (TLD-) and Avoca Lagoon (ALD-) for three wet weather events between 12 October 2019 and 26 May 2020**

Note: The y-axis uses a logarithmic scale. Solid bars are drains and white bars are tributary creeks.

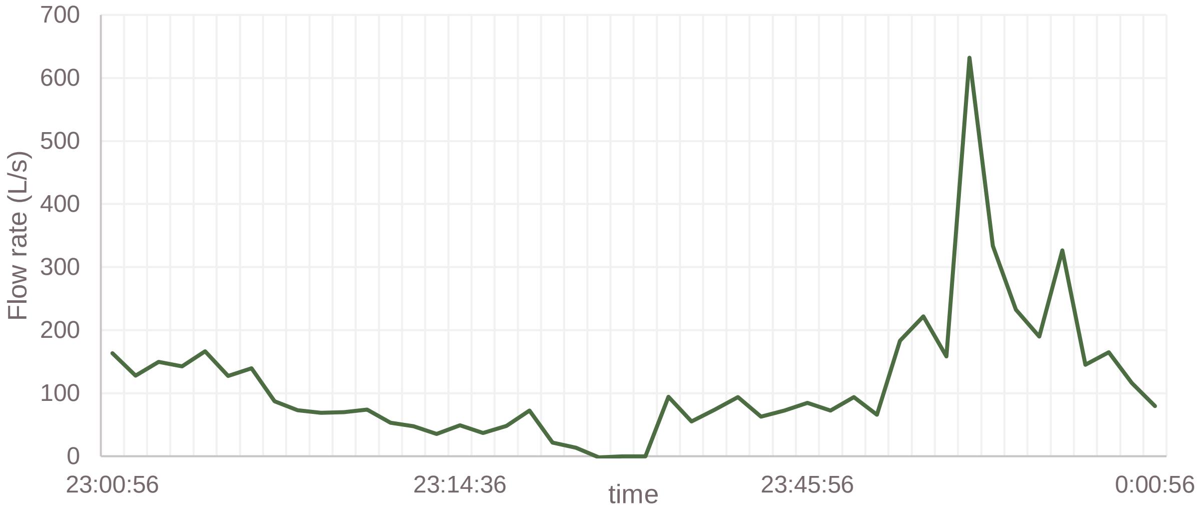

Figure 4 **Stormwater drain flow rates of TSD branch of Terrigal Bay's largest direct stormwater sub-catchment over a 1-hour period during a moderate rainfall event on 17 January 2020**

Drain outlet enterococci concentrations

Mean concentrations of enterococci in stormwater drains were significantly different among drains (df=63, F=1.53, p<0.03) and among rainfall events (df=2, F=11.01, p<0.00005) (Figure 5). In Terrigal Lagoon, enterococci concentrations varied significantly among drains (df = 18, f=2.46, p<0.02) and among different wet weather events (df = 2, f=15.48, p<0.00005). In Avoca Lagoon, enterococci concentrations differed significantly among events (df=2, F=8.66, p<0.001) but no significant differences in enterococci concentrations were found between drains (p>0.5). In contrast, enterococci concentrations differed significantly among the drains of the Terrigal Bay catchment (df=23, F=2.27, p<0.01) but there was no significant difference among events (p>0.8).

The highest enterococci concentrations in drains discharging into Avoca Lagoon were found in the northern arm: ALD16 ($\bar{x}$ = 27,328±7800 cfu/100 mL), ALD18 ($\bar{x}$ = 27,118±9353 cfu/100 mL), ALD19 ($\bar{x}$ = 30,613±14,162 cfu/100 mL), ALD20 ($\bar{x}$ = 31,915±11,980 cfu/100 mL) and in the southern arm at ALD10 ($\bar{x}$ = 27,171±23,474 cfu/100 mL). In the case of ALD10 this was due to extremely high enterococci levels (120,980 cfu/100 mL) recorded during the extreme 152 millimetre wet weather event of 7 February 2020 (Figure 1) rather than recurrent high levels during wet weather. In Terrigal Lagoon, the highest enterococci concentrations were recorded from the northern arm: TLD 21 ($\bar{x}$ = 27,847±12,089 cfu/100 mL), TLD22 ($\bar{x}$ = 26,593±12,586 cfu/100 mL), TLD 16 ($\bar{x}$ = 26,029±11,011 cfu/100 mL) and in the southern arm: TLD10 ($\bar{x}$ = 27,018±6370 cfu/100 mL) and TLD5 ($\bar{x}$ = 23,252±5275 cfu/100 mL). Of the drains discharging directly into Terrigal Bay, the seven-drain complex at the southern end of Terrigal Beach had the highest enterococci concentration ($\bar{x}$ = 34,162±9161 cfu/100 mL).

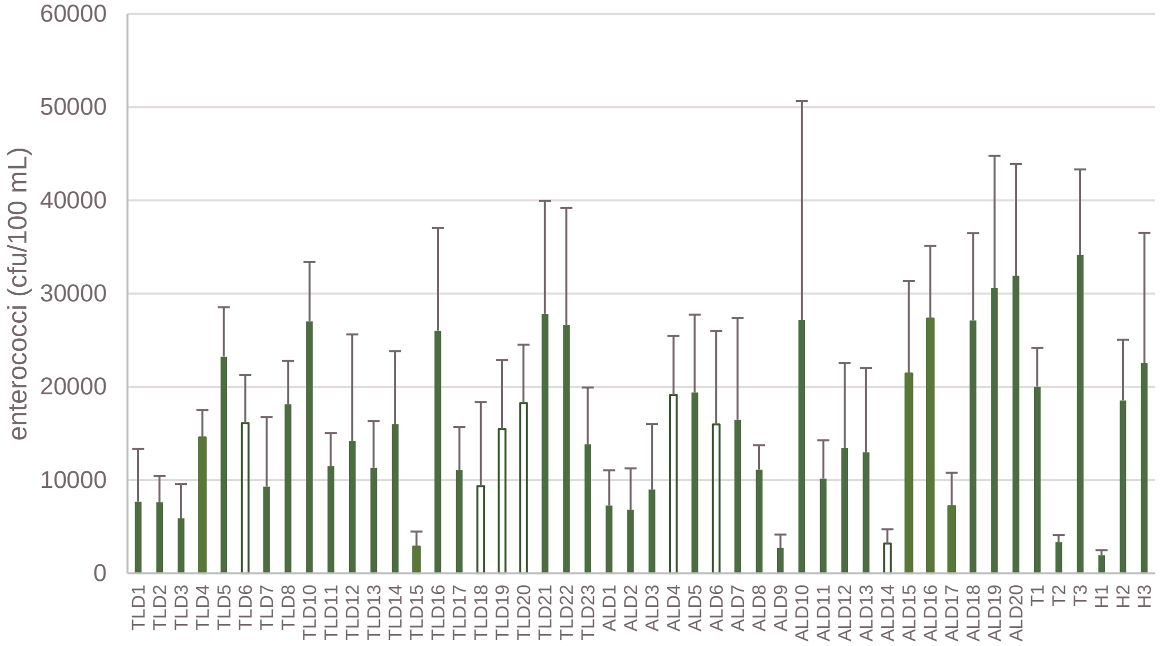

Figure 5 **Mean (±SE) wet weather enterococci concentrations measured in stormwater outlets in Terrigal Bay (T-, H-), Terrigal Lagoon (TLD-) and Avoca Lagoon (ALD-) on 12 October 2019 and 18 January, 7 February, 22 May and 26 May 2020**

Solid bars are drains and white bars are tributary creeks.

Drain outlet enterococci loads

Due to a lack of flow in Terrigal Bay outlets other than the seven-drain complex, replicated enterococci loads were only available for the largest of the Terrigal Bay outlets which had the third highest enterococci load of all assessed discharges ($\bar{x}$ = 108,324,395±63,606,375 cfu/s). In the lagoons, enterococci loads were significantly different between outlets (df=41, F=3.61, p<0.00001) and wet weather events (df=2, F=7.21, p<0.002)(Figure 6).The highest loading into Terrigal Lagoon came from the two natural tributaries: TLD6 ($\bar{x}$ = 210,425,542±117,459,322 cfu/s) in the south arm and TLD20 ($\bar{x}$ = 267,332,495±137,185,552 cfu/s) in the northern arm. Substantial loads also came from the much smaller catchments of TLD4 ($\bar{x}$ = 56,111,693±56,027,454 cfu/s), TLD21 ($\bar{x}$ = 61,534,682±60,959,595 cfu/s) and TLD19 ($\bar{x}$ = 27,544,238±19,186,830 cfu/s). TLD19 constituted about 10.3% of the load in TLD20. Loading from Avoca Lagoon drains was lower than for Terrigal with the dominant discharges from ALD18 ($\bar{x}$ = 31,958,630±20,237,833 cfu/s), ALD19 ($\bar{x}$ = 54,616,448±51,241,627 cfu/s) and ALD20 ($\bar{x}$ = 66,333,089±62,988,927 cfu/s) in the northern arm of the lagoon.

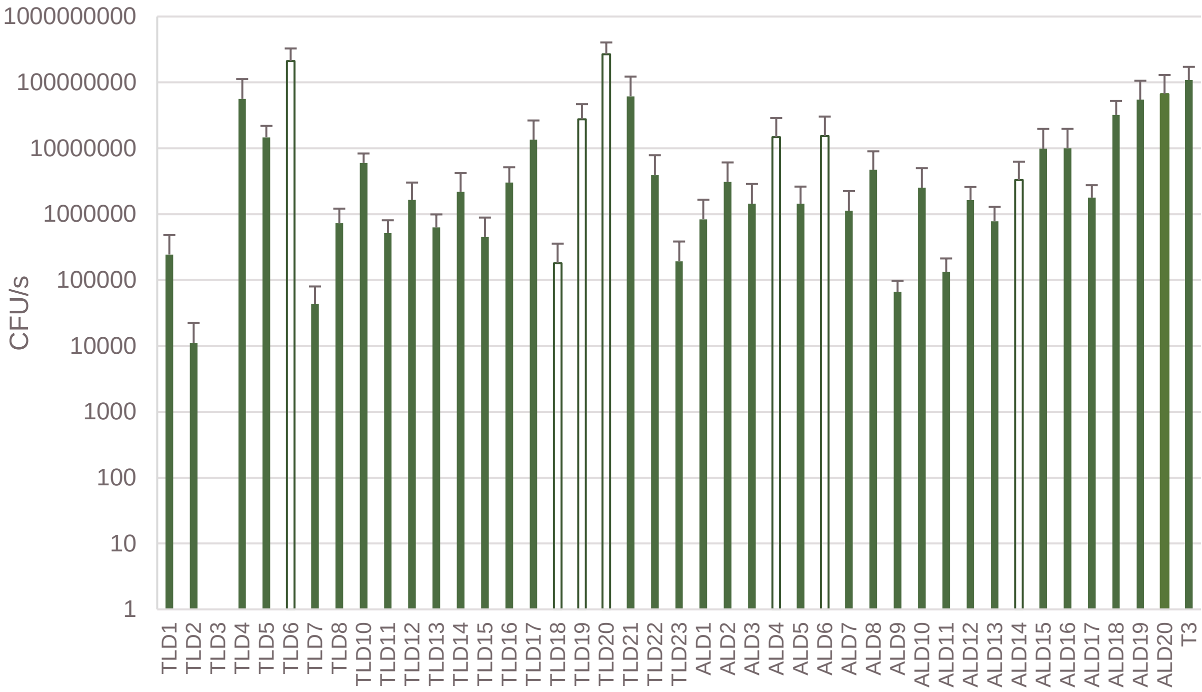

Figure 6 **Wet weather enterococci loads (mean±SE) from stormwater outlets in Terrigal and Avoca lagoons and the seven-drain complex in Terrigal Bay during three wet weather events between 12 October 2019 and 26 May 2020**

Note: The y-axis uses a logarithmic scale. Solid bars are drains and white bars are tributary creeks.

Flow logger and autosampler assemblies installed on the major branches of the Terrigal Bay stormwater catchment were compromised by debris entanglement around pump intake. This inhibited optimal performance and prevented sampler function for the TSD drain line during the 7 February 2020 wet weather event. During spring tides, and as a result of storm surges, the lower areas of the Terrigal Bowl catchment were also impacted by ocean water intrusion resulting in periodic negative flow rates (inflows) and by low outflows or no flows. These tidal induced atypical flows coincided with elevated water depths in the drain outlets as well as impacts on flow due to inflowing water and deposition of sand in the drain mouth impeding outflows (Figure 7).

During the 18 January 2020 wet weather event (Figure 1), when simultaneous data from both stormwater network TSD and TBB2 branches (Figure 2) were available, there was no relationship between enterococci concentration and flow rate (Figure 8a) in the dominant (in terms of flow) southern branch (TSD), while in the north-west branch (TBD2), enterococci concentration was significantly correlated with flow rate ($p<0.04$) (Figure 8b). For this event, despite the TSD branch having higher flow, the TBD2 branch contributed a higher enterococci load to Terrigal Bay (Figure 9).

Mean enterococci loads across all sampling events were used to create a priority map of stormwater outlets (Figure 10) indicating the drain catchments with the greatest impact on receiving water microbial water quality.

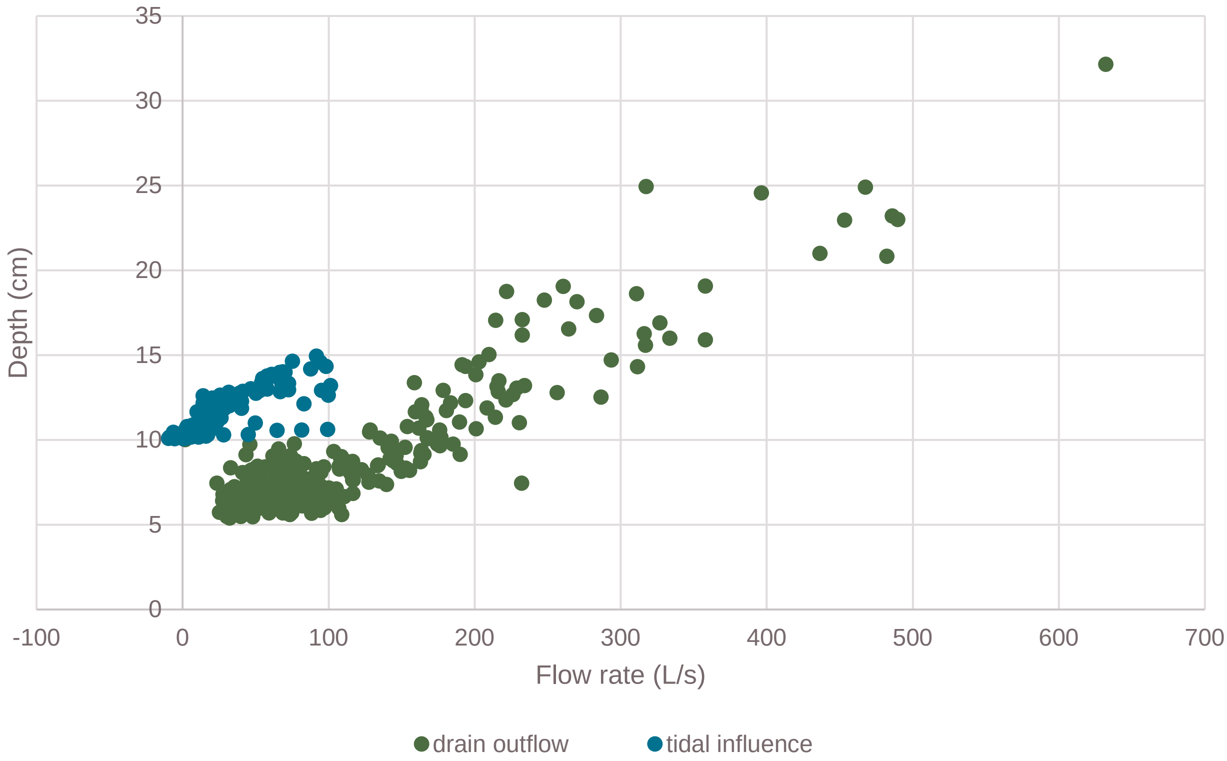

Figure 7 **Water depth vs flow rate relationship in the TSD branch of the main direct stormwater catchment of Terrigal Bay showing the influence of tidal infiltration and sand infilling on drain flow rates on 18 January 2020**

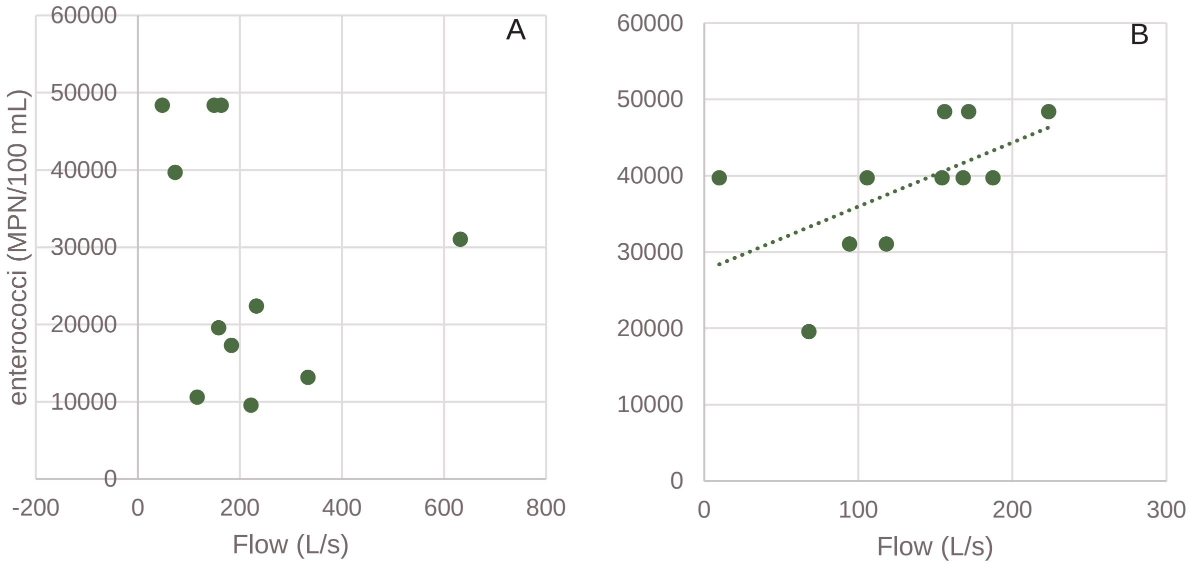

Figure 8 **Changes in enterococci concentration in the major branches of Terrigal Bay's direct stormwater catchment with increasing flow rate on 18 January 2020**

A: TSD branch, B: TBD2 branch.

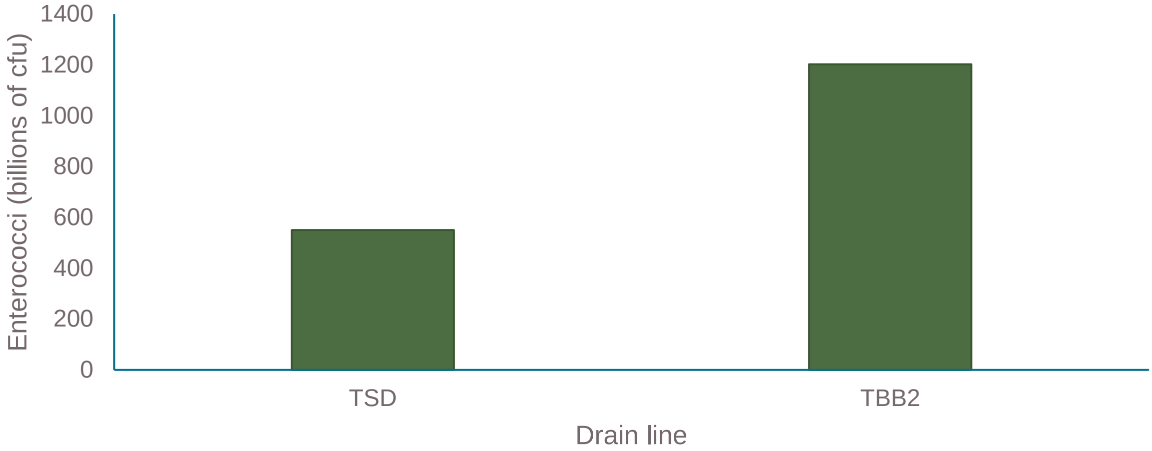

Figure 9 **Total enterococci loads for the major branches of Terrigal Bay's stormwater catchment during wet weather on 18 January 2020**

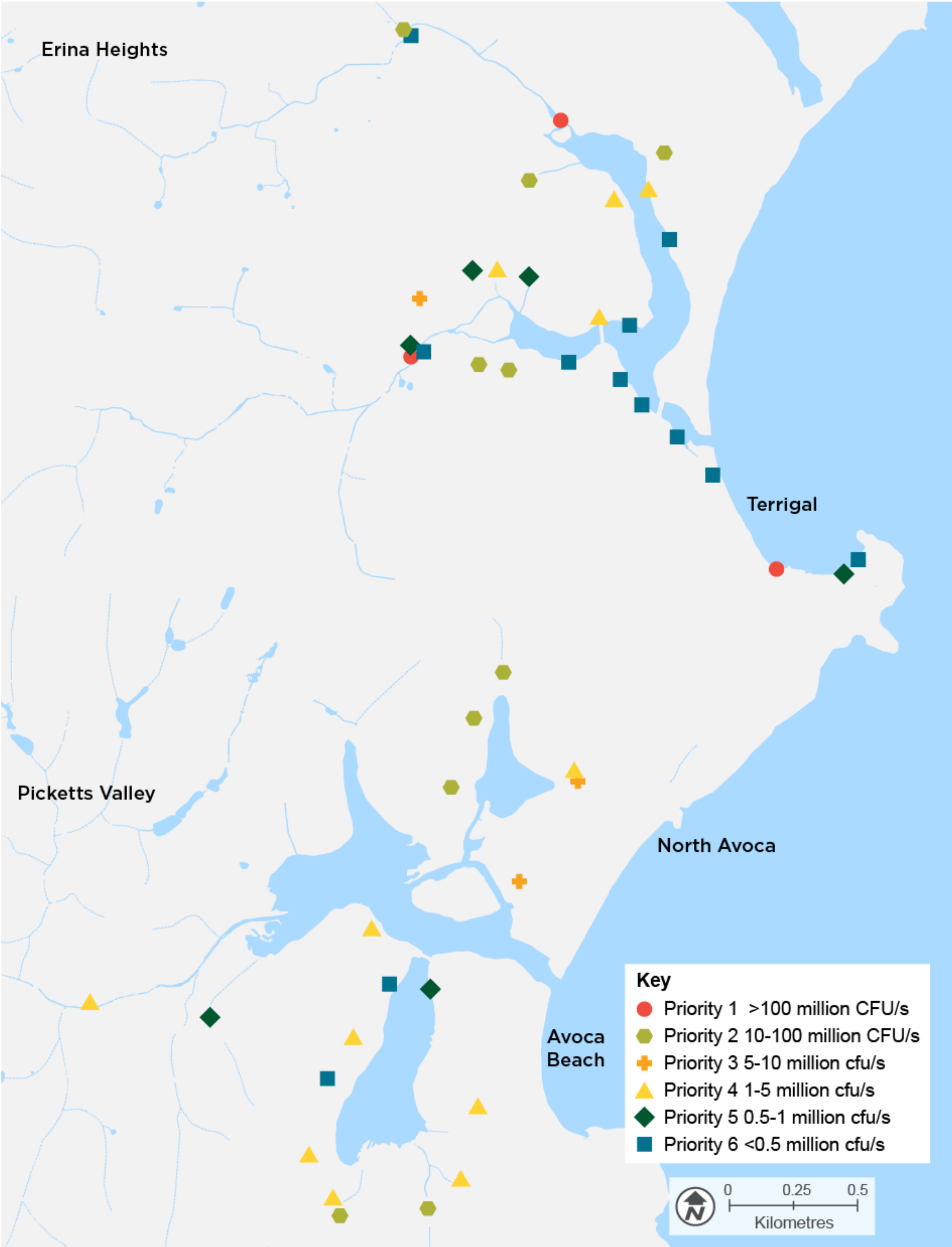

Figure 10 **Map of Terrigal Bay, Terrigal Lagoon and Avoca Lagoon showing major stormwater drain outlets prioritised by impact on receiving waters according to calculated enterococci load**

Priority stormwater drain sub-catchments

Sub-catchment maps for both moderate wet weather (Figure 11) and extreme wet weather (Figure 12) identify the portions of the catchment with the highest enterococci concentrations and likely greatest sewer infiltration of stormwater. In moderate wet weather, 18 sub-catchments were identified as Priority 1 with mean enterococci concentrations over 25,000 cfu/100 mL. Of these, the highest concentrations were found within the Terrigal Bay catchment in the Terrigal CBD and all moderate rainfall enterococci concentrations >30,000 cfu/100 mL were recorded from the Terrigal Bay catchment. However, only one of these sites – 38,799 on Barrington Road – had sufficient flow to be sampled during more than one moderate wet weather event.

During the 152 millimetre wet weather event on 7 February, 21 sites were rated Priority 1 with only six of these in the Terrigal Bay catchment and many of the previously high priority sites having very low concentrations during this event. In contrast Avoca Lagoon had nine sites rated Priority 1 in this event compared to four in moderate conditions, with all additional Priority 1 sites in the southern arm. Terrigal Lagoon had six Priority 1 sites in February but only five in more moderate conditions, though three of these Priority 1 sites for moderate conditions could not be sampled in February due to flooding (TLD 22) or because they were upstream sites that had not yet been identified (TLD10.2 and TLD5.3).

Collecting a sample from Avoca Lagoon catchment. Photo: DPIE

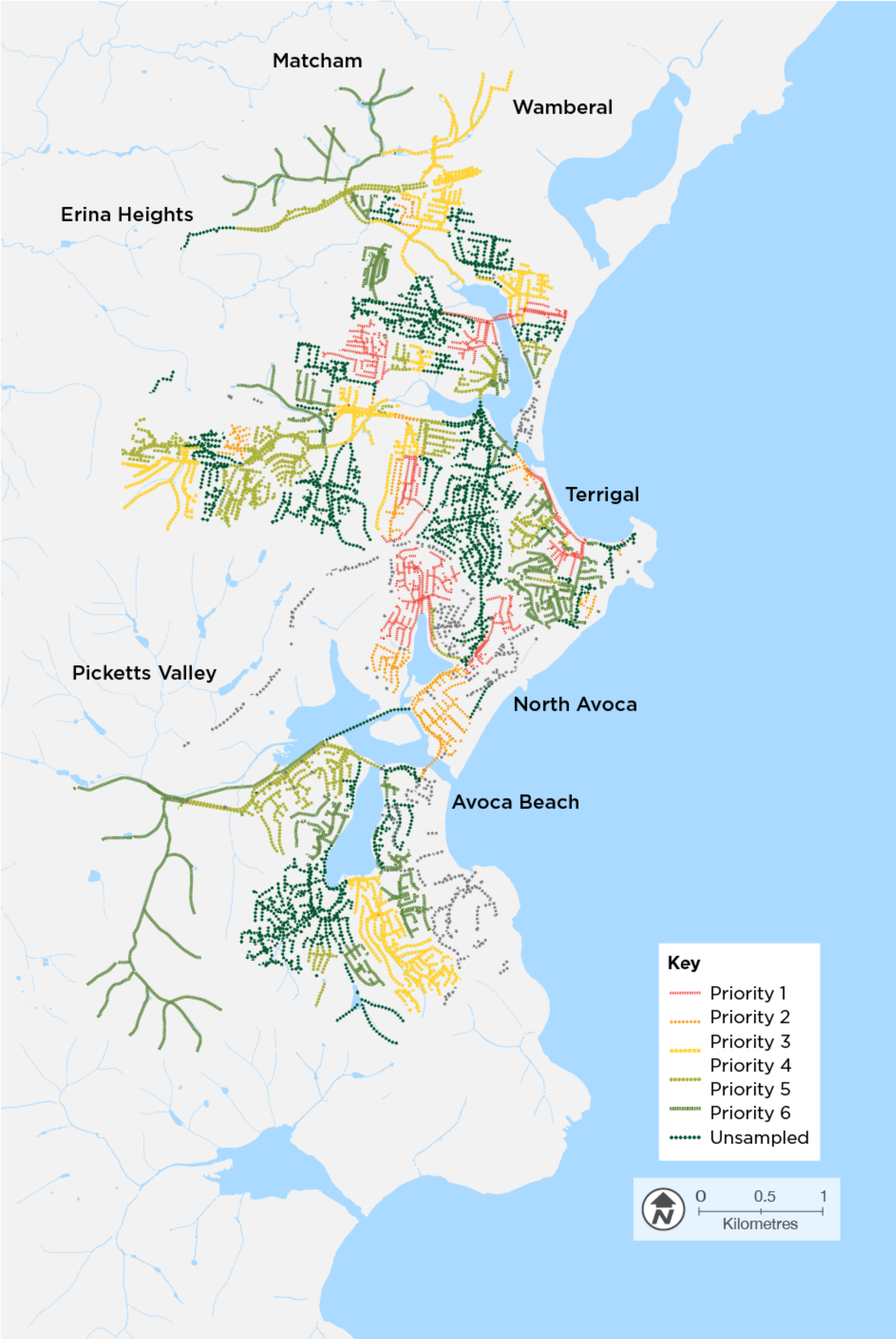

Figure 11 **Terrigal regional wastewater sub-catchments prioritised by mean stormwater enterococci concentrations in moderate wet weather**

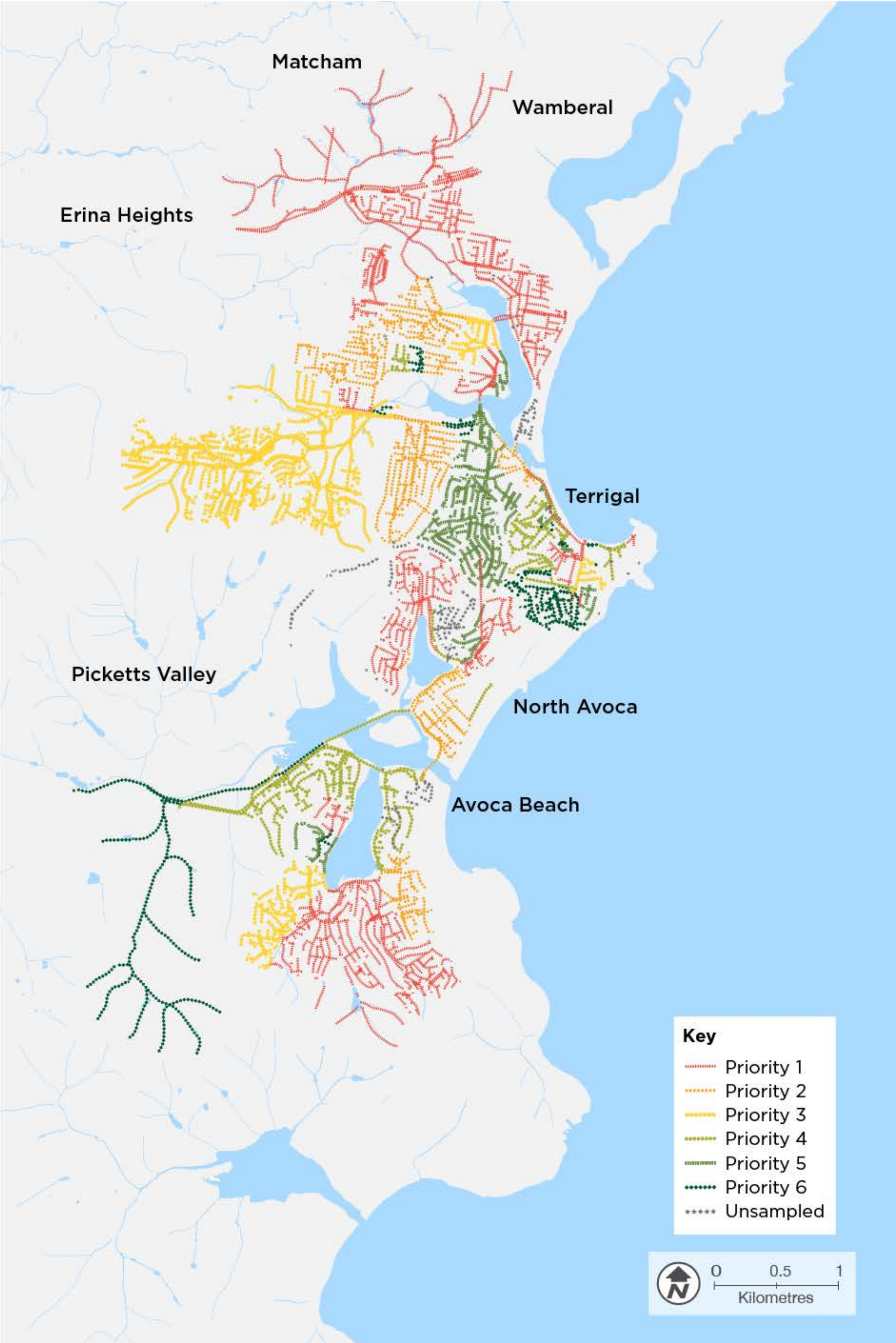

Figure 12 **Terrigal regional wastewater sub-catchments prioritised by mean stormwater enterococci concentrations in extreme wet weather (>150 mm)**

To simplify map images, the number of categories can be reduced by combining priority ranks 1 and 2, 3 and 4, and 5 and 6; as in the individual catchment maps for Terrigal Bay, Terrigal Lagoon and Avoca Lagoon below.

Terrigal Bay

For Terrigal Bay, the highest priority sub-catchments to address sewer infiltration in moderate and extreme rainfall conditions are the central CBD of Terrigal in the location of the infilled ICOLL and the sewer pump station at Pine Tree Lane bounded by Kurrawyba Avenue, Grosvenor Road, Henley Avenue and Ash Street (a), and a small sub-catchment at Barrington Road and Woolunga Avenue (b) (Figure 13).

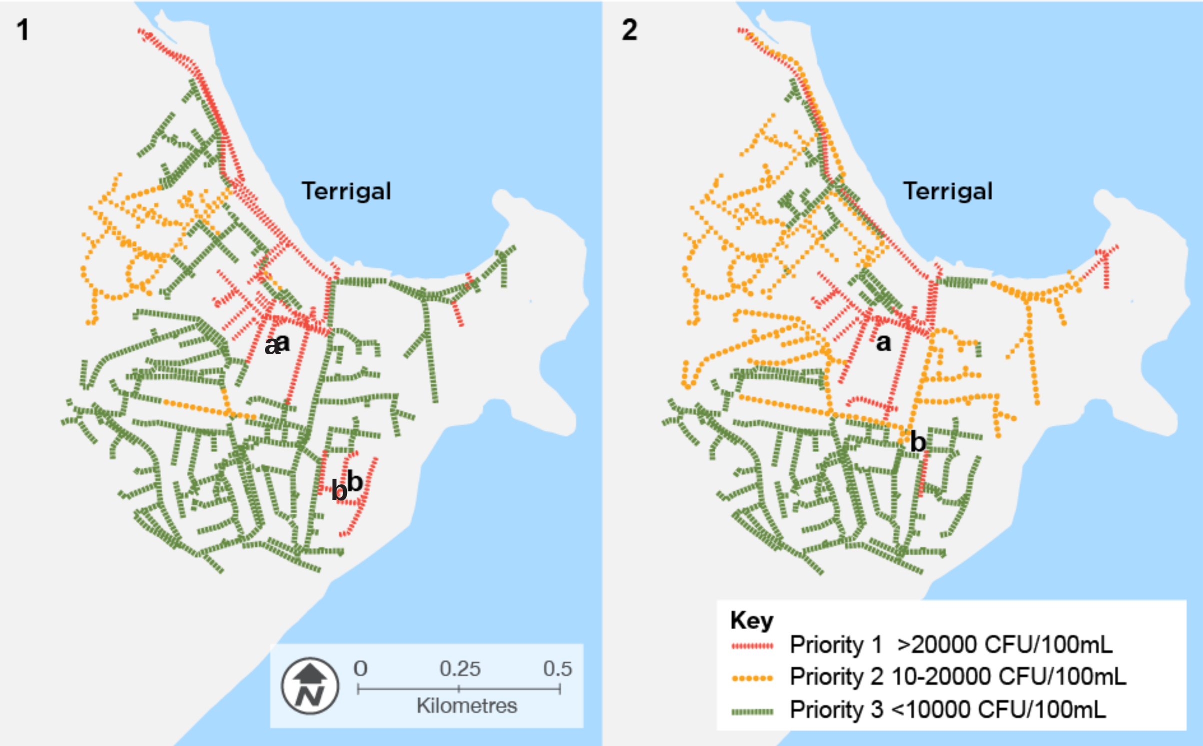

Figure 13 **Terrigal Bay sub-catchments prioritised for remediation based on enterococci concentrations in stormwater under A: moderate rainfall, B: extreme (150 mm+) rainfall conditions**

Terrigal Lagoon

In Terrigal Lagoon in moderate rainfall conditions, the sub-catchments of Ashley Avenue and Anniversary Avenue in the south (a), Banbury, Sainsbury and Cheshire Closes in the south-west (b), Micheala Road, Weemala Crescent and Wycombe Road in the west (c), Edinburgh Circuit in the north-west (d), Beaufort Road and Ogilvie St in the central region (e), and Bundara Ave, Lakeview Road and Renown Street in the north (f) are the biggest contributors of enterococci. In extreme wet weather however, all catchments on the northern bank of the north arm and North Arm Creek, as well as Willoughby Road and the previously described moderate wet weather sub-catchments, are all substantial contributors of enterococci to the lagoon (Figure 14).

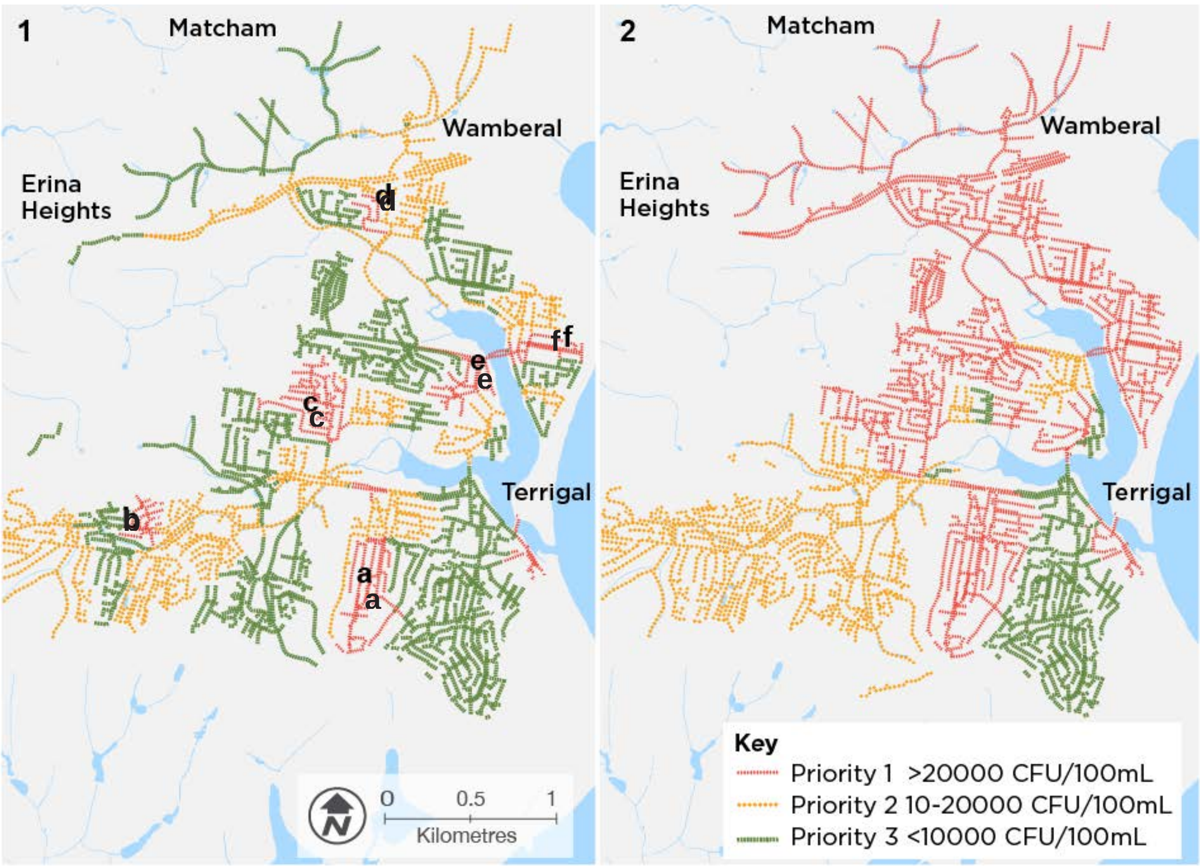

Figure 14 **Terrigal Lagoon sub-catchments prioritised for remediation based on enterococci concentrations in stormwater under A: moderate rainfall, B: extreme (150 mm+) rainfall conditions**

Avoca Lagoon

In Avoca Lagoon, the bulk of enterococci inputs in moderate wet weather conditions originate in the sub-catchments of the northern arm along Lakeshore Drive west from Gulgong Road (a), and the sub-catchment encompassing the sewer pump station on Surf Rider Avenue (b), along with the flat region of North Avoca between the ocean beach and the lake (c). In extreme wet weather as well as these areas, stormwater sub-catchments along The Round Drive between its intersections with Cape Three Points Road and Walder Crescent (d), as well as in the central western portion of the lagoon's southern arm (e), are heavily infiltrated with sewage (Figure 15).

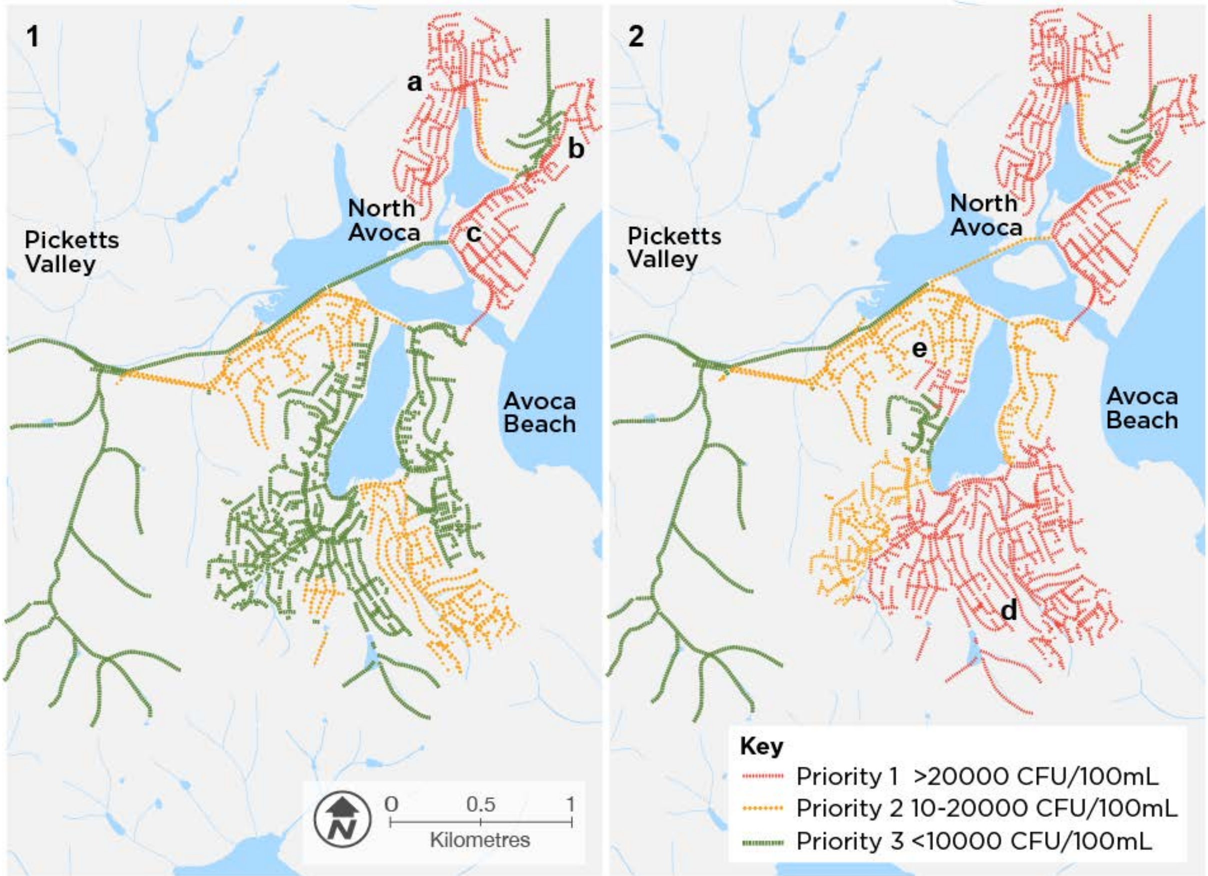

Figure 15 **Avoca Lagoon sub-catchments prioritised for remediation according to enterococci concentrations in stormwater in A: moderate rainfall, and B: extreme (150 mm+) rainfall conditions**

Discussion

The swimming waters of Terrigal Bay and Terrigal and Avoca lagoons are heavily impacted by sewage contamination following rainfall (Reports 1, 2 and 5), which has been the primary driver of poor recreational water quality ratings reported by statewide swimming risk monitoring (DPIE 2019). Sewage is being delivered indirectly to the bay and lagoons via the stormwater network.

There are several potential mechanisms by which stormwater can become contaminated with sewage. In principle, these water infrastructure systems should remain separate from one another despite often being in close proximity. Sewerage is a sealed system between input drains and the treatment facility, while the stormwater network is deliberately porous to allow uptake of diffuse source water from both surface runoff and groundwater to alleviate flooding in storm events. This porosity in the stormwater system means that while direct sewerage to stormwater connections are uncommon (though do happen), sewage infiltration of the stormwater network can occur through any process that allows sewage to escape from the sewer network. Damage to the sewerage system typically results from tree root intrusion, pipe movement, adjacent construction works or as a result of material failure due to ageing infrastructure. All of these factors can cause leakage of sewage that will then infiltrate the stormwater system. In addition, as a sealed system, the sewer has a specified capacity beyond which it will overflow or rupture.

To avoid infrastructure damage or backflow of raw sewage into residences and businesses, deliberate designated overflow points are built into the network to release pressure when required. These designated overflow points are typically located adjacent to waterbodies or stormwater systems to ensure rapid removal of sewage from the discharge site, to safeguard human health. Overloading of sewerage pipelines and associated overflows can occur at any time as a result of pipe blockages due to root intrusion, from build-ups of flushed non-biodegradable solid matter such as wet wipes and congealed grease (fatbergs), or due to infrastructure failure. In addition to these dry weather causes, wet weather overflows are exacerbated by infiltration of stormwater into the sewerage system especially via direct stormwater to sewer connections, poorly situated or badly maintained sewer manhole covers or other damage to sewer infrastructure allowing water ingress during rain events. Overflows have the potential to discharge large volumes of sewage.

While this study did not identify physical sources of sewerage infrastructure failure, it was able to identify priority areas in the sewerage system for further investigation. Further investigation in this study was limited by high temporal variability in stormwater flows and lack of base flows in the majority of the relatively steep stormwater catchments being assessed. This was compounded by an atypically dry year in 2019 and the curtailing of fieldwork in 2020 due to restrictions on people’s movements to help stop the spread of COVID-19. Despite this, identification of highest priority sewer infrastructure for investigation via evaluation of stormwater contamination within the sub-catchments, can now focus urgent assessment and remediation. After completion of sewer network assessment and remediation, measurable improvements in swimming water quality should be apparent.

The very large enterococci concentrations and proportions of raw sewage estimated suggest that even in moderate flows there is substantial contribution of sewage that can be best explained by a significant input from sewerage overflow points or substantial system failure, rather than small-scale leaks and infiltration. Remediation must focus on identification of potential sources of large-scale inputs in addition to small-scale cross connections, leaks and breakages.

In the catchment of Terrigal Bay, considerable recent remediation has been conducted by Central Coast Council in the Haven, which is likely to have addressed the priority areas identified in that catchment. Likewise, the high priority region around Barrington Road has been traced to a sewer leakage that has now been found and scheduled for repair. Assessment of high priority areas in the central CBD has found damaged and infiltrated pipes that council is addressing. It is noteworthy that the largest sewer infrastructure damage detected within the CBD, a collapsed sewer main in Ash Street, was replaced in August, prior to the monitoring reported here. Ash Street was not identified as a priority site in our sampling, which shows that the area is no longer contributing to poor water quality. The lack of any dilution of enterococci with increasing flow rates in the major drainages for Terrigal Beach indicates wet weather sewage overflows are now likely to be the main contributors to sewage infiltration in this region, particularly within the topographic bowl containing Terrigal township. Monitoring of potential sewer overflows in this area would be beneficial to ensure any required upgrades of sewer infrastructure are adequate and correctly sited.

Despite the current persistence of this wet weather driven sewer infiltration, many of the community complaints regarding dirty water and offensive smells around the major stormwater discharge at the southern end of Terrigal Beach occur in dry weather. Monitoring of the lower portions of the major drainage network of Terrigal Bay has confirmed substantial tidal encroachment into this system, often creating considerable drift algae deposits within these drain lines before sand deposition largely occludes their discharge. The decomposition of this material within pipes and periodic sudden discharge due to breach of the sand berm within the pipes is likely responsible for the bulk of these reported sudden releases of smelly, dirty water in dry weather.

In Terrigal Lagoon catchment, despite a clear dominance of the natural tributaries as contributors to total enterococci load, only two small high priority areas have been identified in their catchments under moderate rainfall. Whilst these areas require the most urgent attention, the large Priority 3 regions in the catchments of both these creeks will also require further investigation. It is likely these areas are the sources of much of this input, and have a propensity for wet weather overflows in more extreme rainfall conditions. The remaining high priority sub-catchments in the southern arm of the lagoon are relatively small, though those around Anniversary and Ashley Avenues in particular are substantial contributors of sewage to the lagoon. In the northern arm of Terrigal Lagoon, the remaining two high priority areas are connected by a sewer pressure main which should also be a high priority for further assessment. This whole area is vulnerable to wet weather overflows in extreme rainfall conditions.

In Avoca Lagoon, under moderate rainfall conditions, most of the sewer inputs are derived from North Avoca. Assessment of all sewer infrastructure surrounding this arm of the lagoon is critical particularly given the substantial array of pressurised sewer infrastructure in this area. Any adverse impacts from the sewer pressure main surrounding the lower lagoon were not assessable in this study due to its position downstream from stormwater infrastructure. Any further investigation of the sewer system in this area will need to examine these mains. In more extreme rainfall, little change was detected in the northern portion of Avoca Lagoon, indicative that only minor rainfall is required to overload this system or that systemic failure is present in this area. In contrast, in southern Avoca Lagoon, a large portion of the southern-most catchment is vulnerable to wet weather overflows. In the smaller high priority area in the central west of this southern arm, the sampled stormwater was apparently in close proximity to a substantial overflow, as the enterococci count (>120,000) indicates that sampled water was approximately 24% raw sewage (in the absence of large environmental enterococci inputs) based on an indicative raw sewer enterococci concentration of ~0.5 million cfu/100 mL (Srinivasan et al. 2011).

Conclusion

The wet weather domination of likely sewage contamination in the Terrigal region and a general, though discontinuous, increase in enterococci contamination with increased drain flow in monitored stormwater lines implies the bulk of sewer inputs to Terrigal Bay, and Terrigal and Avoca lagoons are a result of wet weather overflows within the identified catchment areas. Inspection of the public and private sewer system in priority sub-catchment areas identified here will facilitate remediation in this area to provide measurable reductions in sewage contamination of stormwater.

In such a large region it is also imperative that remote monitoring of any directed overflows within priority catchments is commenced or reinstated to help determine where and if broader-scale sewer upgrades are necessary.

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