

HYDRODYNAMIC AND WATER QUALITY MODELLING IN SYDNEY HARBOUR

Pei Tillman, Jonathan Dixon, Yue-Cong Wang and Merran Griffith¹

The Sydney Harbour waterway modelling suite examines the changes in water quality in the harbour estuary and its tributaries associated with stormwater runoff and wet weather sewage overflows from the upstream catchments, in Sydney Australia. This paper discusses the development and performance of the numerical models. The models have been used to investigate the spatial variability of catchment pollutant loads and the impacts of sewer overflows on the water quality in the Sydney Harbour estuary. The scenario modelling results demonstrate that sewer overflows have a minimal impact on the Sydney Harbour estuary water quality, with stormwater dominating most changes in water quality.

Keywords: Sydney Harbour; catchment; stormwater; wet weather sewer overflow; hydrodynamics; water quality; numerical modeling

INTRODUCTION

Sydney Water is Australia's largest water utility, supplying water, wastewater, recycled water and some stormwater services to more than five million people. Sydney Water's sewage network is licenced under Environment Protection Licenses for each wastewater treatment system issued by the New South Wales Environment Protection Authority (EPA). Under licenses issued in 2000, overflow frequency targets were applied to all overflows in the system, regardless of system size, environmental value and cost/benefit. Sydney Water has been working with the EPA to transition to a new risk-based approach for wet weather overflow abatement by using an effects-based assessment (EBA). The EBA approach assesses the relevant water body as a whole. Water quality modelling is one of the tools to help assess public health and environmental impacts, and to separate the contributions from stormwater and overflows. This is done by comparing the predicted concentration levels from the proposed mitigation options for different sewage overflow events with a base case. The model outcomes assist the wet weather overflow abatement (WWOA) decisions and regulatory discussions regarding a risk licensed approach and prioritising site remediation. For this purpose, Sydney Water developed the Sydney Harbour hydrodynamic and water quality models between 2013 and 2017. This included monitoring for the model calibration and validation.

The Sydney Harbour catchment covers an area of approximately 482 km². The catchment is highly urbanised with approximately 48% imperviousness. It is comprised of 47% residential land use, 12% commercial and industrial, 20% road and railways and 21% park and bushland (Table 1). There are 549 sewer overflows in the Sydney Harbour catchment. The bubble size in Figure 1 indicates total sewer overflow volume over the ten year (1985 to 1994) weather conditions. The Sydney Harbour model consists of four upstream tributary models and the downstream Sydney Harbour estuary model (Figure 1). These four upstream tributaries are the Upper Parramatta River, Upper Lane Cove River, Upper Duck River and Vineyard Creek. The four freshwater systems are modelled separately to accommodate the presence of weirs, other flow control structures and the steepness of waterway in upstream reaches. The outflows from the four upstream models feed into the Sydney Harbour estuary model.

Region	Catchment area (km ²)	Impervious (%)	Residential (%)	Commercial & Industrial (%)	Park & Bushland (%)	Transport (%)
Sydney Harbour estuary	285	52	44	14	21	21
Upper Parramatta River	108	45	53	9	17	20
Upper Lane Cove River	66	30	48	10	25	17
Upper Duck River	19	63	47	15	18	20
Vineyard Creek	4	46	58	1	22	19
Total	482	48	47	12	21	20

¹ Sydney Water, 1 Smith Street, Parramatta, NSW 2150, Australia

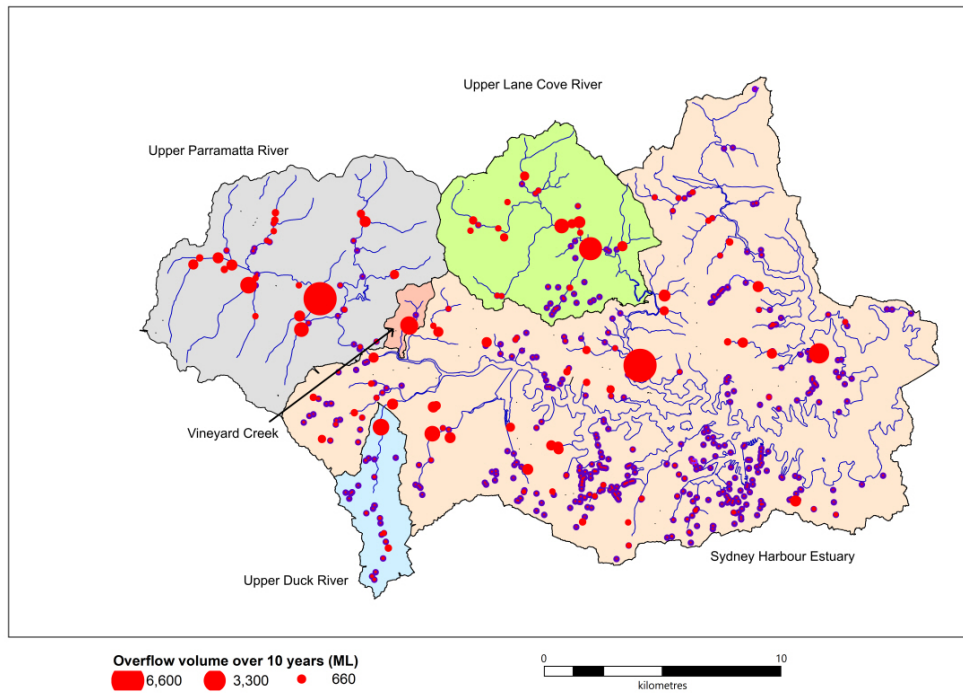


Figure 1. Sydney Harbour model catchments

APPROACH

Figure 2 illustrates the Sydney Harbor modelling framework. It consists of a catchment rainfall-runoff model, a model for urban sewers (MOUSE), and depth-average hydrodynamic and water quality models for the rivers and estuary (RMA2/RMA10 and RMA11). The Sacramento rainfall-runoff model was used to estimate the stormwater quantity and quality (diffuse source) from the catchments. The MOUSE model was used to estimate water quantity and quality from the sewer overflows discharged into the waterway. Stormwater and overflow discharges generated from both the catchment and MOUSE models were used as inputs to the Resource Modelling Associates (RMA) models. The RMA modelling suite was used to simulate the hydrodynamic movement, advection, dispersion and chemical/biological reactions of introduced constituent concentrations in rivers and the Sydney Harbour estuary.

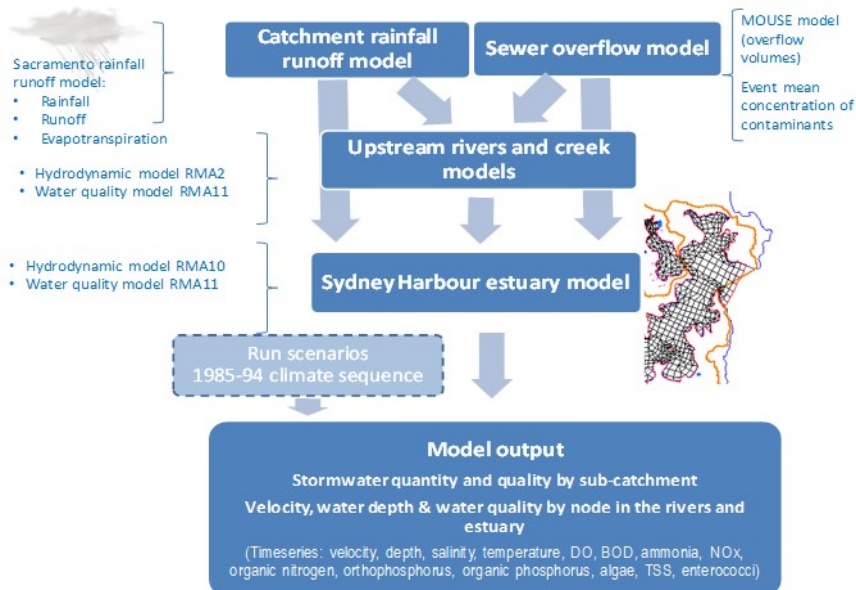


Figure 2. Sydney Harbour modelling framework

Monitoring campaign

To inform the model build, calibration and validation, Sydney Water implemented a monitoring campaign to ensure adequate data was available. The locations of monitoring sites within the Sydney Harbour catchments are shown in Figure 3. Monitoring included the collection of extensive bathymetry data, monitoring wet weather overflow discharge quality using autosamplers, and an intensive wet weather water quality sampling campaign. The intensive wet weather campaign involved the collection of grab samples from 25 sites every five days immediately following a large wet weather event. This also included water quality profiles at each site of standard physico-chemical measurements. In addition, we coordinated a widespread campaign where Acoustic Doppler Current Profile (ADCP) transects were taken at twelve sites during wet weather and seven sites during dry weather over the full flood and ebb tidal cycle. This included measurements of conductivity, water temperature and depth, as well as water quality profiles, at a minimum of three locations along each transect.

Assumptions

There were three main water quality assumptions used in the Sydney Harbour models (Tables A-1 to A-3 in the Appendix). These included: background water quality concentrations in the waterways; stormwater water quality; and wastewater overflow water quality. The stormwater water quality model is based on the assumptions of the event mean concentrations (EMCs) and the dry weather concentrations (DWCs) assigned to each land use. The EMCs and DWCs are also used as tuning parameters for the models. The final values adopted for this project were within the ranges provided by Duncan (2006). The EMC for the wastewater overflows were based on observations at several overflow locations and events in the region.

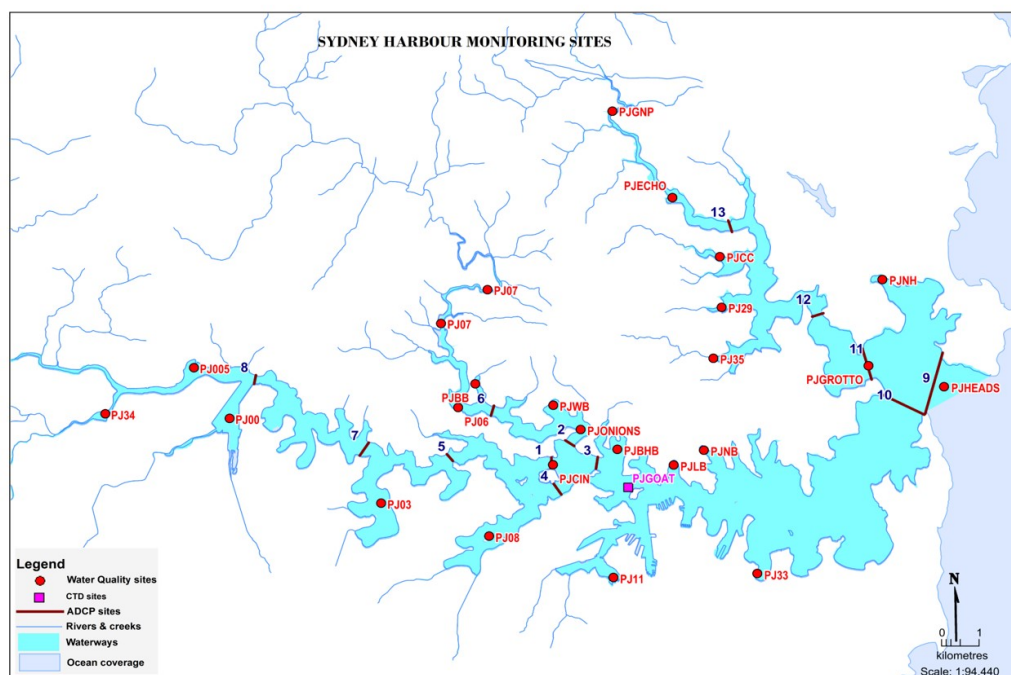


Figure 3. Sydney Harbour monitoring sites

MODEL PERFORMANCE

The hydrodynamic and water quality models were calibrated and validated using data collected during 2013 and 2014. We used several statistical measures to assess the closeness of the model results to the observations. These included the Nash-Sutcliffe coefficient of efficiency (NSE), percent bias (PBIAS), the ratio of the root-mean-square error to the standard deviation of the field observation (RSR) (Moriassi et al, 2007) and the correlation coefficient (r^2). Table 2 shows the acceptability criteria used as a guideline to assess model performance. The water quality model acceptability criteria were generally less strict than the hydrodynamic model due to the smaller sample dataset.

Figures 4 to 5 show the model performances using acceptability criteria at the monitoring sites across time. The orange circles and black arrows indicate which part of the charts was in the acceptance range of the performance. Outside of the circle is for NSE, between the circles for PBIAS, inside of the circle for RSR and outside of the circle for the correlation coefficient (r^2). With these results achieved, the models were considered fit for the scenario modelling.

Model	NSE	PBIAS	RSR	r^2
Hydrodynamic model	> 0.5	within \pm 25%	< 0.7	> 0.5
Water quality model	> 0.2	within \pm 50%	< 0.9	> 0.5

SCENARIO MODELLING

Ten-year rainfall data (1985 to 1994) was applied across the Sydney Harbour models for scenario modelling. This ten-year period comprises a range of weather conditions including both wet, dry and average monthly rainfall and provides a common basis in Sydney Water's wastewater system planning framework. The scenario of 'Stormwater Only' along with the existing conditions of 'Stormwater and overflows' were modelled to assess the impact of the overflow discharges into the Sydney Harbour estuary. The statistical percentiles of modelling outputs from the full ten-year scenario modelling period provided robust profiles of water quality concentrations throughout the Sydney Harbour estuary.

Spatial variability of catchment loads

The Sacramento model in this modelling framework generated the stormwater quantity and quality exports to the upstream rivers and estuary. The combined stormwater and sewer overflows determined the water quality of the waterways. Figure 6 illustrates the spatial variability of the combined stormwater and overflow yield per km^2 across the catchments. The map was derived from averaging the 10-year time series of 'Existing' scenario modelling results normalised by each sub-catchment area. It showed the high stormwater yield was more likely in the catchments of Middle Harbour and the lower estuary. This was mainly due to increasing annual rainfall toward the coast. The size of bubble in Figure 7 represented average annual rainfall for each virtual rain station used in the scenario modelling over the ten year period (1985 to 1994). The low imperviousness in the catchments of the Upper Lane Cove River contributed to low yield rates of stormwater in that area. The extreme high yield ($>90 \text{ m}^3/\text{hour per km}^2$) in the upstream reaches were caused by overflows.

Figure 8 shows the flow weighted average concentrations of *Enterococci* from each sub-catchment discharge. The highly urbanised catchments around the Parramatta River and the lower Sydney Harbour estuary contributed to the high *Enterococci* concentration distribution in these areas. The same trend was apparent for total nitrogen, total phosphorus and total suspended solids loads from the sub-catchments (Figure 9).

The majority (70%) of discharges to the Sydney Harbour estuary were from the catchments directly in the Sydney Harbour estuary region, whereas 18% came from the Upper Parramatta River region and 8% from the Upper Lane Cove (Figure 10). These figures also reflect the size of catchment areas in each region. In the combined stormwater and overflow discharge loads, sewer overflows contributed only 2% of the total discharge volume (Figure 11). Due to high concentrations of *Enterococci* and nutrients in overflows, overflows contributed 95% of total *Enterococci* pollutant load, 29% of total nitrogen load, 23% of total phosphorus load and 3% of total suspended solids load.

Tables 2 and 3 list the discharge quantity and quality from four upstream catchments to the estuary. These figures were derived from a ten-year time series of the scenario modelling outcomes. The Upper Parramatta River had the highest flow yield ($737 \text{ ML/yr per km}^2$) and the Upper Lane Cove River had the lowest flow yield ($459 \text{ ML/yr per km}^2$) as a result of the high and low imperviousness areas in these two key catchments, respectively. Upper Parramatta River discharge had an annual average flow of 80 GL, transporting 108 tonnes of total nitrogen, 15 tonnes of total phosphorus, 5,190 tonnes of total suspended solids and 61 trillion (cfu) *Enterococci*.

After summation of the catchment yields from the five model regions, the entire Sydney Harbour model catchments had a flow yield of 710 ML/yr km^2 , a total nitrogen yield of 992 kg/yr km^2 , a total phosphorus yield of 145 kg/yr km^2 and a total suspended solid yield of $63,171 \text{ kg/yr km}^2$ (Table 5). The nutrient and total suspended solids loads entering the Sydney Harbour estuary in this study are consistent with the ranges presented by Birch et al (2010). Birch et al (2010) made a comparison of modelled load with other catchments across the world and defined three categories of catchments: most

pristine catchments are considered to have a total nitrogen (TN) yield of 80-200 kg km² year⁻¹; moderately modified 500-2,000 kg km² year⁻¹; and heavily influenced >10,000 kg km² year⁻¹. Based on these categories, the Sydney Harbour estuary is considered as moderately influenced by the catchment pollutant discharges. There is one large sewer overflow located in the Vineyard Creek catchment that frequently overflows during large rainfall events. Vineyard Creek is a small tributary with low dilution capacity compared to the Upper Parramatta River. Therefore, the nutrient and *Enterococci* concentrations from the Vineyard Creek discharges (Table 3) were significantly higher than the other three upstream discharges.

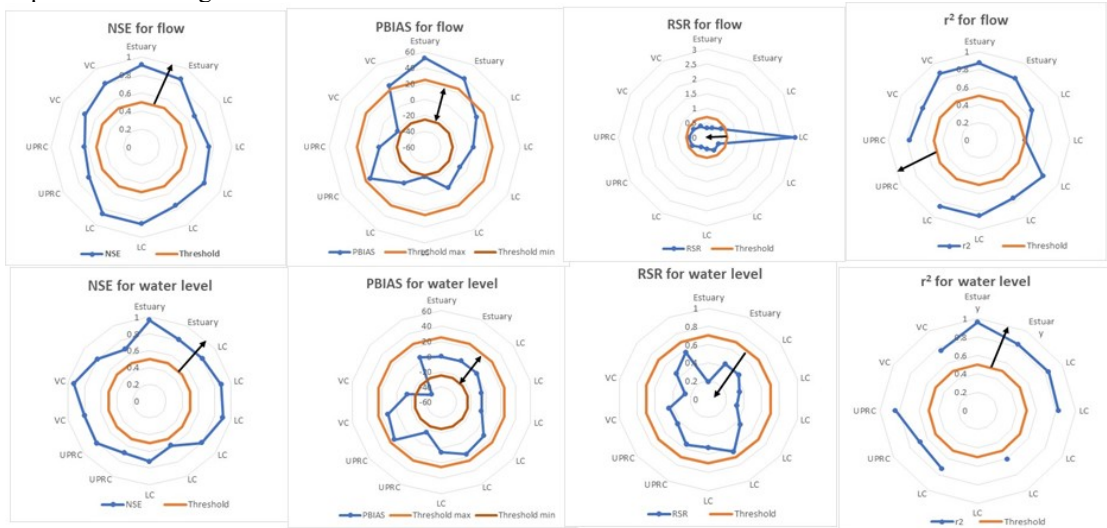
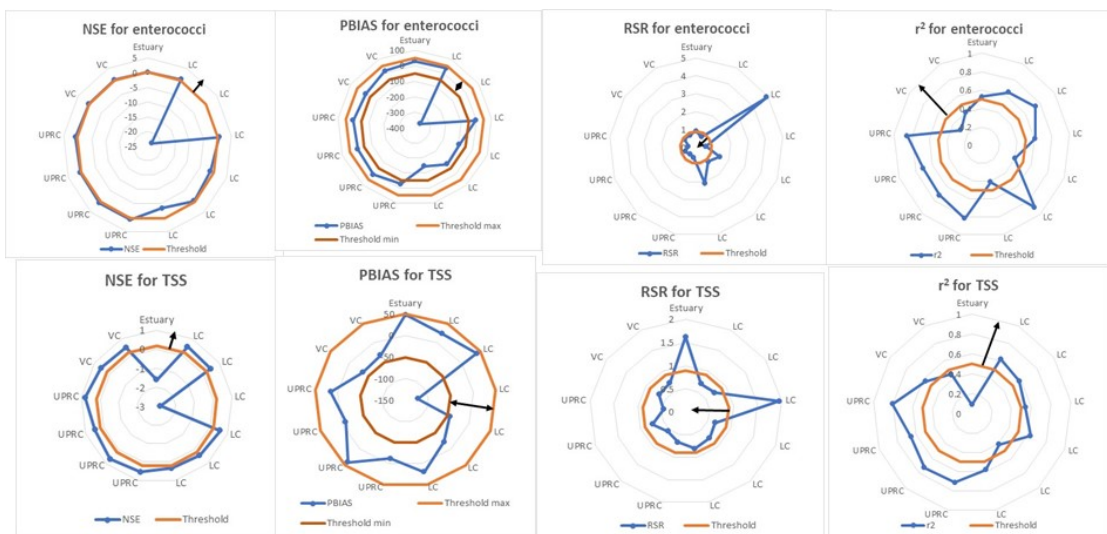


Figure 4. Hydrodynamic model performance



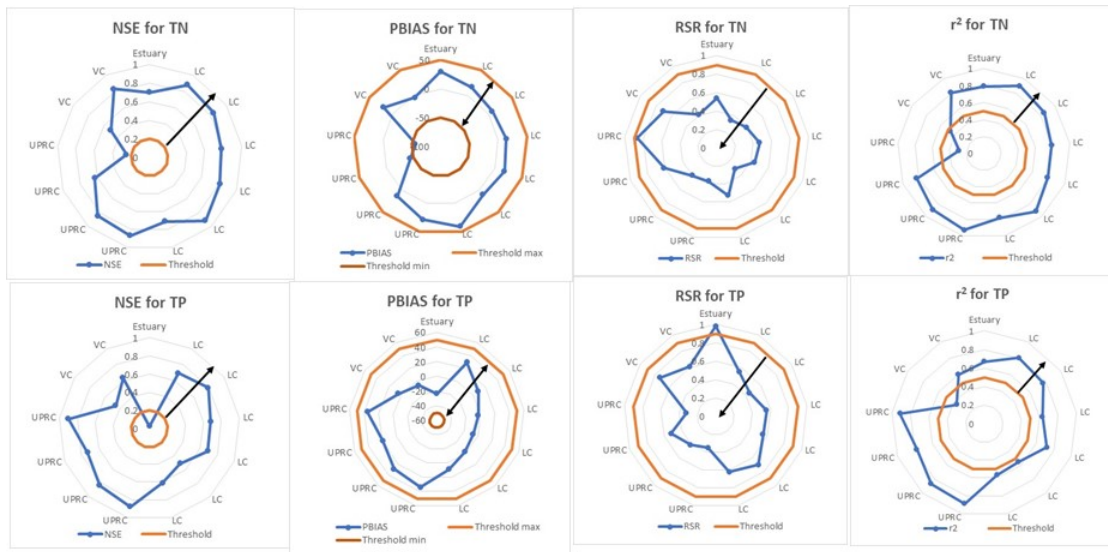


Figure 5. Water quality model performance

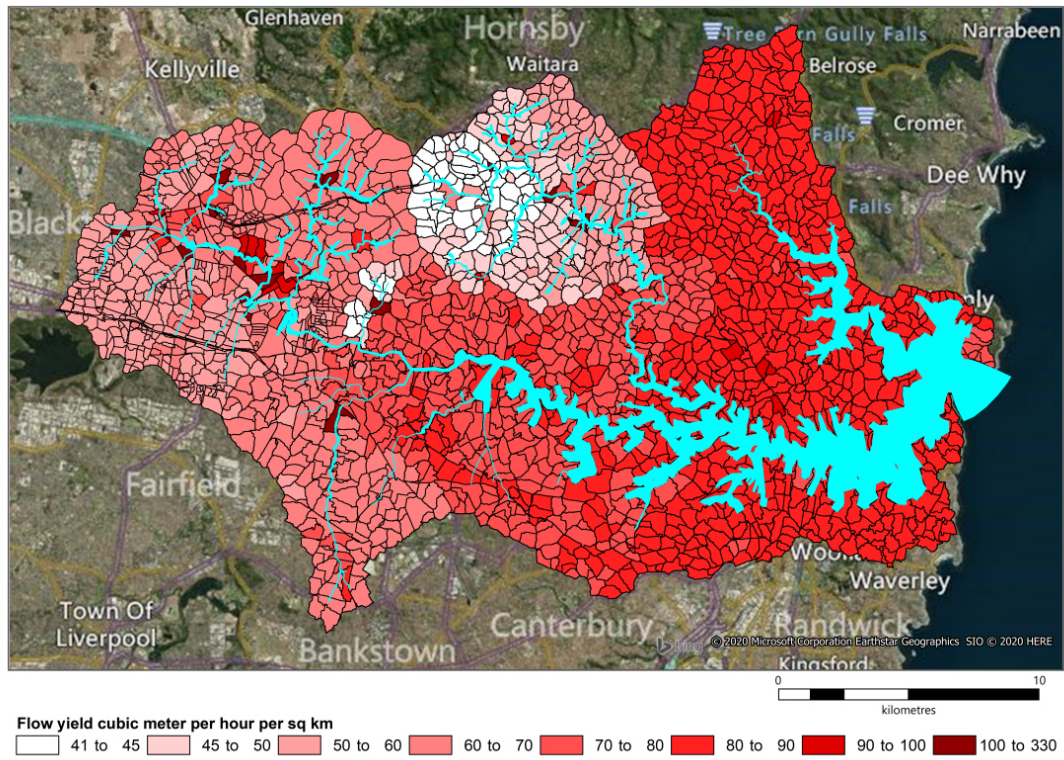


Figure 6. Spatial variability of average combined stormwater and overflow yield ($m^3/hour km^2$)

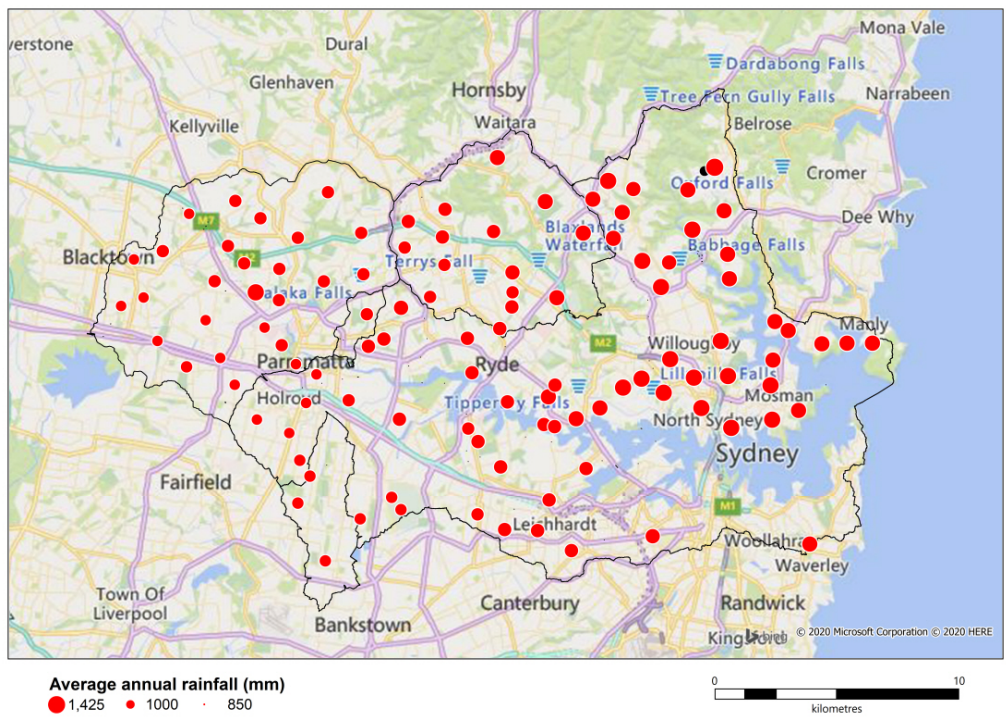


Figure 7. Spatial variability of 10-year rainfall

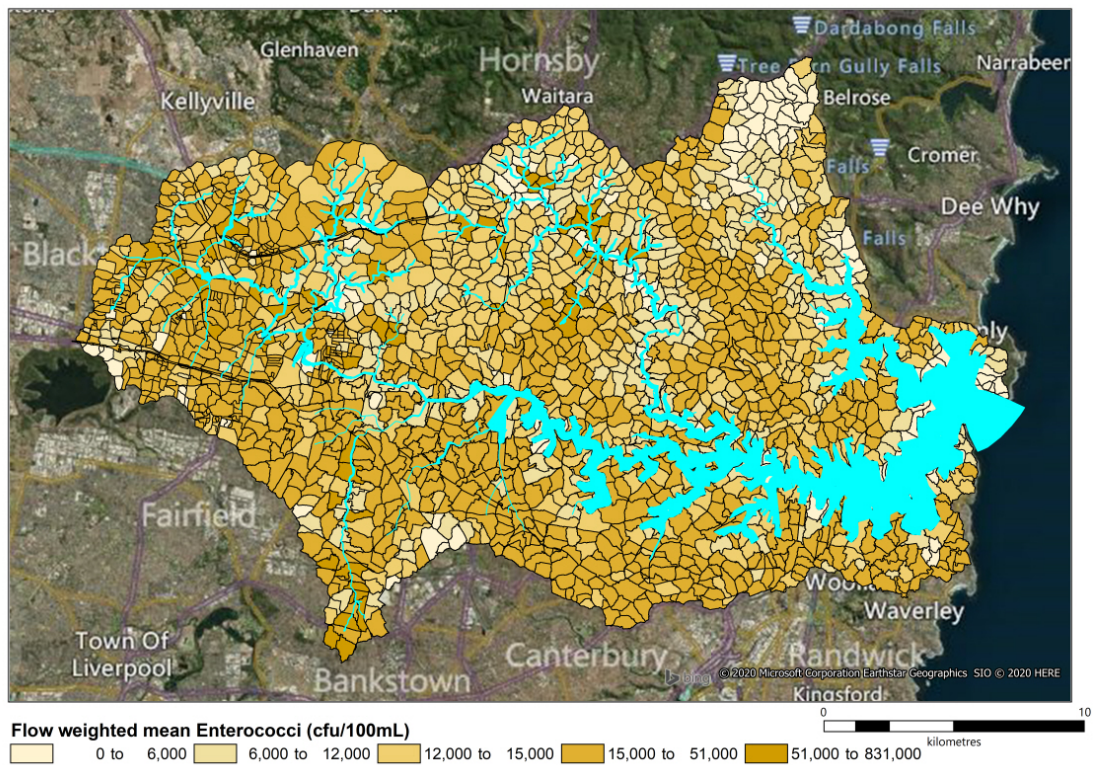


Figure 8. Spatial variability of catchment average *Enterococci* concentration

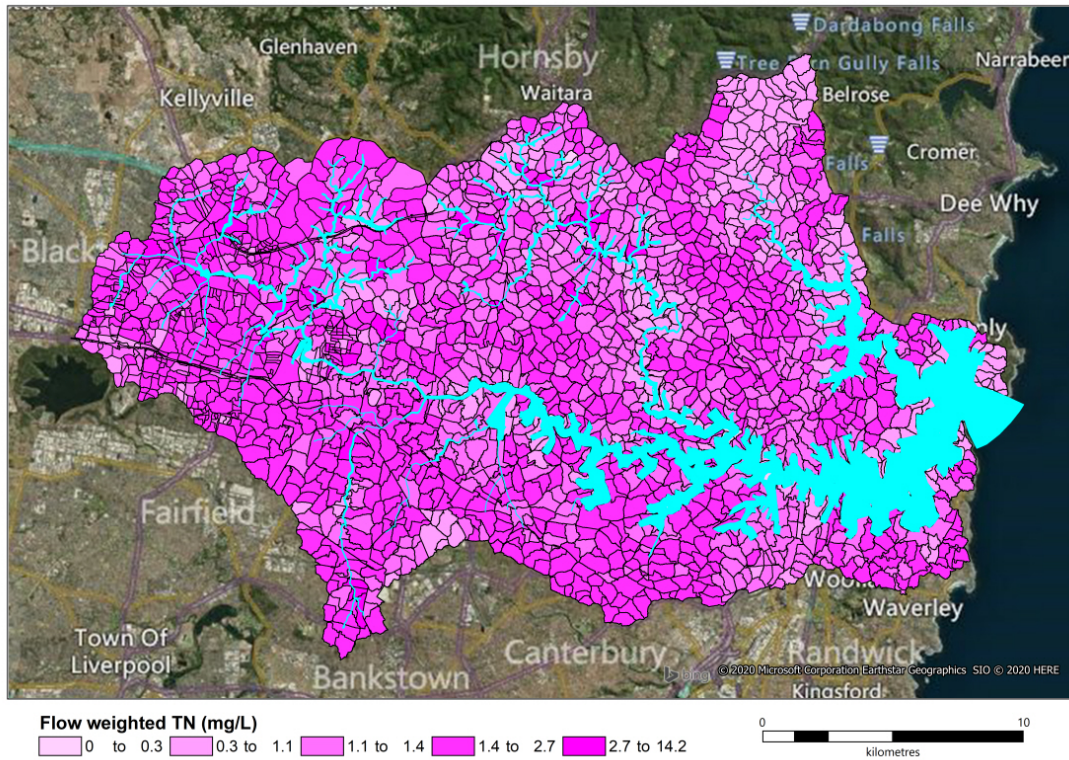


Figure 9. Spatial variability of catchment average total nitrogen concentration

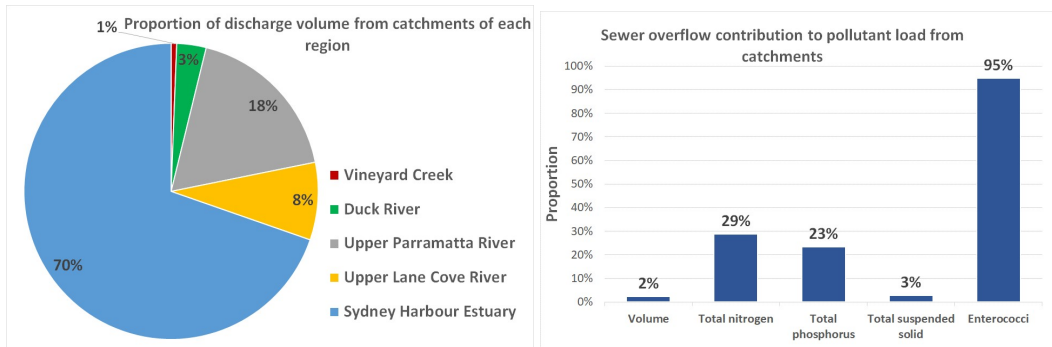


Figure 10. Contributions of pollutant volume from each region and sewer overflow to pollutant loads

		Upper Parramatta River	Upper Lane Cove River	Upper Duck River	Vineyard Creek
Flow (ML/yr)	Lower limit	23,452	11,218	5,211	711
	Mean	79,640	30,319	12,529	2,278
	Upper limit	215,547	60,955	20,335	4,809
TN (t/yr)	Lower limit	24	9	6	1
	Mean	108	46	23	10
	Upper limit	240	120	42	25
TP (t/yr)	Lower limit	3	1	1	0.1
	Mean	15	5	3	1
	Upper limit	32	14	6	3
TSS (t/yr)	Lower limit	1,608	253	352	30
	Mean	5,190	1,517	1,046	127
	Upper limit	10,864	3,942	1,819	293
Enterococci (cfu/yr)	Lower limit	1.33E+13	2.21E+12	2.40E+12	5.47E+11
	Mean	6.10E+13	2.20E+13	1.11E+13	5.67E+12
	Upper limit	1.48E+14	6.35E+13	2.15E+13	1.46E+13

		Upper Parramatta River	Upper Lane Cove River	Upper Duck River	Vineyard Creek
TN (mg/L)	Lower limit	0.2	0.4	0.3	0.1
	Mean	0.6	0.6	1.0	0.5
	Upper limit	5.0	6.1	6.6	11.9
TP (mg/L)	Lower limit	0.0	0.01	0.0	0.0
	Mean	0.1	0.03	0.11	0.05
	Upper limit	0.6	0.73	0.79	1.42
TSS (mg/L)	Lower limit	0	0	0	0
	Mean	9	5	14	5
	Upper limit	404	328	322	236
Enterococci (cfu/100mL)	Lower limit	0	0	0	0
	Mean	897	535	621	1,623
	Upper limit	31,752	30,382	29,513	70,439

Area (km ²)	Volume (ML/year km ²)	TN (kg/year km ²)	TP (kg/year km ²)	TSS (kg/year km ²)
482	710	992	145	63,171

Sydney Harbour estuary water quality profiles

The 'Stormwater and overflows' scenario provided the median salinity profile in the Sydney Harbour estuary under existing conditions (Figure 11). The dark blue colour represents the area where the salinity level was greater than 32 ppt, which is close to the ocean salinity level of around 35 ppt. Salinity decreased gradually with increasing distance upstream along the Parramatta River, Lane Cove and Middle Harbour due to the influence of freshwater inflows from upstream tributaries. Figure 12 displays the 95th percentile concentration maps of *Enterococci* from both scenarios of 'Stormwater and overflows' and 'Stormwater Only'. The 95th percentile concentration is a summary of the distribution which takes greater account the top-end variability in concentrations other than measures such as the mean. It is a threshold value for which *Enterococci* concentrations are below 95% of the time. The colour category follows the National Health and Medical Research Council (NHMRC, 2008) guidelines for managing risk in recreational water use. The blue color is suitable for swimming (<40 cfu/100mL) and the green color is suitable for secondary recreational water use such as boating (between 40 and 200 cfu/100mL). The maps indicate little difference between the two scenarios. Both showed the small change in the upstream reaches largely driven by the influence of sewer overflows. Overflows contributed 95% of *Enterococci* load, but as this occurred during major storms and *Enterococci* only live for a short period, it had less overall impact. This highlights that stormwater dominates changes in *Enterococci* in the Sydney Harbour estuary, with overflows having minimal impact. Similar trends were also demonstrated in Figures 13 to 15 for total nitrogen, total phosphorus and total suspended solids.

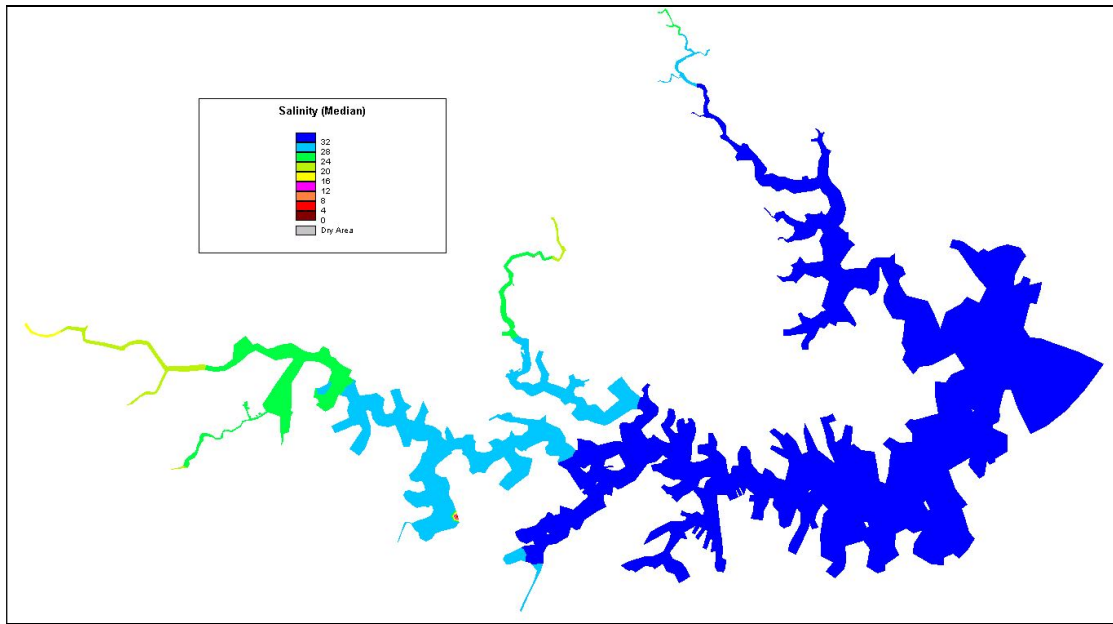
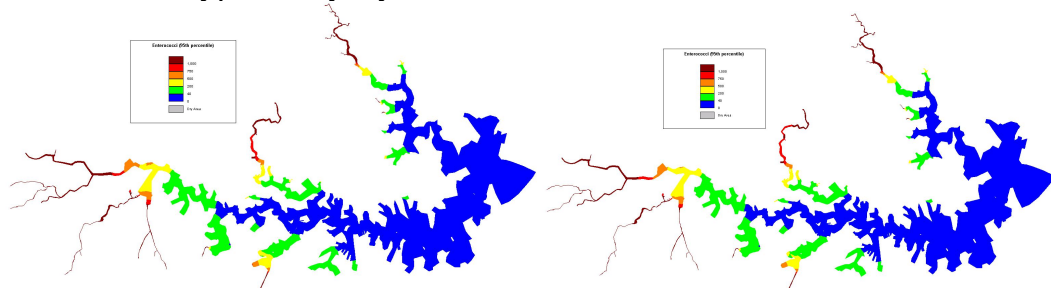
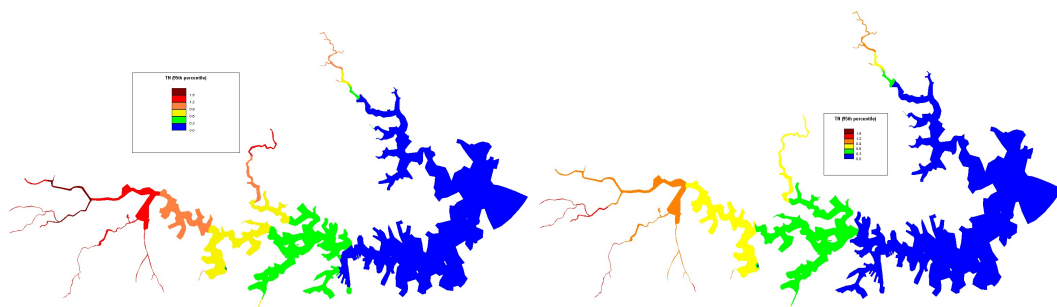


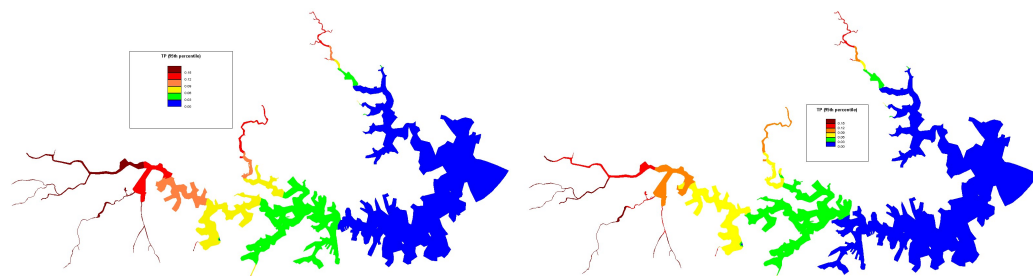
Figure 11. Median salinity profile in Sydney Harbour



(a) 'Stormwater and overflows' (b) 'Stormwater Only'
 Figure 12. 95th percentile of *Enterococci* from two scenarios in Sydney Harbour



(a) 'Stormwater and overflows' (b) 'Stormwater Only'
 Figure 13. 95th percentile of total nitrogen from two scenarios in Sydney Harbour



(a) 'Stormwater and overflows' (b) 'Stormwater Only'
 Figure 14. 95th percentile of total phosphorus from two scenarios in Sydney Harbour

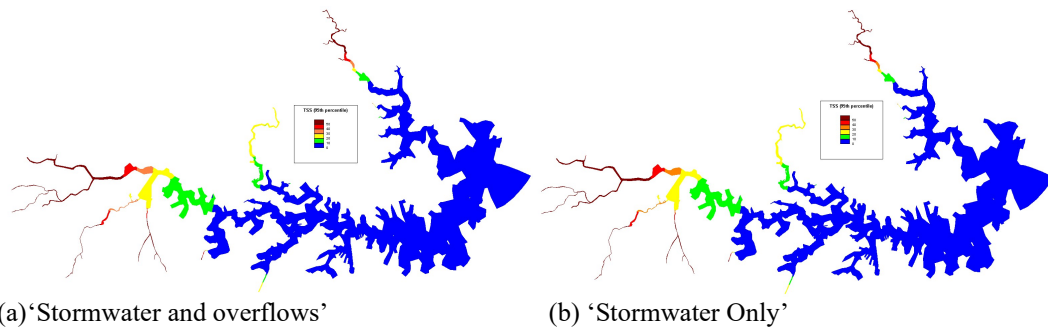


Figure 15. 95th percentile of total suspended solid from two scenarios in Sydney Harbour

SUMMARY

The Sydney Harbour and tributary models were calibrated and validated using the data collected between 2013 and 2014. The model results compared well with the field data for both hydrodynamic and water quality models. The models are suitable for examining the change of water quality in the receiving waterbody associated with stormwater runoff and wet weather sewage overflows. Total annual loads of quantity and water quality from key upstream catchments to the Sydney Harbour estuary were estimated in this study. The Sydney Harbour estuary received 70% of stormwater discharge volume from the estuary catchments, 18% from the Upper Parramatta River and 8% from the Upper Lane Cove River. The catchment discharge loads were within the ranges in the literature. Sewer overflows contributed 2% of total discharge volume, 95% of *Enterococci* pollutant load, and 23% to 29% of nutrient pollutant loads to the Sydney Harbour estuary. *Enterococci* are generally short-lived. During wet weather events, contaminants and nutrients may exist in the estuary for a short period, before mixing and dilution with tidal exchange. The scenario modelling results demonstrated that sewer overflows had a minimal impact on the Sydney Harbour estuary water quality and stormwater dominated most changes in water quality.

ACKNOWLEDGMENTS

Authors would like to acknowledge previous colleagues Peter Tate and Scott Manning, and the Sydney Water field monitoring team for their contribution to the project.

APPENDIX

Table A-1. Event mean concentrations associated with land use for catchments										
Parameters	B ¹	P ²	R ³	C ⁴	I ⁵	R ⁶	R ⁷	R ⁸	W ⁹	S ¹⁰
<i>Enterococci</i> (cfu/100ml)	4,000	4,000	4,000	20,000	20,000	20,000	20,000	20,000	0	1,000,000
BOD (mg/L)	6	6	6	18	18	18	18	18	0	120
TN (mg/L)	0.65	0.93	1.13	1.31	2.5	1.13	1.85	1.53	0	16.8
TP (mg/L)	0.089	0.1	0.296	0.309	0.512	0.349	0.257	0.25	0	2.0
Algae (mg/L)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0	0.03
DO (mg/L)	6	6	6	6	6	6	6	6	0	0
TSS (mg/L)	87	37	111	97	184	200	116	218	0	100

¹ Bushland; ² Parkland; ³ Rural; ⁴ Commercial; ⁵ Industrial; ⁶ Railways; ⁷ Residential; ⁸ Roadways; ⁹ Water; ¹⁰ Sewer overflows

Table A-2. Dry weather concentrations associated with land use for catchments

Parameters	B ¹	P ²	R ³	C ⁴	I ⁵	R ⁶	R ⁷	R ⁸	W ⁹	S ¹⁰
<i>Enterococci</i> (cfu/100ml)	200	200	200	4000	4000	4000	4000	4000	0	0
BOD (mg/L)	0	0	0	0	0	0	0	0	0	0
TN (mg/L)	0.51	0.51	0.64	0.625	1.12	0.62	0.62	0.76	0	0
TP (mg/L)	0.03	0.03	0.09	0.1	0.17	0.115	0.09	0.08	0	0
Algae (mg/L)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0	0
DO (mg/L)	6	6	6	6	6	6	6	6	0	0
TSS (mg/L)	10	5	15	10	25	25	15	25	0	0

¹ Bushland; ² Parkland; ³ Rural; ⁴ Commercial; ⁵ Industrial; ⁶ Railways; ⁷ Residential; ⁸ Roadways; ⁹ Water; ¹⁰ Sewer overflows

Table A-3. Baseflow concentrations

Parameters	Upper Parramatta River	Upper River Duck	Vineyard Creek	Upper Lane Cove
<i>Enterococci</i> (cfu/100ml)	0	0	0	0
BOD (mg/L)	0	0	0	0
TN (mg/L)	0.335	0.32	0.22	0.55
TP (mg/L)	0.04	0.01	0.01	0.01
Algae (mg/L)	0.03	0.03	0.03	0.03
DO (mg/L)	6	5	6	6
TSS (mg/L)	0	0	0	0

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