Haverson, David

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David Haverson
Centre for Environment, Fisheries & Aquaculture Science
Lowestoft, UK
david.haverson@cefas.co.uk

***Abstract*— To help assess the dispersion of pollution in Port Vila, Vanuatu, a 3D baroclinic model was developed using TELEMAC-3D. Scenarios were tested to investigate the vulnerability of the system and identify control measures. Model results show those undertaking recreation activities in the bay are vulnerable to exposure to high concentrations due to a buoyant plume forming along the waterfront. Fatumara Bay contains ecologically important sea grasses which are particularly vulnerable as the model shows high concentrations quickly build up. The purpose of the model is to provide a tool for investigating the potential problems and solutions for water quality within Port Vila. The control measures tested with the model were shown to be effective, but there are no substitutes for a fully functioning sewage treatment system.**

I. Introduction

Vanuatu is a Pacific Island nation in the South Pacific Ocean and is an archipelago made up of over 80 islands. Port Vila is the capital of Vanuatu on the island of Efate and is of interest as part of a wider water quality programme in the region for the Commonwealth Marine Economies (CME) Programme. Water quality issues have become increasingly more important as population, tourism and coastal infrastructure grow and expand. Accurate water quality data enables national decision makers and local stakeholders to plan how to use and manage the bay's natural resources for sustainable marine economic development for a range of purposes, such as diving and other tourism activities or the identification of areas suitable for aquaculture sites. This ensures multi-use activity whilst protecting the marine environment into the future.

In Vanuatu, only 46 % of the population have piped drinking water. 47 % of all private households use a pit latrine, while 21 % use a flush toilet. Access to flushable toilets is 65 % in urban areas and only 6 % in rural ones. Nutrient data collected around Port Villa show a gradient of change related to the proximity of site to the Port Villa coast line and the influence of the storm-water drains. Interpolation analysis of the water quality data clearly shows the hot spots for Port Villa close to shore and clustered around the main storm water drains, identifying that urban runoff is a serious issue for the surrounding coastal area. Outputs of previous 2D modelling showed that the movement of the pollutants is influenced by the location of drains, and identified the priority actions around the storm-water drains that could be taken to reduce the pollution inputs into the bay.

As part of the water quality assessment of the CME programme, the aim of the hydrodynamic modelling project has been to improve upon the existing 2D hydrodynamic modelling and converting it to a 3D model. This is to provide a more accurate assessment of pollutant dispersion and test potential control mechanisms.

II. Hydrodynamic Model

A. Model Description

A 3D hydrodynamic model has been developed using the hydrodynamic software TELEMAC-3D (v7p2r2). The model domain, as shown in Figure 1 has been built using an unstructured triangular mesh and the spatial coverage has been expanded upon the existing 2D model domain. The domain now extends between 165.967 °E – 170.587 °E and 15.559 °S – 19.802 °S. The 2D mesh was discretised with 53,872 nodes

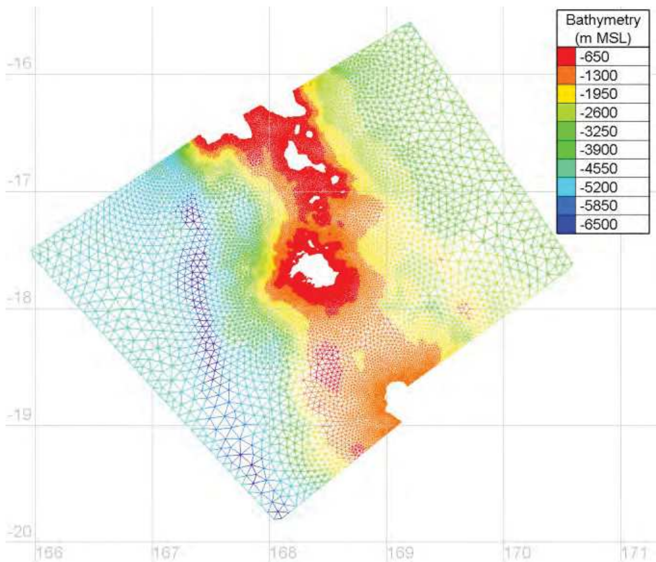

Figure 1: 3D model domain.

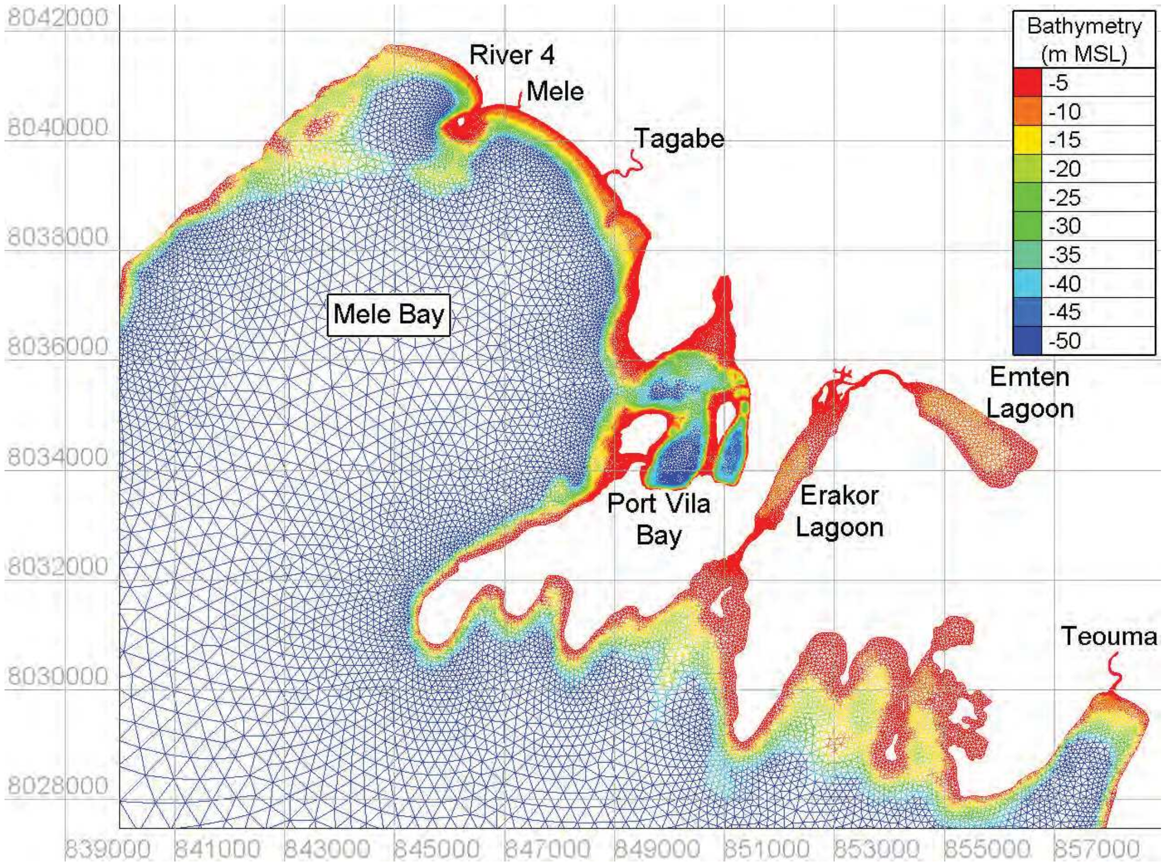

Figure 2: 3D model domain, zoomed into Port Vila.

and 102,160 elements. The 2D mesh has a resolution of approximately 8 km along the open boundaries. In Mele Bay, the resolution is refined to approximately 50 m and again refined further to approximately 20 m in Port Vila Bay. Furthermore, a new addition to the model domain was the inclusion of the Erakor and Emten lagoons, the Teouma River into Teouma Bay and the Tagabe, the Mele and an unnamed fourth river into Mele Bay, which are all shown in Figure 2.

Bathymetry for the model was provided by several sources. The bathymetry surrounding Efate island up to approximately 25 km from shore was provided by EOMAP at a resolution of 50 m [1]. Beyond this, the remainder of the model domain was sourced from GEBCO with a resolution of 1.5 km [2]. From the shoreline to depths less than 25 m have been sourced from optical clear satellite derived bathymetry, provided by EOMAP, with a spatial resolution of 10 m. Within Port Vila Bay bathymetry was provided by the UK Hydrographic Office at a resolution of 5 m. The vertical datum of the bathymetry in the model domain is with respect to Mean Sea Level (MSL).

The models vertical plane distribution was split into 10 layers with a sigma transformation with given proportions (MESH TRANSFORMATION = 2). The proportions, as a percentage of depth, are: 1, 2, 10, 20, 50, 80, 90, 95, 98 and 100. The layers were distributed to provide a more accurate representation of currents and pollution dispersion near the sea surface.

The hydrodynamics are forced along the open maritime boundaries using 11 tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4 and MN4) from the OSU TPXO Pacific Ocean 1/12° regional model [3]. The TPXO harmonics are used to drive the prescribed elevations with free velocities. However, due to steep bathymetric gradients on the open boundary, this can lead to numerical instability. To overcome this, the bathymetry has been smoothed so there are no lateral bathymetric gradients on the boundary. All bathymetry below the 1000 m depth contour has been smoothed to 1000 m. Due to the large distance between the open boundary and the area of interest and the depths included in the model domain, the bathymetry smoothing is not considered to have greatly affected the velocities in the near vicinity around Efate Island.

As the tidal range in Port Vila is small, 1.64 m, and the main source of pollution into Port Vila bay is introduced at the sea surface, the dispersion of pollution is likely to be heavily influenced by wind driven surface currents. Therefore, wind forcing has been included in the model in addition to tidal forcing. A yearly record of hourly winds for Port Vila has been sourced from the Australian Bureau of Meteorology for 2016 [4]. The data shows that the mean wind speed is 1.29 m/s with a peak of 8.4 m/s. The predominant wind direction is from the South-West.

B. *Modelling Temperature and Salinity*

To investigate the water quality in Port Vila Bay, the pollution in the model was represented by a passive tracer.

Specifically, the pollution was represented by the level of Dissolved Inorganic Nitrogen (DIN). The main sources of DIN, investigated with this model, are introduced through the sewage and storm water system. The associated salinity of the sources is treated as freshwater which is considerably different from the salinity of Port Vila Bay (i.e. sea water). As such, the effects of salinity have been included in the model.

During the field measurement campaign in December 2017, temperature and salinity profiles were collected in Port Vila Bay using a handheld CTD. Figure 3 and Figure 4 show two temperature and salinity profiles from within Port Vila Bay. The first was collected by the cruise ship dock (168.303 °E, 17.735 °S), one of the deepest points in the bay, and the second by the mouth of Port Vila Bay north east off Ifira Island (168.311 °E, 17.755 °S). As the main area of interest is within Port Vila Bay and that the salinity profiles show little stratification, a constant salinity has been applied to the whole model domain, both vertically and horizontally.

In addition to the sewage and storm water system, fresh water is introduced into the model at the source of the four rivers, whose location is shown in Figure 2. During the field measurement campaign in December 2017, the flow rate was measured at the Teouma, the Tagabe, the Mele and an unnamed fourth river into Mele Bay. The river flow was measured using the SonTek FlowTracker2 (FT2) handheld Acoustic Doppler Velocimeter (ADV). For each river, the velocity was measured at three points across the river along with the cross-sectional area of the river, to compute a flow rate. The observations are summarised in TABLE 1. In addition, the pH, salinity, dissolved oxygen and temperature were also measured, but not presented.

Since the storm drains are open to the environment, the difference between source temperature and background is very small. As such, the temperature of the source terms is considered to be that of the ambient air. The difference between the air temperature and the water temperature, as recorded by the Australian Bureau of Meteorology, is on average 1.6 °C. Furthermore, the temperature profiles shown in Figure 3 and Figure 4, show little stratification. As such, the temperature tracer has not been included in the model.

TABLE 1. OBSERVED RIVER FLOWS.

River	Depth	Velocity Sample 1	2	3	Area	Flow rate
	m	m/s	m/s	m/s	m²	m³/s
Teouma	0.80	0.67	0.71	0.69	6.29	4.46
Tagabe	0.85	0.82	0.92	0.91	4.68	4.29
Mele	0.52	0.61	0.65	0.62	1.30	0.84
Unknown	0.63	0.56	0.53	0.58	1.58	0.91

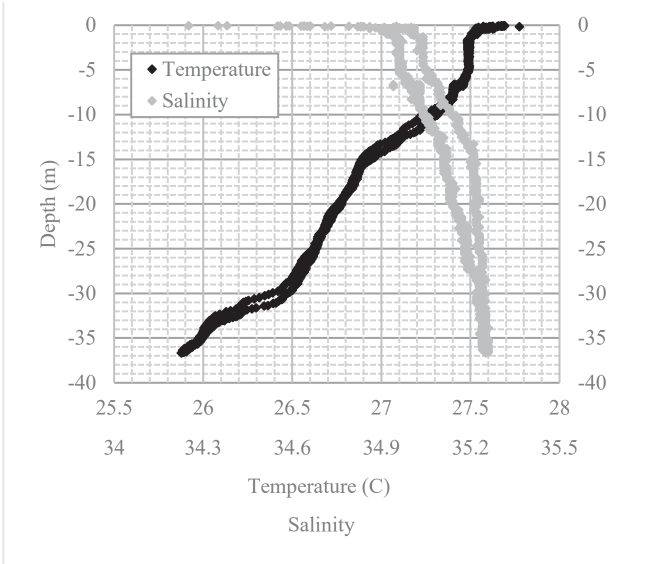

Figure 3. Temperature and salinity profile at cruise ship port.

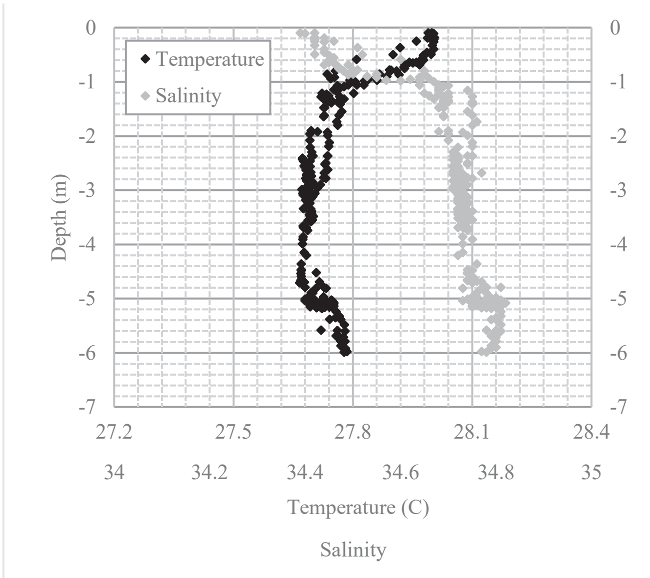

Figure 4. Temperature and salinity profile at Ifira Island.

III. MODEL VALIDATION

To assess the model performance, the tidal elevations were validated against data obtained from the tide gauge in Port Vila (168.308 °E, 17.755 °S), as provided by the Australian Bureau of Meteorology. After a spin up period of 10 days, the model was run for 30 days to cover a full spring-neap cycle. The model showed good agreement to observed tidal elevations. Figure 5 shows the comparison of observed and model elevation. The solid black line denotes a $y=x$ relationship, with the dashed black line representing a linear regression of best fit of the data. TABLE 2 summarises the validation statistics of the Port Vila tide gauge comparison.

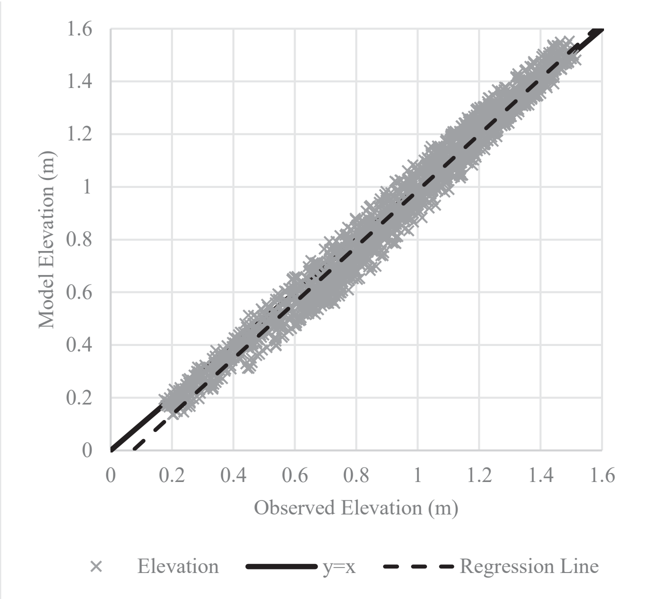

Figure 5: Comparison of observed and modelled free surface elevation at Port Vila tide gauge. The black line represents a *y=x* relationship with the dashed line representing a regression line of best fit.

TABLE 2. VALIDATION STATISTICS OF PORT VILA TIDE GAUGE.

Tide Gauge	R^2	RMSE (m)	Scatter Index (%)
Port Vila	0.979	0.051	5.450

IV. Water Quality Assessment

A. Sewage Outfalls

Along the newly developed waterfront in Port Vila, sewage outfalls can be seen within the sea wall at the height of the sea surface. A number of these are in immediate proximity to public access points into the water for recreation activities, such as swimming. A total of 17 outfalls have been identified and included in the model whose location into Port Vila Bay and Fatumara Bay have been obtained from the PVUDP Civil Design Sketches of the Port Vila Urban Development Project on behalf of the Port Vila Ministry of Infrastructure and Public Utilities. The outfalls source positions are located one node in from the solid boundary and are shown in Figure 6. It is known that there are outfalls into the Erakor and Emten lagoons. However, due to the uncertainty in their location, no outfalls into the lagoons were included.

Presently, there are no known monitored flow rates at the outfall locations and observations could not be obtained during the field measurement campaign. Although, significant surface runoff during a rainfall event was witnessed. In the absence of measurements, comparable regional values were obtained from the Solomon Islands. The Solomon Water 5 Year Action Plan: 2017 to 2022 details the design capacity of the sewage system at Honiara [5]. The report provides three values:

- Average Dry Weather Flow rate – 25.9 l/s
- Peak Dry Weather Flow rate – 93.3 l/s
- Peak Wet Weather Flow rate – 178.8 l/s

These values provide the basis for the subsequent scenarios tested by the model. Whilst flow rates are likely to vary throughout the day, for simplicity the model assumed a constant flow rate.

B. DIN Concentrations

As the samples collected during the December 2017 field campaign could not be analysed in time for the modelling, samples collected during August 2016 were used for the parameterization of DIN. Combined with the river flow measurements, a horizontal tracer diffusion coefficient of 0.1 m^2/s was found to give a good representation. Based on DIN measurements, the background concentration for DIN was 5 mg/l, which was applied uniformly to the whole model domain. For the rivers, a concentration of 40 mg/l was applied to the Tagabe River, 200 mg/l for the Mele River and 200 mg/l for River 4. As no measurements were taken for the Teouma River or in the surrounding area, the background concentration for DIN was applied, negating any contribution. However, a fresh water input was still applied as this would influence the local hydrodynamics.

From the May and August 2016 DIN observations, only two samples match the location of outfall positions. The two concentrations were 11 mg/l and 4451 mg/l. The range is indicative of treated waste compared to untreated waste. During the December 2017 field trip, it was discovered 4 of the 5 sewage treatment plants in Port Vila were not functioning. As this will adversely affect water quality and is a worst case extreme, all the subsequent modelling will assume values representing non-functioning sewage treatment plants. Initially, a conservative estimated concentration of 200 mg/l was applied uniformly to every outfall, but was found to underestimate values observed within Port Vila Bay. As such, a concentration of 500 mg/l was applied and results showed improvements.

C. Model Scenarios

To investigate how water quality evolves throughout Port Vila Bay under various conditions, four different scenarios were considered for testing with the model. The first two scenarios consider the influence of the flow rate. For Scenario 1, a constant average dry flow rate of 25.9 l/s with a concentration of 500 mg/l was applied uniformly to all 17 outfalls. For Scenario 2, a constant peak dry flow rate of 93.3 l/s with a concentration of 500 mg/l was applied uniformly to all 17 outfalls.

Many of the sewer outfalls along the Port Vila Bay seafront are next to public access points to the water at the sea surface. To improve public health, Scenario 3 tests the impact of moving the outfall positions further offshore and releasing just above the seabed. The sources along the waterfront have been moved approximately 100 m offshore, as shown in Figure 10. As Fatumara Bay is very shallow, 3 outfalls were moved further offshore at the shelf edge of Fatumara Bay at approximately 20 m depth. The remaining outfalls in Fatumara Bay have been left at their original location as they are not near any public access points but have been set to release at the

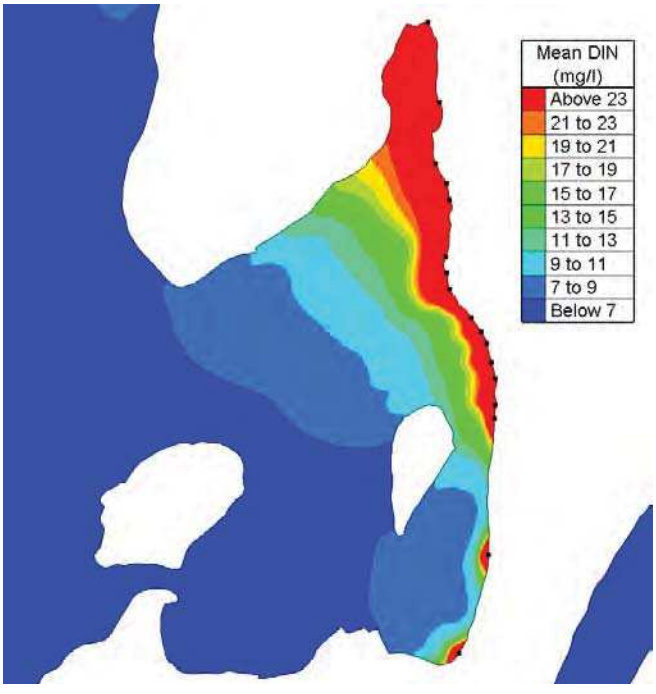

Figure 6: Mean concentrations of DIN at the sea surface for Scenario 1. The black dots represent the outfall positions.

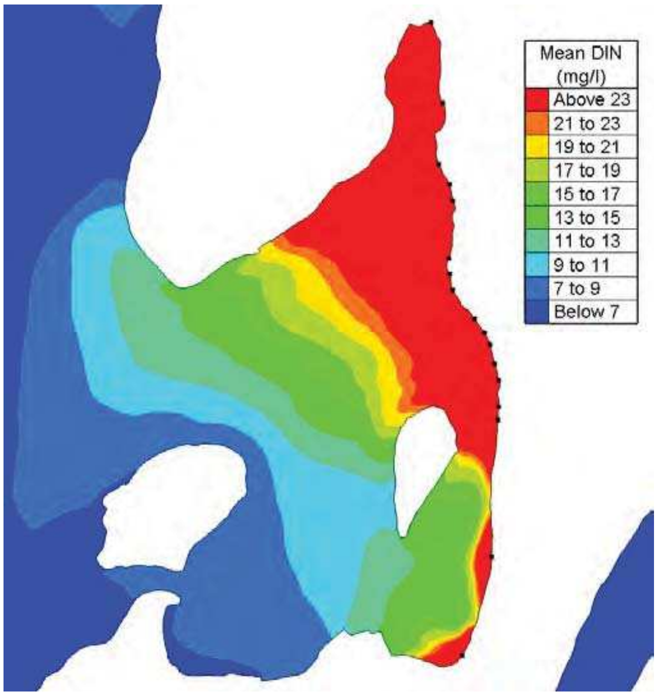

Figure 7: Mean concentrations of DIN at the sea surface for Scenario 2. The black dots represent the outfall positions.

seabed instead of the sea surface. For comparison with Scenario 1, the flow rates are set to 25.9 l/s, and the concentrations set to 500 mg/l.

The final scenario considers reducing the impact on Fatumara Bay as it contains ecologically important sea grasses. As depths are very shallow and the tidal exchange between Fatumara and Port Vila Bay is very small, high concentrations can build up quickly. In order to reduce concentrations, Scenario 4 uses only 12 of the 17 outfalls, with the five outfalls within Fatumara Bay closed off. The remaining 12 outfalls are positioned as in Scenario 3 with the same flow rate, concentration and seabed release.

V. Results

A. Scenario 1

Whilst the base case for validation was run for 30 days, the tracer studies were limited to 12 days. This encompassed the spring tides, representing the largest tidal range and fastest flows, meaning the dispersion of DIN would travel its furthest. Figure 6 shows the mean concentration of DIN at the sea surface, excluding the first 24 hours. The first 24 hours are excluded as the concentration of DIN starts uniformly at the background value and would bias the mean value. The black dots represent the position of the 17 outfalls.

The results agree with the trend seen in the observations in that the high concentrations are found in front of the Port Vila waterfront. The model also shows that concentrations within Fatumara Bay are even higher, with the mean concentration exceeding 30 mg/l, over 5 times the background value. The concentrations quickly start to build up within Fatumara Bay and after only four days the tracer distribution starts to resemble the mean values at the sea surface. Outside of

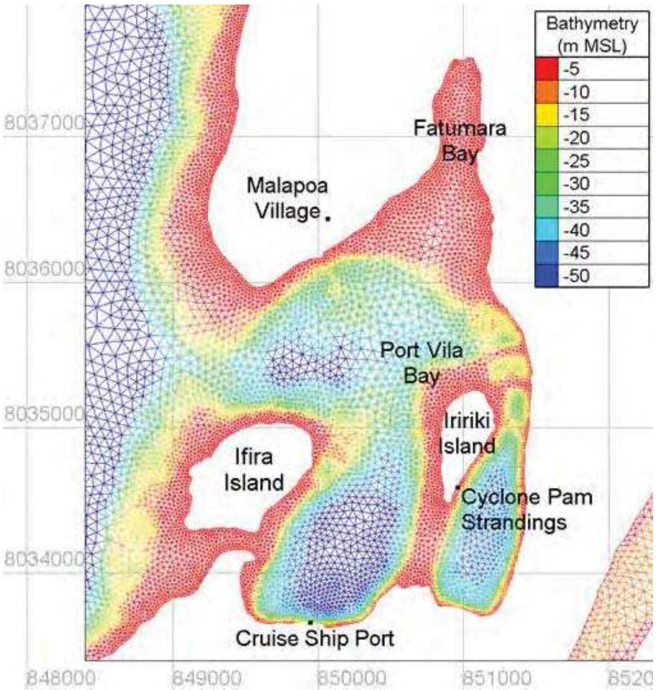

Figure 8: Bathymetry and key locations in Port Vila Bay.

Fatumara Bay, elevated concentrations permeate into the wider Port Vila Bay. However, the highest concentrations are limited to the immediate vicinity of the outfall positions and tend to hug the coastline, forming a narrow band of high concentration along the Port Vila waterfront. Whilst the model does show DIN from the outfalls leave Port Vila Bay, it quickly diffuses once into Mele Bay, as the bathymetry rapidly drops from approximately 45 m to over 300 m. The southern

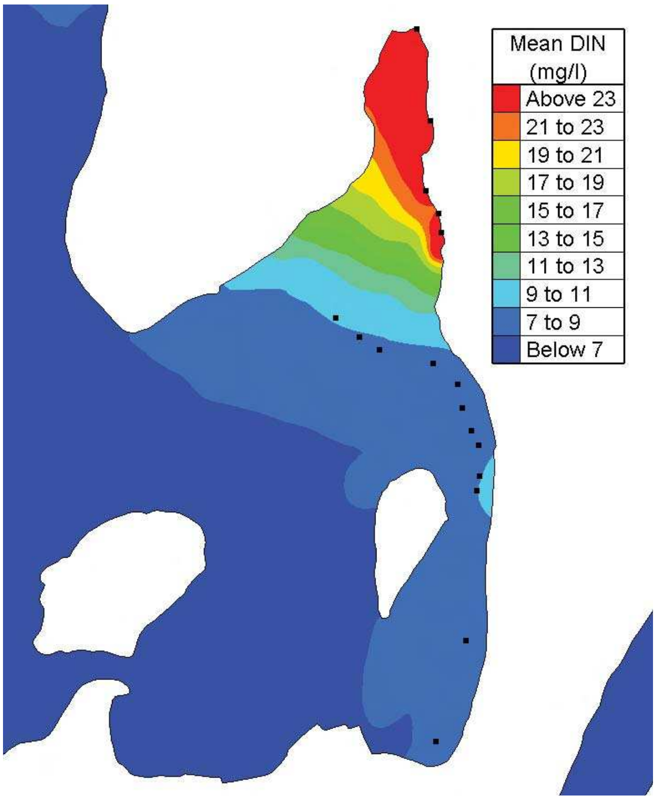

Figure 10: Mean concentrations of DIN at the sea surface for Scenario 3. The black dots represent the outfall positions.

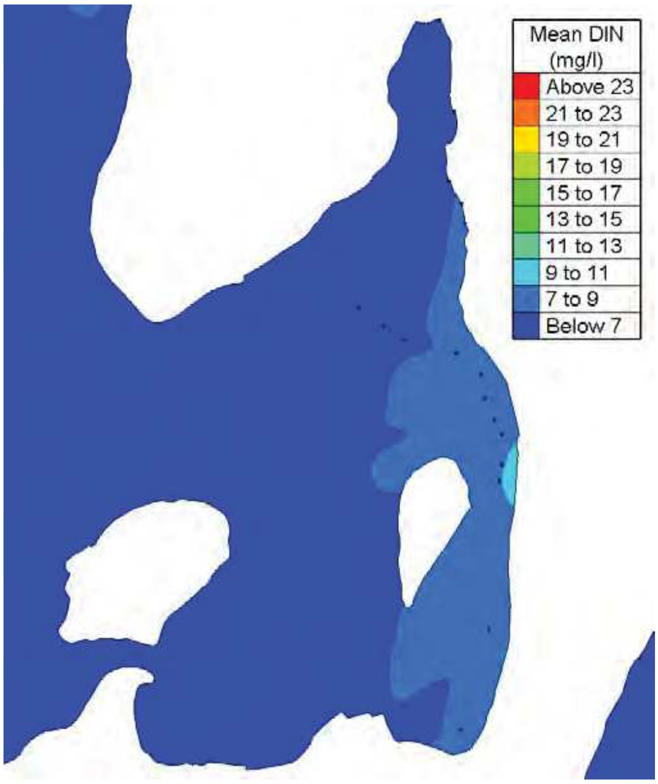

Figure 9: Mean concentrations of DIN at the sea surface for Scenario 4. The black dots represent the outfall positions.

half of Port Vila Bay can be split into two halves by Iririki Island and a bar that extends from its southern tip to the port harbour. Either side of this bar, the bathymetry drops into two deep craters, approximately 40 m deep. The result is the bar effectively acts as a barrier containing the higher concentrations within the eastern half.

B. Scenario 2

The results of Scenario 2 show a similar spatial distribution of DIN throughout Port Vila Bay as seen in Scenario 1. Unsurprisingly, the result of higher flow rate is a higher concentration of DIN throughout the Bay, as shown in Figure 7. Concentrations within Fatumara Bay now exceed 50 mg/l, over 10 times the background concentration. Within the wider bay, the DIN plume extends further west than Scenario 1 and the narrow band of high concentrations along the Port Vila waterfront extends almost 4 times further. Whilst higher concentrations reach into Mele Bay, they also dissipate quickly.

C. Scenario 3

Scenario 3 investigates the impact of moving the outfalls further offshore and releasing from the seabed. Figure 10 shows the mean concentration of DIN at the sea surface, with the new outfall positions shown as black dots.

The result is a dramatic reduction in the concentration of DIN at the sea surface, particularly in front of the Port Vila waterfront. Whilst the concentrations are still high at the seabed, by the time the concentrations have diffused through the water column to the sea surface, the values are significantly lower. Approximately 100 m off the Port Vila waterfront, the concentrations are reduced by 20 mg/l. This value rises to an excess of 100 mg/l reduction within the first 25 m off the waterfront where the public access points to water are located. Whilst there is a reduction in the mean concentrations within Fatumara Bay, the concentrations at the sea surface are still in excess of 25 mg/l.

D. Scenario 4

Scenario 4 investigates the impact of not allowing the outfalls to release in to Fatumara Bay using the same outfall positions as used in Scenario 3. Figure 9 shows the mean concentration of DIN at the sea surface. For comparison, the location of the outfall positions within Fatumara Bay are included in the figures, but the top five outfalls release no tracers.

The result of Scenario 4 shows the same response, as in Scenario 3, a dramatic reduction in the concentration of DIN at the sea surface. The difference between Scenario 3 and 4 clearly shows that the main contribution to the high concentrations within Fatumara Bay are from the outfalls not included and not the outfalls along the Port Vila waterfront. Whilst there is a small plume from the waterfront outfalls, the high concentrations attributed to these outfalls remains within close proximity to the waterfront.

VI. Discussion

One of the main problems with assessing the performance of the model is that it is significantly difficult to give an accurate quantitative assessment due to the number of

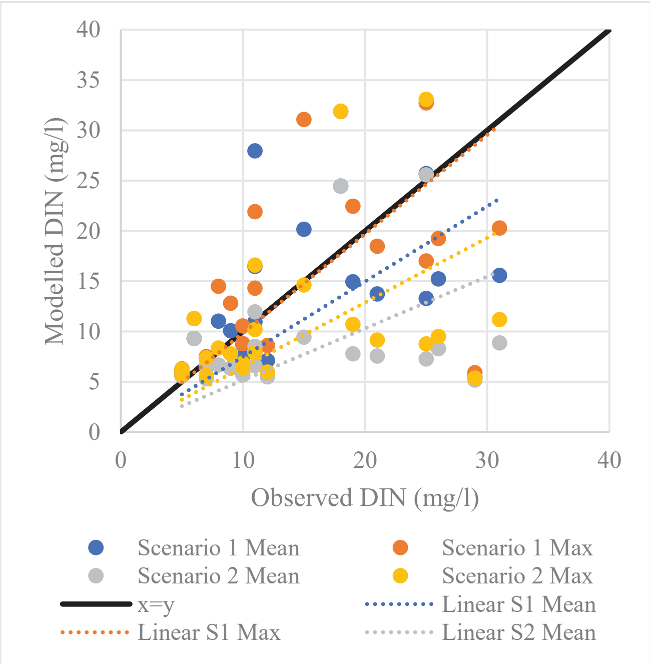

Figure 11: Comparison of the August 2016 observations and the mean and maximum concentrations of Scenario 1 and 2.

uncertainties with the model, notably the outfall flow rates and concentrations. One of the model assumptions is a constant flow rate and concentrations uniformly applied to every outfall. Realistically, these are likely to vary with time. Figure 11 shows the comparison between the observed concentrations in August 2016 and the mean and maximum concentrations of Scenario 1 and 2.

The lower flow rates of Scenario 1, overall, provide a closer representation of the observed concentrations. However, the model both under-predicts and over-predicts concentrations. Overall the model does qualitatively perform well, agreeing with the trends in the observations and representing many key features, such as the high concentrations in front of the Port Vila waterfront and the higher concentrations in the eastern half of the southern Port Vila Bay. One trend the observations show is that the concentrations in the eastern half of the southern Port Vila Bay are higher than the western half. The model shows this but under-predicts the concentrations in the eastern half. Whilst one solution would be to alter the outfall source conditions, the potential cause of the discrepancy is the lack of other sources. For example, there are no sources from the Port Harbour nor Iririki Island. The outfall for the Iririki Island resort is believed to be located to the south-east of the Island but could not be confirmed. The addition of this source, even with a constant flow rate and concentration is likely to improve the results. There are a number of other potential sources not included in the model that might change results, such as leeching from the stranded vessels from Cyclone Pam, the cruise ship port, the boat cleaning/repair site to the west of the cruise ship port, outfalls from the population of Ifira Island and outfalls from the population of Malapoa Village on the western shore of Fatumara Bay. These locations are shown in Figure 8 The likely consequence of including these additional sources is to raise the levels of DIN even higher within the bay.

Despite these uncertainties, the model does provide a good representation of the characteristics of the bay and can be readily applied to a number of different scenarios or assimilate any additional observation data. The purpose of the model is to provide a tool for investigating the potential problems and solutions for water quality within Port Vila, to which it has successfully demonstrated.

Presently, the outfalls along the Port Vila waterfront release at the sea surface. This is a potential hazard to those using the public access points for recreational activities, such as sea swimming, because of the buoyancy of the outfall plume. As a result, anyone entering the water must travel through the outfall plume. Figure 12 shows how the concentration of DIN develops in the vertical profile over the model run for a point approximately 175 m in front of outfall position number 13 from Scenario 1.

The results show that the concentration of DIN only disperses into the top layers, with the highest concentrations staying within the top two layers. Layer 7 represented a depth of 80 % of the water column. At this location, the depth was 15 m, meaning the plume was extending 3 m deep. Scenario 3 and 4 was effective at reducing the concentration of DIN along the waterfront by moving the outfalls further offshore into deeper water. By releasing from the seabed, the plume disperses both laterally and vertically. As there is significantly more water above the release point, the plume has a larger quantity of water to dilute and the concentration at the sea surface is dramatically reduced. However, this is also why Scenario 3 is not as effective at reducing the concentrations within Fatumara Bay as the bay is only a few meters deep. The plume permeates through the entire water column. The only solution to dramatically reduce the concentrations is to not release within Fatumara Bay, as shown in Scenario 4.

To provide a comparison between the four scenarios and to visualize the effectiveness of the proposed control measures, a horizontal profile of the concentration of DIN has been taken at the sea surface extending from within Port Vila Bay to the top of Fatumara Bay. Figure 13 shows the horizontal profile of the mean DIN concentrations at the sea

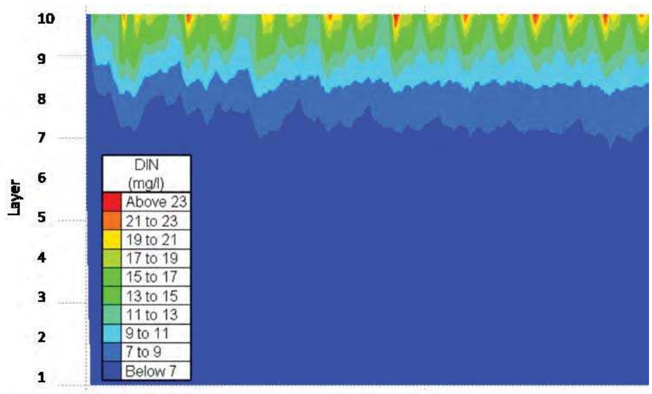

Figure 12: Vertical profile of DIN concentration in Scenario 1, approximately 175 m in front of outfall No.13.

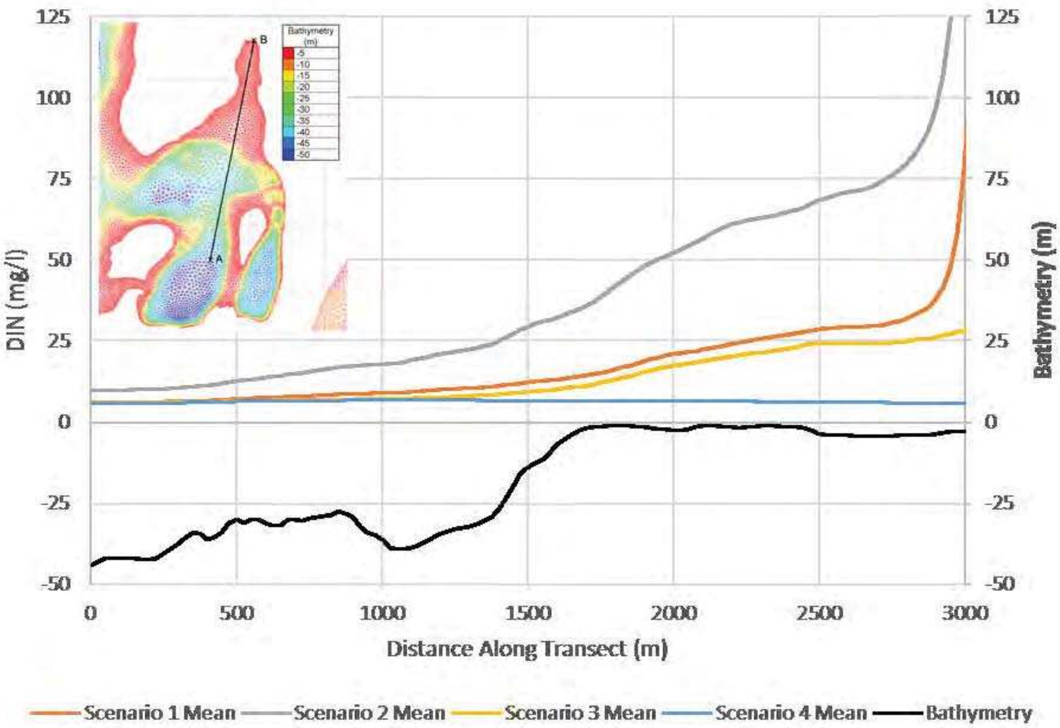

Figure 13: Horizontal profile of the mean DIN at the sea surface for all four scenarios.

surface for all four scenarios. In addition, the black line shows the depth contour along the transect.

By increasing the flow rate, in Scenario 2, to over three times that in Scenario 1, the concentration of DIN is almost doubled. Furthermore, it can be clearly seen that the concentrations dramatically increase as the depth of water reduces into Fatumara Bay. Again, the figure reiterates the only way to radically reduce concentrations in Fatumara Bay is to not release within the Bay. The 3 m depth contour along the shelf edge of Fatumara Bay would provide a natural delineation in which to mark a no release zone.

VII. Summary

A 3D barotropic model of Port Vila, on the island of Efate, has been developed as part of the wider water quality monitoring programme in Vanuatu. Integrated analysis of the water quality data identified the coastal hot spots for Port Vila, and showed that urban run-off is a serious issue in the coastal area. The purpose of the model was to provide a more accurate representation of pollutant dispersion in Port Vila Bay, over the existing 2D model.

Those undertaking recreation activities in the bay, such as swimming, are vulnerable to exposure to high concentrations. The model shows that outfalls form a buoyant plume along the Port Vila waterfront. Moving the outfall positions approximately 100 m offshore and releasing at the seabed was shown to be effective at reducing concentrations. Fatumara Bay contains ecologically important sea grasses which are particularly vulnerable. The model shows high concentrations quickly build up due to the shallow depths and small tidal exchange between Fatumara and Port Vila Bay. Whilst the outfalls along the waterfront do contribute to the build-up, the outfalls in the bay are the main problem. The most effective way to limit concentrations is to allow no outfalls to release into Fatumara Bay. The 3 m depth contour along the shelf edge of Fatumara Bay would provide a natural delineation in which to mark a no release zone.

The purpose of the model is to provide a tool for investigating the potential problems and solutions for water quality within Port Vila. The control measures tested with the model were shown to be effective, but there are no substitutes for a fully functioning sewage treatment system. The model is readily adaptable to test alternative solutions.

Acknowledgement

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