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Developing a water quality modelling toolkit: Load estimates in Port Phillip and Western Port catchments

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Abstract:

Waterways transport nutrients, sediment, organic matter and other pollutants from catchments to coastal environments. This is a dynamic process influenced by a range of factors, including climate, land use, topography and hydrology. These processes and the potential impacts to waterways and receiving waters can be difficult to characterise, particularly at large spatial scales. Therefore, the development of reliable methods for quantifying these complex processes is important for understanding the threat to aquatic ecosystems and targeting management interventions.

Water quality models are an effective tool to simulate the mobilisation, transport and delivery of pollutants at catchment-scale. The simulations can predict pollutant loads at catchment outlets, which represent the cumulative effects of these water quality processes. To this end, Melbourne Water together with the Victorian government and Jacobs as a technical partner, have established a modelling framework to estimate catchment loads to Port Phillip Bay (PPB) and Western Port (WP). A water quality model was developed in 2015 using eWater Source platform as a tool to estimate catchment loads (the “model”). Since then, the model has been further developed and refined, with significant upgrades in 2017 and 2019, to improve the reliability of the model outputs.

The model spans the catchments of PPB and WP and estimates the daily delivery of pollutants and flow from major catchments surrounding these two bays. It provides inputs to marine hydrodynamic modelling of the PPB and WP receiving waters, and has capabilities for predictive analysis, such as climate and land use change assessments and testing of catchment interventions. The model is a useful tool for estimating annual loads when observed data is sparse and assessing changes over time by simulating longer time periods that could be determined by traditional monitoring alone.

To illustrate the value of this modelling framework, we describe a recent application of the model to estimate annual pollutant loads over the last twenty years for input to the State of Marine and Coastal Environment (SMCE) Report for Victoria. The results for nitrogen and sediment indicate that the long-term mean annual load (MAL) for the period 2000 to 2023 are within pollutant load objectives for PPB and WP, however, there is year-to-year variation that is closely correlated with rainfall. A comparison of the long-term MAL against the mean from the last 3 years (2020-23), indicates an increased trend in nitrogen and sediment loads over this recent period that was largely driven by high rainfall events.

In conclusion, the PPB and WP model is a valuable method for estimating catchment loads of key pollutants to receiving waters. The predictions are useful for evaluating long-term condition and decadal change, as well as understanding the key drivers of pollutant loads. There are some known limitations of the model, including sources of uncertainty and constraints on confidence for model outputs. But when coupled with other assessment tools, such as empirical monitoring of in-stream water quality and calculations of observed loads, it can form an important part of an environmental risk assessment approach for catchment managers. Therefore, an ongoing process of model development to enhance this modelling toolkit is necessary to address key limitations, reduce uncertainty and incrementally improve the reliability of the model outputs.

Keywords: *Water quality modelling, pollutant loads, nutrients, sediment*

1. INTRODUCTION

Transport of aquatic pollutants from catchments to receiving waters is a dynamic process that is influenced by a range of factors, including climate and rainfall, land use, topography and hydrology. These features of the landscape affect the sources, mobilisation and delivery of pollutants to receiving waters (Lintern et al., 2018). There are various indicators that measure water quality and the associated pollution inputs to waterways. Water quality indicators are often reported as a concentration, which represents condition at the time of sampling at a set location. However, there are instances when a total mass or 'load' is a more informative approach for assessing pollutants from a defined catchment area. Loads can reflect the cumulative impact on receiving waters and, when estimated annually, can be used to assess whether key pollutants are changing over time.

Port Phillip Bay (PPB) and Western Port (WP) are enclosed embayments in central Victoria. They are susceptible to catchment inputs due to limited mixing with oceanic waters. In particular, nitrogen is critically important for PPB because the bay is a biologically dominated system and catchment inputs of nitrogen influence phytoplankton dynamics (CES, 2016). In contrast, in Western Port suspended sediment is a key contributor to reduced water clarity and altered light availability for seagrass habitats (MW, 2018). Estimating loads of pollutants, such as nutrients and sediment, is therefore important in evaluating the potential impact of catchment inputs on the health of these ecosystems.

Table 1. Pollutant load objectives for Port Phillip Bay and Western Port (EPA, 2021).

Region	Pollutant	Indicator	Objective (annual average)
Port Phillip Bay	Nitrogen	TN from surrounding waterways	1,500 to 2,200 tonnes
		TN from the Yarra and Maribyrnong Rivers	Contribution of total nitrogen load not to exceed 70% of total annual average load from all surrounding waterways
	Sediment	TSS from surrounding waterways	60,000 to 70,000 tonnes
		TSS from the Yarra and Maribyrnong Rivers	Contribution of TSS load not to exceed 70% of annual average load from all surrounding waterways
Western Port	Sediment	TSS from surrounding waterways	28,000 tonnes

The Environment Reference Standard (ERS) for Victoria includes pollutant load objectives for PPB and WP, as shown in Table 1. The ERS objectives are intended to drive management interventions and investment to reduce pollution across catchments. They represent a benchmark to assess risk to the environmental values of these waterbodies, but are difficult to quantify using monitoring alone. Models are a useful tool to quantify water quality processes at catchment-scale and estimate pollutant loads to receiving waters. A water quality model using the eWater Source platform was developed in 2015 as a tool to estimate annual loads of nutrients and sediment from the PPB and WP catchments ("the model"). Since then, Melbourne Water together with the Victorian government and Jacobs as a technical partner, have developed and refined the model to improve reliability and reduce uncertainty in the model's outputs (Cetin *et al*., 2022). The model was recently used to estimate pollutant loads for input to the State of Marine and Coastal Environment (SMCE) Report. This application demonstrates the value in ongoing refinement of the model to assess trends over time and identify the key drivers of pollutant loads.

2. METHOD

2.1. Study Area

The Port Phillip and Western Port region is located in Victoria, Australia, and spans over 16,000 km² (Figure 1). There are two large cities, Melbourne and Geelong, which support more than 5.5 million people. The major PPB river basins are the Yarra, Maribyrnong, Werribee, and Dandenong. The catchments of the Bunyip, Lang Lang, Bass Rivers, and Cardinia Creek flow into WP.

The landscape features a diverse mix of land use, including urban (14%), agriculture (44%) and forested (42%) areas. There are significant conservation reserves and protected water supply catchments that are located at the headwaters of the river basins. There are also important biodiversity hotspots in the region, such Ramsar wetlands, and an UNESCO Biosphere Reserve.

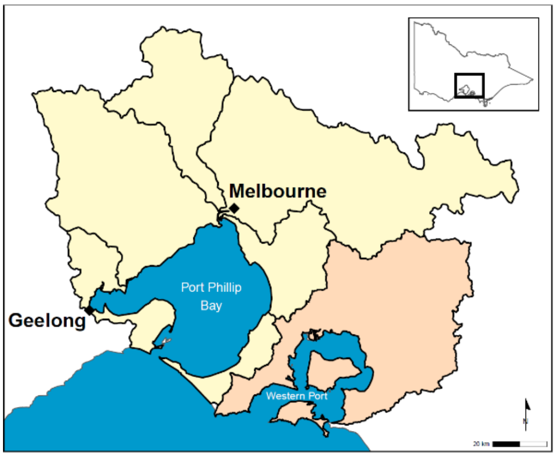

Figure 1: Location of Port Phillip Bay and Western Port, and their catchments (PPB - yellow, WP - orange).

2.2. Modelling framework

The PPB and WP catchment model is a regional-scale water quality model designed to calculate monthly and annual loads of nutrients and sediment to the bays. The model is a valuable tool for estimating annual loads when observed data is sparse. In addition, it provides inputs to biophysical hydrodynamic modelling of both PPB and WP marine environment, and predictive analysis, such as climate and land use change assessments and testing catchment intervention.

The model was developed in 2015 using the eWater Source platform as a tool to estimate annual loads of nutrients and sediment from the catchments to PPB and WP and was used to inform development of Port Phillip Bay Environmental Management Plan (2017). In 2019, several enhancements were made to the model and since then Melbourne Water, in partnership with DEECA, have made successive updates to reduce uncertainty and improve usability. In 2023, the model was separated into two distinct parts:

- **Port Phillip Bay catchments -** Source model for estimating nutrient and sediment loads from catchments draining to PPB using an EMCDWC approach for nutrient and sediment generation.
- **Westernport catchments**- Source + dSedNet model for modelling nutrient and sediment loads from catchments draining to WP using the daily SedNet model for sediment generation, developed in partnership with CSIRO (Cuddy *et al*., 2019), and an EMCDWC approach for nutrient generation.

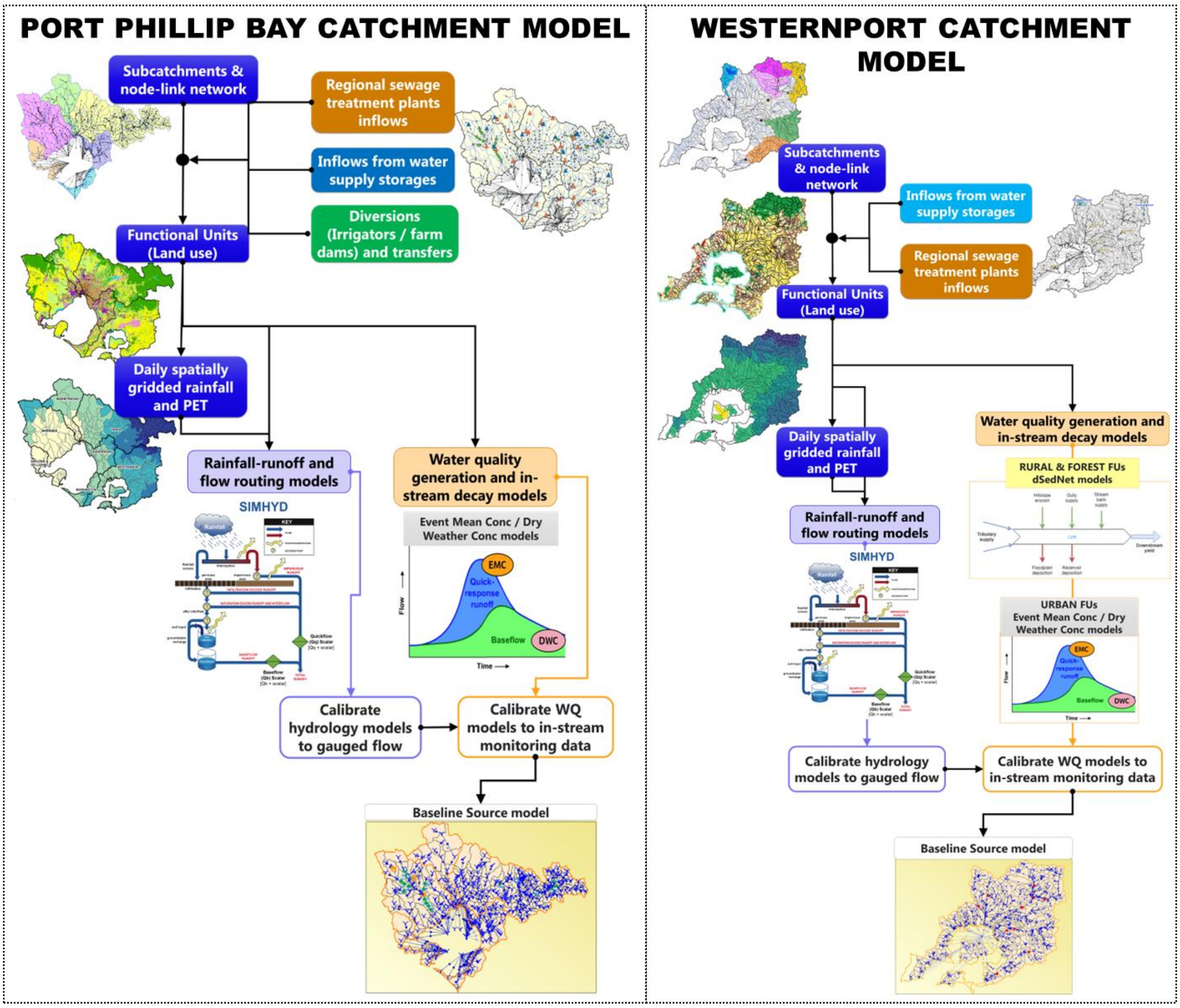

Figure 2: Overview of the PPB and WP model framework, structure, key features and inputs.

The model has numerous spatial inputs, including sub-catchment boundaries, node-link network of the river systems, land use and spatially gridded climate (Figure 2). The node-link network of the river systems includes daily timeseries of point-source discharges, such as from regional sewage treatment plants (STPs), releases from drinking water storages and rural demands. Runoff is generated by SIMHYD rainfall-runoff models and pollutant concentrations from different land uses are generated by Event Mean Concentration Dry Weather Concentration (EMCDWC) models. In-stream processing models attenuate pollutant loads through the node-link network.

Water quality parameters currently included in the model are total nitrogen (TN), total phosphorus (TP) and total suspended solids (TSS), as well as daily flow (ML/d). The model has been calibrated to 40 measured streamflow and 32 in-stream concentration data from Melbourne Water's stream monitoring networks. In addition, a loads monitoring program called 'NLOADS' run by Melbourne Water from 2006 to 2015 has been used to validate model estimates. This program included grab sampling during rainfall events and produced annual estimates of 'measured' loads (Moroka, 2016), in comparison to modelled loads. However, not all areas of the catchments were able to be measured by this program (76% of PPB catchments, 40% of WP catchments, remaining areas ungauged).

The PPB model estimates nutrient and sediment loads at a daily time step, with a full simulation period of 1 Jan 1975 to 31 Dec 2024. A slightly shorter simulation period is adopted for the WP model due to the length of the available cover factor inputs which are constrained to 1 Jan 2001. Note that for simplicity, only TN (for PPB only) and TSS (for PPB and WP) are discussed in this paper. These parameters are considered critically important for both bays and have corresponding load objectives for comparing trends over time.

The calibration strategy adopted for the model follows best practice modelling approaches (e.g. Vaze et al., 2011) and assess model performance against industry standard criteria (Moriasi et al, 2015). The model performs well in predicting flows across the major river basins of PPB and WP (Table 2). The PPB model simulates nutrient annual loads reasonably well but substantially underestimates sediment loads (Table 2). The model is also limited at predicting annual nutrient loads for years with major flood events, such as in 2011 (Figure 3). The adoption of dSedNet for WP has resulted in a good fit to measured annual TSS loads, particularly with loads generated during years with peak flow events (Figure 3).

Table 2. Model performance statistics (% bias – difference between modelled and measured means; Nash–Sutcliffe Efficiency (NSE) - goodness-of-fit between model and observed data, where 0 is poor and 1 is a perfect fit to observed data). Performance statistics are estimated based on the combined flows and loads at the major watercourses draining to PPB and WP.

		Daily Flows	Annual TN Loads	Annual TSS Loads
Port Phillip Bay	% bias	-8.1%	11%	54%
	NSE	0.76	0.63	0.07
Western Port	% bias	-0.1%	4%	-25%
	NSE	0.71	0.5	0.85

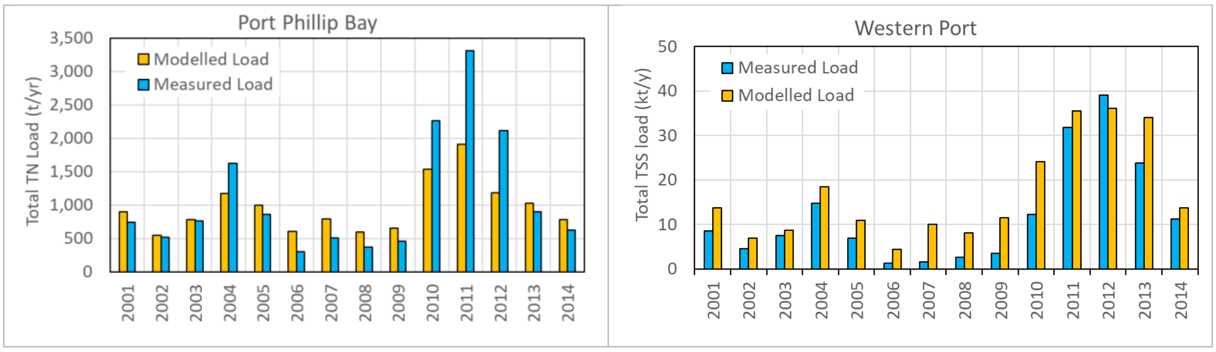

Figure 3. Comparison of annual TN and TSS loads from PPB and WP respectively, calculated from observed and modelled data.

3. RESULTS AND DISCUSSION

3.1. Port Phillip Bay (PPB) and catchment

The annual load estimates to PPB from the catchments for TN and TSS (tonnes/year) from 2000 to 2023 are presented in Figure 4. It shows that the model estimates of annual loads are generally within ERS objectives, with some exceptions during 2010-11 and 2020-22. The year-to-year variation is largely driven by rainfall-runoff processes, as shown by the close correlation with mean annual rainfall. The periods where loads are estimated to have exceeded ERS objectives correspond to wetter years. The 2020-23 period was particularly wet, with above average rainfall occurring in three consecutive years driving higher load generation from the catchments. The last time this occurred was during 2010-11 when there were significant flood events in the PPB catchments.

Figure 5 shows the relative contribution of TN and TSS from each of the major PPB catchments. Uncertainty estimates for modelled annual loads are in the order of ± 30-55% for nutrients and sediments, determined through a Monte Carlo Simulation with Latin-Hypercube sampling approach (Cetin et al., 2022). The Yarra River has the largest catchment area and correspondingly produces the highest annual loads of both TN and TSS. The proportion of TN from the Yarra and Maribyrnong catchments is estimated at 62% (average 2000-23) of total catchment loads to PPB, which is below the ERS objective of 70% from all surrounding waterways. Similarly, the average proportion of TSS load from the Yarra and Maribyrnong was estimated at 52%, below the 70% target.

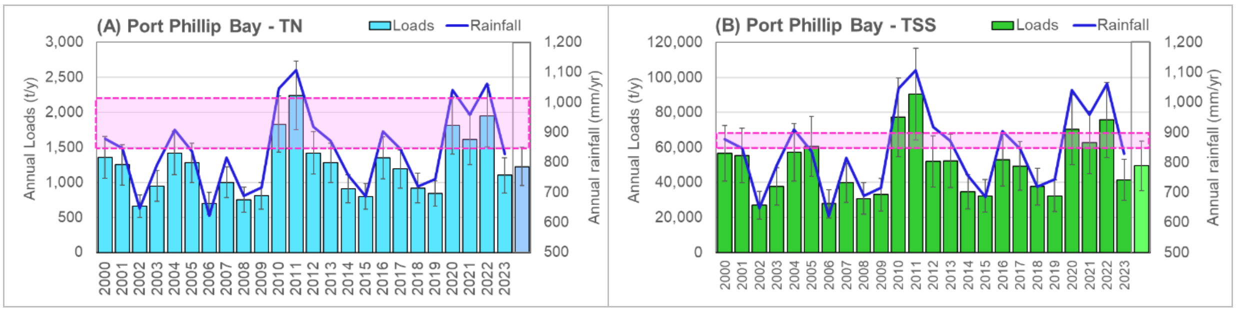

Figure 4: Modelled annual loads to PPB, with 95% confidence interval for (A) TN and (B) TSS. The modelled mean annual loads across the 2000 – 2023 period is presented in the far-right column. Pink dash lines indicate the ERS load objectives. Mean annual rainfall calculated from catchment average AWAP data used as input to the models.

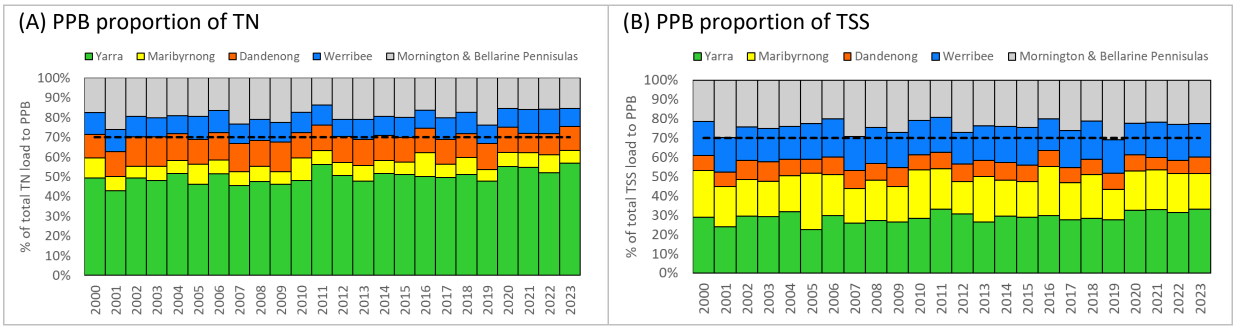

Figure 5: Proportion of (A) annual nutrient and (B) sediment loads to Port Phillip Bay from the major river catchments.

Table 3 shows a comparison of the long-term average in mean annual load (MAL) for the period from 2000-2023, against more recent periods of 2016-2019 and 2020-2023. The results for PPB indicate an increased trend in nitrogen and sediment MAL over the most recent period, largely driven by high flow events in 2020-22. Despite the elevated mean annual nutrient loads over the 2020 to 2023 period, the model estimates TN loads to be within the ERS objectives overall at 1620 t/yr, below the upper limit of the ERS of 2200 t/yr. Similarly, the TSS loads were within the ERS load objectives overall at 62,525, below the upper limit of 70,000 t/yr.

Table 3. Comparisons of mean annual load (MAL) model estimates to PPB and WP for the last 3 years (2020 to 2023), previous 3 years (2016 to 2019), the long-term average (2000 to 2023), and measured loads calculated from NLOAD catchments.

	Port Phillip Bay		Western Port
Mean annual load (t/y)	**TN**	**TSS**	**TSS**
MAL (2020 – 2023)	1,620	62,525	30,070
MAL (2016 - 2019)	1,075	43,000	18,890
Long-term MAL (2000 – 2023)*	1,225	49,475	22,400
Measured loads (2000 – 2015)	1,300	69,000	29,000

*For Western Port this period is 2001-2023.

3.2. Western Port (WP) and catchment

The annual TSS loads to WP from the catchment as estimated by the model for the period 2001 to 2023 are presented in Figure 6A. It shows that the annual load estimates are generally within the ERS objectives, with some exceptions including between 2010-13 and 2020-22. Similar to PPB, the year-to-year variation in WP modelled loads is largely driven by rainfall-runoff processes, with increased loads during wetter periods in 2020-23 and 2010-13. Figure 6B shows the relative contribution of TSS from each of the major WP catchments. The Bunyip River and the Lang Lang Rivers are the largest contributors of sediment compared to the other catchments.

Table 3 provides the annual load estimates for TSS for the reporting period of 2001 to 2023. These are compared to the most recent 3-year periods of 2020-2023 and 2016-19, as estimated by the catchment model. Similar to PPB, the results indicate an increased trend in sediment loads over the 2020 to 2023 period, largely driven by high flow events in 2020-22. Most notable is in 2022 for the rural dominated catchments where major flooding occurred. Over the long-term reporting period, mean annual TSS loads are below the ERS load object at 22,400 t/yr, although the ERS objective is exceeded during the 2020 to 2023 reporting period with a MAL of 30,070 t/yr.

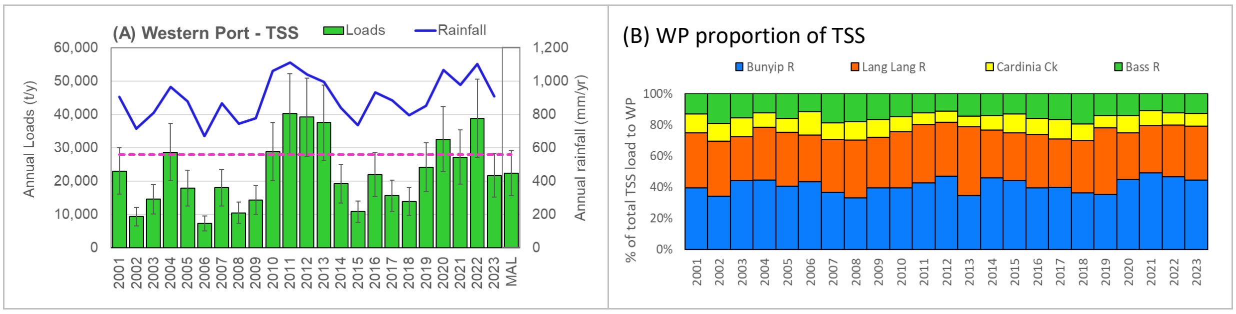

Figure 6: (A) Modelled annual TSS loads to WP, with 95% confidence interval. The mean annual load across the 200023 period is presented in the far-right panel. Pink dash lines indicate the ERS load objective. Mean annual rainfall calculated from catchment average AWAP data used as input to the models. (B) Proportion of TSS loads to WP from the major river catchments.

3.3. Major drivers of pollutant loads

A key driver of catchment nutrient and sediment loads is rainfall-runoff processes. Wetter periods can increase the mobilisation of pollutants, such as nutrients and sediment, and transport these to waterways and bays. In contrast, long-periods of dry weather can reduce runoff and streamflow but increase salinity and water temperatures. The 2020-22 period had three consecutive years above average rainfall, as shown in Figure 4 for PPB and Figure 6A for WP. From 2020 to 2023, there was a protracted (multi-year) La Niña together with a negative phase of the Indian Ocean Dipole and a positive phase of the Southern Annular Mode, which began around October 2020 and subsided in the summer of 2023 (BoM, 2023). El Niño emerged in the autumn of 2023 and persisted for the remainder of the year (BoM, 2023). The protracted La Niña resulted in substantial rainfall events and flooding across much of Melbourne, contributing to an increase in nutrient and sediment mean annual loads from PPB and WP catchments during 2020 to 2023. Whereas, with the onset of El Niño in 2023 and a return to average annual rainfall totals, loads reduced to similar levels observed during 2016 to 2019.

3.4. Limitations

A significant challenge is developing a modelling framework that represents the hydrology and pollutant export of highly modified catchments (e.g. channelised waterways and substantial river regulation) at large spatial scales, which is commensurate with available data. The framework needs to be of sufficient complexity to capture diverse hydroclimatic conditions, diffuse pollutant loads from a diverse range of land uses, point-sources and both existing and potential integrated water management practices. The model developed for PPB and WP catchments endeavours to balance these complexities by adopting a regional spatial scale for deriving daily estimates of catchment flows and pollutant loads, and introducing complexity where local knowledge, scientific understanding and quality data will support it.

Adopting the daily SedNet functionality for the WP catchment model has notably improved TSS annual load predictions and the confidence in annual sediment load predictions. While the PPB model is considered reliable for predicting annual nutrient loads, the model is less reliable for predicting sediment loads, and therefore there is less confidence in these results. The modelled distribution in annual loads gives an indication of the potential magnitude of loads that can be estimated by the model. For nutrients, these are within the range for loads calculated with measured data. This is not the case for sediment loads, which are significantly underestimated (Table 3).

The performance of the model in predicting event loads during high flows is limited. A large proportion of the annual load is typically delivered during high rainfall and flow events in short time frames (Moroka, 2019). However, the model has limitations in estimating loads for years with large flow events. The EMCDWC model structure is simplistic and does not represent the complex water quality processes that generate catchment loads. EMC data, by its very nature, is less common than DWC hence it is more difficult to parameterise. This gives rise to uncertainty that is more obvious in flood dominated years.

3.5. Future development of the model

Over several years, MW in partnership with DEECA have invested in maintaining and improving the model to enhance data outputs and reduce uncertainty in annual load estimates. This has enabled its use for scenario analysis, including future applications such as assessing climate and land use change impacts on catchment flows and loads, and evaluating catchment management interventions. Recent research and targeted event-based water quality data offer opportunities to recalibrate the model and refine EMCDWC parameters, leading to more reliable estimates and stronger predictive capability for load reduction strategies.

4. CONCLUSIONS

The PPB and WP catchment model is a valuable tool for estimating annual nutrient and sediment loads, especially in areas with limited stream flow gauging or water quality data. The model effectively simulates annual load trends and year-to-year variability driven by rainfall-runoff processes and land use characteristics. While the PPB model performs reasonably well for nutrient loads, it significantly underestimates sediment loads and is limited at predicting years with major flood events. Adopting dSedNet for modelling sediment loads from WP catchments has improved the prediction of annual TSS loads. Overall, the year-to-year variation in modelled loads is primarily driven by rainfall-runoff processes, whereas differences in the spatial distribution of annual loads is influenced by land use and the associated generation parameters. The model offers strong potential for regional-scale scenario testing of catchment interventions to further understand the key drivers of pollutant loads.

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