Lake Parramatta, 2015. Photograph by Chris Frape.

# Strategic Analysis of Water Quality in the Parramatta River

Parramatta River Catchment Group

PARRAMATTA RIVER OUR LIVING RIVER

## Technical Analysis Report

Parramatta City Council | FINAL

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JACOBS

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## Contents

## Appendix A. Additional Information

# Executive Summary


The objective of this report was to review existing water quality data to determine the current condition of proposed swimming sites in the Parramatta River Catchment with respect to recreational suitability and general ecosystem health. In order to achieve this, water quality data was provided from councils and stakeholders within the catchment, collated and analysed. Data that was current (2010 onwards) and of sufficient quantity and quality were assessed to determine recreational suitability and aquatic ecosystem health.

At the time of publication, four sites were currently open for swimming (Cabarita beach, Chiswick Baths, Dawn Fraser Pool and Lake Parramatta) and an additional 11 sites had been nominated as proposed swimming sites by 2025. Enterococci data were used as the primary determinant of recreational suitability, in line with current Beachwatch methodology, however only limited data was available. Only the four sites currently open to swimming and an additional site in the Parramatta CBD had sufficient data to assess recreational suitability. Results indicate that those sites currently open are generally suitable for swimming during dry weather. However, following wet weather, enterococci numbers increase, making the sites unsuitable for swimming at times. Enterococci numbers at the remaining site, the Parramatta River in the CBD, were frequently elevated above safe swimming levels and the site would not currently be suitable for swimming during dry or wet weather.

Water quality data for selected indicators, including pH, ammonia, total nitrogen, total phosphorus and chlorophyll-*a,* were collated for various catchment tributaries of the Parramatta River, the river itself and the estuary. These indicators were chosen as they provide a good indication of ecosystem health and can identify potential causes of poor water quality. Additionally, they were the indicators most commonly measured throughout the catchment. Frequency of monitoring varied across sites however, due to different agencies having collected this data for different purposes. Despite this, some general conclusions could be made from the data to help understand possible influences on water quality at the proposed swimming sites. Overall, the majority of streams could be considered eutrophic with elevated nutrient and chlorophyll-*a* (where data were available) concentrations. The water quality is representative of urban streams that are impacted from stormwater and wastewater overflows and runoff from urbanised and industrial areas.

Overall this technical analysis has highlighted that data is limited throughout the catchment, particularly with respect to assessing recreational suitability. Therefore a targeted sampling and analysis program should be devised to fill in data gaps and provide information for future management decisions to make the river swimmable again.

# 1. Introduction

This report has been prepared by Jacobs and the University of New South Wales for the Parramatta River Catchment Group (PRCG) as part of the *Our Living River* Initiative. The Initiative is being supported by the Parramatta River Masterplan which will identify an evidence based strategy to achieve the PRCG mission to make the river swimmable by 2025.

This technical analysis is one of four deliverables under the project '*Strategic Analysis of Water Quality Monitoring in the Parramatta River*', which forms the first key phase of the Masterplan.

This report presents a technical analysis of current and proposed swimming sites along the Parramatta River. All known data from across the catchment was collated and assessed to help understand current recreational water quality at each site, as well as likely catchment influences affecting these sites.

The other three deliverables were:

- A review of current scientific literature to identify existing knowledge regarding water quality in the Parramatta River with direct relevance to the potential for primary contact recreational activities such as swimming. Future approaches to monitoring recreational water quality in the Parramatta River were also considered. The review titled "*How should recreational water quality in the Parramatta River be assessed? A review of current literature*" is provided in Appendix A.

- A Swim Report that provides a brief narrative of how water quality has changed over time in the catchment and how it relates to the suitability of sites for swimming.

- A Business Case for a Riverwatch monitoring program.

## 1.1 Study Area

The Parramatta River is the main tributary of Sydney Harbour, a branch of Port Jackson, NSW. The headwaters of the Parramatta River are formed by the confluence of Toongabbie Creek and Darling Mills Creek in North Parramatta. The total catchment area of the river is approximately 257 square kilometres and consists of a total of 29 sub-catchments.

The upstream waters are controlled by a series of four weirs, including Kiosk Weir and Upstream Weir in Parramatta Park, and Marsden Street Weir and the Charles Street Weir in the Parramatta CBD. The weirs were originally constructed to provide freshwater for farmers. Flooding of the Parramatta River occurs on a periodic basis as a result of rainfall events in the catchment.

The river is tidal to Charles Street Weir in Parramatta, approximately 30km upstream from Sydney Heads. The major waterways flowing into the Parramatta River include Vineyard Creek and Ponds/Subiaco Creek at Rydalmere, Duck River at Silverwater, Archer Creek, Smalls Creek and Charity Creek at Meadowbank, Haslams Creek and Powells Creek at Homebush Bay, Iron Cove Creek (Dubroyd Stormwater Channel) at Five Dock, Hawthorne Canal at Iron Cove, and Tarban Creek at Huntleys Point. The majority of the minor drainage lines entering the watercourses have largely been straightened, narrowed and lined to increase outflow of excess water and reclaim adjacent lands for development (Cardno 2008).

The Parramatta River catchment consists of numerous land uses including residential, commercial, environmental protection, education, industrial, open space and recreation services, transport and communications (Cardno 2008). Historically, the catchment was heavily impacted by industry, which has resulted in contaminated sediments, with high concentrations typically associated with point sources (e.g. former industrial sites at Homebush Bay) or where creeks and stormwater outlets enter the estuary in the upper reaches of embayments (Cardno 2008). In addition to contaminated sediments, there are areas that have a high probability of occurrence for Acid Sulphate Soils throughout the catchment.

Generally, water quality is dominated by catchment inputs including stormwater and waste water overflows. Human activities have resulted in elevated levels of nutrients and gross pollutants. Sediment contamination, due to urbanisation and industrialisation of the catchment, has also had an impact on water quality throughout the catchment (refer Section 3.2).

## 1.2 Objectives

The main objectives of the Technical Analysis are to:

- Identify and collate all existing water quality data in the Parramatta River Catchment.
- Assess the adequacy and relevance of this information.
- Compile and assess the data against relevant water quality guidelines.
- Determine ecosystem health and recreational suitability of sites within the Parramatta River Catchment.
- Identify information gaps and therefore research and monitoring needs.

## 1.3 Report Outline

The report is divided into the following sections:

**Section 2** provides the methodology adopted for this technical analysis.

**Section 3** reports on the recreational water quality of proposed swimming sites, sediment contamination in the catchment and ecosystem health.

**Section 4** provides data gaps and key recommendations.

**Section 5** provides a conclusion.

# 2. Methodology

Water quality data used in this report comes from a variety of stakeholders including Councils, Office of Environment and Heritage, Sydney Water, Sydney Olympic Park Authority and the University of Western Sydney. Each organisation has its own monitoring objectives for their monitoring and as such, data are variable throughout the catchment, spatially, temporally and in the types of indicators that are monitored. Some organisations have routine water quality monitoring programs, whilst others only monitor water quality for specific projects.

Data used in this technical analysis was from 2010 onwards as it was considered most representative of contemporary (2016) water quality. Additionally, only data that had a credible number of results (>10) were included in the analysis. This allows for a realistic representation of water quality variability. A summary of the available data used for assessing recreational and ecosystem health at various sites discussed in this report are provided in Table 2-1.

Table 2-1 Summary of Water Quality Data

| Site | Number of Samples | | | | | |
|---|---|---|---|---|---|---|
| | pH | Ammonia | TN | TP | Chl-a | Enterococci |
| Hunts Creek (The Hills Shire Council) | 19 | ND | 50 | 50 | ND | ND |
| MER Estuary (OEH) | 18 | 6 | 6 | 6 | 24^ | ND |
| Blacktown Creek, Grantham Creek and Lalor Creek (Blacktown City Council) | 34 | 18 | 34 | 34 | ND | ND |
| Greystanes Creek (Blacktown City Council) | 33 | 29 | 33 | 33 | ND | ND |
| Vineyard Creek (Sydney Water) | 107 | 102 | 102 | 102 | ND | ND |
| Toongabbie Creek (Blacktown City Council) | 34 | 18 | 34 | 34 | 26 | ND |
| Lake Parramatta (City of Parramatta Council) | 190 | ND | 188 | 188 | ND | 254 |
| Parramatta CBD (City of Parramatta Council) | 35 | ND | ND | ND | ND | 117 |
| Ermington Bay and Upstream Duck River Water Quality Buoys (City of Parramatta Council) | >100,000 | ND | ND | ND | >100,000 | ND |
| Duck River (Cumberland Council) | 61 | ND | ND | ND | ND | ND |
| Parramatta River at Ermington Wharf (Sydney Water) | ND | ND | ND | ND | 57 | ND |
| EPA (beachwatch) | ND | ND | ND | ND | ND | 241 |

ND – No Data
^ twice daily over 12 days

## 2.1 Recreational Water Quality

For the purposes of understanding recreational suitability of a site, the number of enterococci coliform units (a type of bacteria) has been used. Studies have shown a direct relationship between the density of enterococci and the risk of gastrointestinal illness associated with swimming in the water. A high density of enterococci indicates the water has been contaminated with faecal material from human and/or animal sources (e.g. wastewater overflows, domestic and native animals). The NHMRC guidelines (NHMRC 2008) provide a number of categories for determining microbial water quality of recreational waters. Table 2-2 indicates the category of recreational water bodies using the 95th percentile of all enterococci sampling data. The 95th percentile means that 95% of all samples collected should have enterococci levels below those shown in the Table 2-2 for each particular category.

Table 2-2 Recreational Microbial water quality assessment categories - enterococci (NHMRC 2008)

| Category | Microbial water quality assessment category (95th percentile – intestinal enterococci/100mL) |
|---|---|
| A | <40 |
| B | 41-200 |
| C | 201-500 |
| D | >500 |

Recreational water quality is typically very strongly related to rain, as rainfall tends to flush pollutants from wastewater and stormwater systems into waterbodies. The number of wet weather days in any one year will influence the overall rating of a site for its suitability to swimming. Therefore our data were separated into dry weather and wet weather. Wet weather was determined by calculating rainfall for 3 days preceding each water quality sample (i.e. the day of the sample combined with the two days preceding). For the purposes of this report, “dry weather” means <1 mm rainfall recorded at the North Parramatta weather station during the day of the sampling date and the two previous days (in total). “Wet weather” means at least 1mm of rainfall over those three days at the same weather station.

## 2.2 Ecosystem Health

Water resources are of major environmental, social and economic value, and if water quality becomes degraded this resource will lose its value. A healthy environment is one which water quality supports a rich and varied community of organisms and protects public health. The water quality of a body of water influences the way in which communities use the water for activities such as swimming. Aquatic ecosystems play an important role in maintaining water quality and are valuable indicators of not only water quality but of the water’s suitability for other uses such as recreation.

Aquatic ecosystems can range from freshwater to marine and comprise the animals, plants and micro-organisms that live in or around the water and the physical and chemical environment in which they interact. Aquatic ecosystems have been impacted upon by multiple anthropogenic (human caused) pressures including changes in flow regime, modification or destruction of key habitats, development, and resultant poor water quality. There is also a number of naturally occurring physical and chemical stressors that can cause degradation of aquatic ecosystems. Both natural and anthropogenic stressors are discussed below.

### 2.2.1 Nutrients

Nutrients in aquatic environments can promote the growth of algae and increase turbidity, which in turn reduces light and may affect plant growth. Nutrients consist of various forms of nitrogen (including total nitrogen, oxidised nitrogen and ammonia) and phosphorus (including total phosphorus and filterable reactive phosphorus).

Nitrogen is an essential nutrient for biota but, when in excess, can stimulate the growth of aquatic plants including macrophytes such as water hyacinth and microscopic plants or algae such as cyanobacteria. Total Nitrogen encompasses all forms of nitrogen including inorganic forms such as oxidised nitrogen (nitrate + nitrite) and ammonia plus organic forms such as urea.

Oxidised nitrogen includes the inorganic forms nitrate plus nitrite. Nitrate is generally low in surface waters, but increased concentrations can be an indicator of fertiliser contamination from runoff. Elevated nitrate can also be found in wastewater effluent as a result of the oxidation of ammonia.

Ammonia represents the most reduced form of inorganic nitrogen available, and is preferentially utilised by plants and aquatic micro-organisms. The main sources of ammonia in aquatic ecosystems are found to be from human and animal wastes and also by release during the decomposition of organic material by bacteria. When ammonia is present in high concentrations it can be toxic to fish.

Phosphorus occurs in water in both dissolved and particulate forms. Particulate forms include phosphorus bound in organic compounds or adsorbed to suspended particulate matter including sediment particles. Dissolved phosphorus includes inorganic orthophosphate which is readily available for plant uptake. Total phosphorus is a measure of both the dissolved and particulate forms and can occur in elevated concentrations due to a variety of anthropogenic and catchment disturbances ranging from the discharge of wastewater to poor streambank management.

### 2.2.2 Chlorophyll-a

Chlorophyll-*a* is an estimate of the biomass of microscopic plants such as phytoplankton. Elevated chlorophyll-*a* levels are generally an indication of increased nutrient loads and eutrophication.

### 2.2.3 pH

pH is a measure of the acidity or alkalinity of a waterbody. Changes in pH can impact the ability of aquatic organisms to maintain basic functions such as respiration. pH also controls the bioavailability of metals, nutrients and other organic molecules. Potential sources of changes to pH in the Parramatta River include changes in the level of organic matter within the system, runoff from low pH soils and changes in salinity.

### 2.2.4 Trigger levels

In order to assess the health of these ecosystems, the Australian and New Zealand guidelines for fresh and marine water quality (ANZECC/ARMCANZ (2000)) recommended default trigger values for a range of physical and chemical indicators for slightly to moderately disturbed ecosystems. However, these default trigger values are not always the most appropriate measure of ecosystem health, depending on the state of the catchment that is being assessed. The Parramatta River and its tributaries could be classified as urban streams. Urban streams can be defined as ‘a stream where a significant part of the contributing catchment consists of development where the combined area of roofs, roads and paved surfaces results in an impervious surface area characterising greater than 10% of the catchment’ (DSEWPaC 2013). In these instances ANZECC/ARMCANZ (2000) recommends deriving site specific trigger values.

Tippler *et al* (2013) adopted this approach for the Georges River catchment (another urban catchment within Greater Sydney). Using existing data collected from waterways within that catchment, they created site specific trigger values (SSTVs) for a range of ecosystem types, with consideration of current state (degraded water quality, riparian vegetation and macroinvertebrate communities) and percentage of impervious catchment. Given that the Parramatta River Catchment is highly modified and urbanised and impacted by a number of pressures including stormwater, industry and wastewater overflows, the site specific trigger values for urban streams with 5-19% impervious surfaces have been adopted in this assessment (Tippler *et al* 2013). These values are provided in Table 2-3. In the absence of SSTVs for chlorophyll-*a,* the ANZECC/ARMCANZ (2000) default trigger value of 3µg/L and 4µg/L has been adopted for freshwater and estuarine streams respectively.

Table 2-3 Site specific trigger values for urban stream assessment and restoration (Tippler et al 2013)

| Indicator | Adopted Guideline |
|---|---|
| pH | <7.88 |
| Ammonia | <0.04 mg/L |
| Total Nitrogen | <0.5mg/L |
| Total Phosphorus | <0.05mg/L |
| Chlorophyll-*a*^ | 3µg/L (freshwater) 4µg/L (estuarine) |

^ ANZECC/ARMCANZ (2000)

## 2.3 Interpretation of results

Water quality data were collated and checked for any inconsistencies prior to undertaking statistical and comparative analysis. Monitoring sites were classified based on their location and in accordance with the ANZECC/ARMCANZ (2000) catchment position so that appropriate guideline ranges and values could be assigned.

The number of sampling events, median and various percentiles were calculated for selected water quality monitoring data. The 95$^{th}$ percentile was also calculated for Enterococci. The statistical analysis of all water quality data was performed using a Microsoft Access Database. Box plots were generated for the sites to display summary data, allowing for meaningful comparisons between these sites (Figure 2-1).

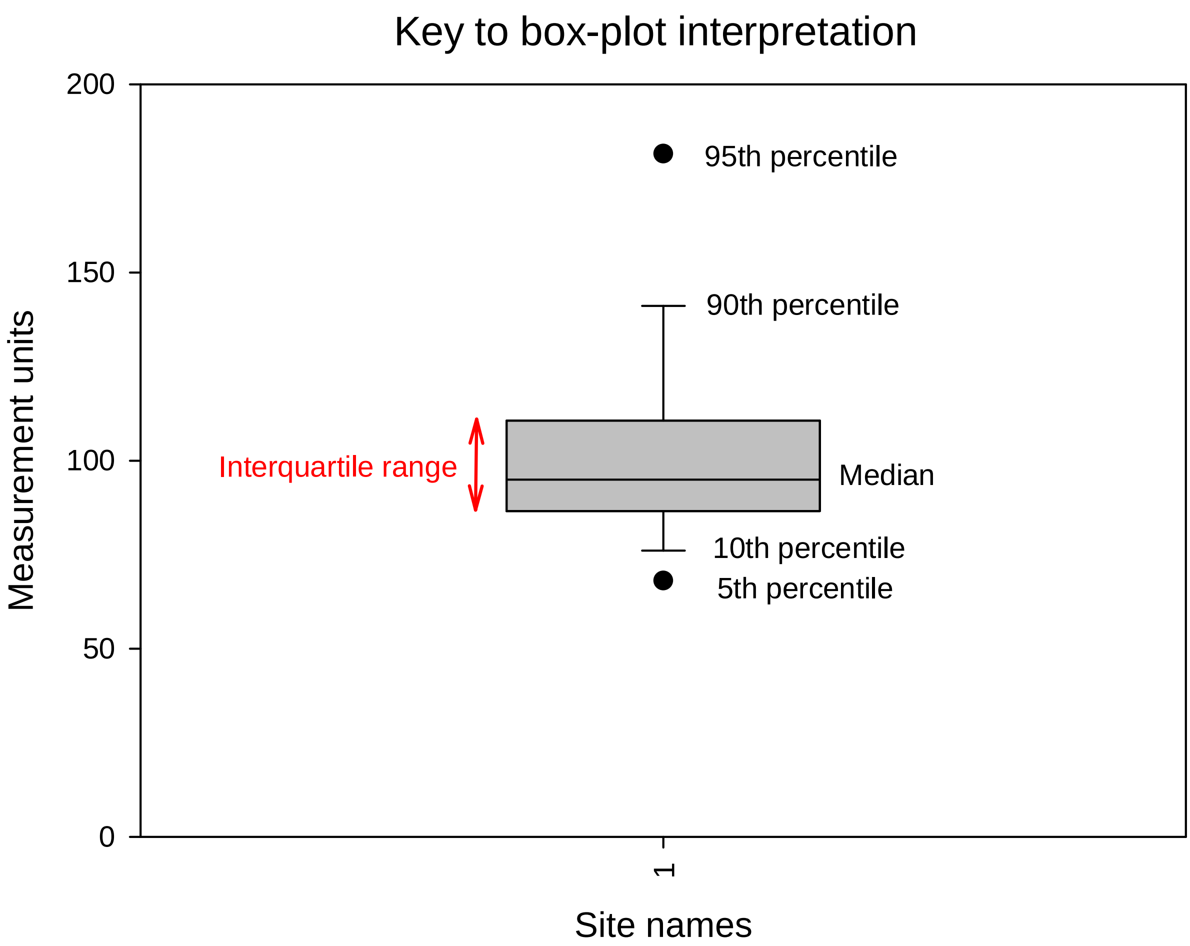


Figure 2-1 Box-plot interpretation

# 3. Results and Discussion

## 3.1 Recreational Water Quality

Enterococci data collected from 2010 onwards was available for five sites, four of which are already current swimming sites. The data has been analysed under two conditions: (1) dry weather only and (2) with both dry and wet weather data combined. Data at specific sites have also been separated into varying rainfall, not to indicate suitability for recreation but to show how enterococci numbers increase following wet weather. The results are presented in Figure 3-1 and Figure 3-2 and discussed below. In addition to those sites with enterococci data, descriptions of potential water quality for all other nominated swimming sites are included in the sections below.

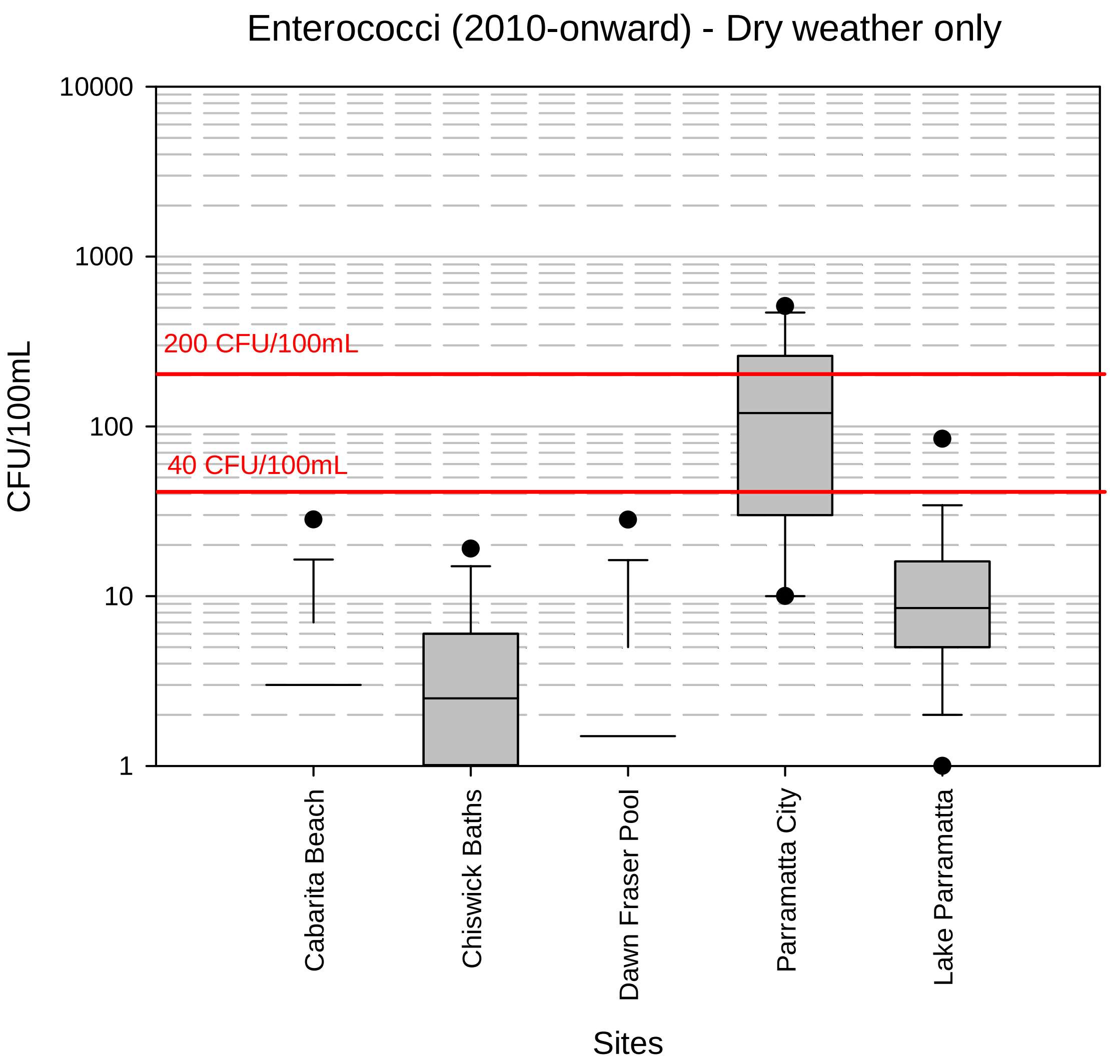


Figure 3-1 Enterococci results (dry weather 2010-2016)

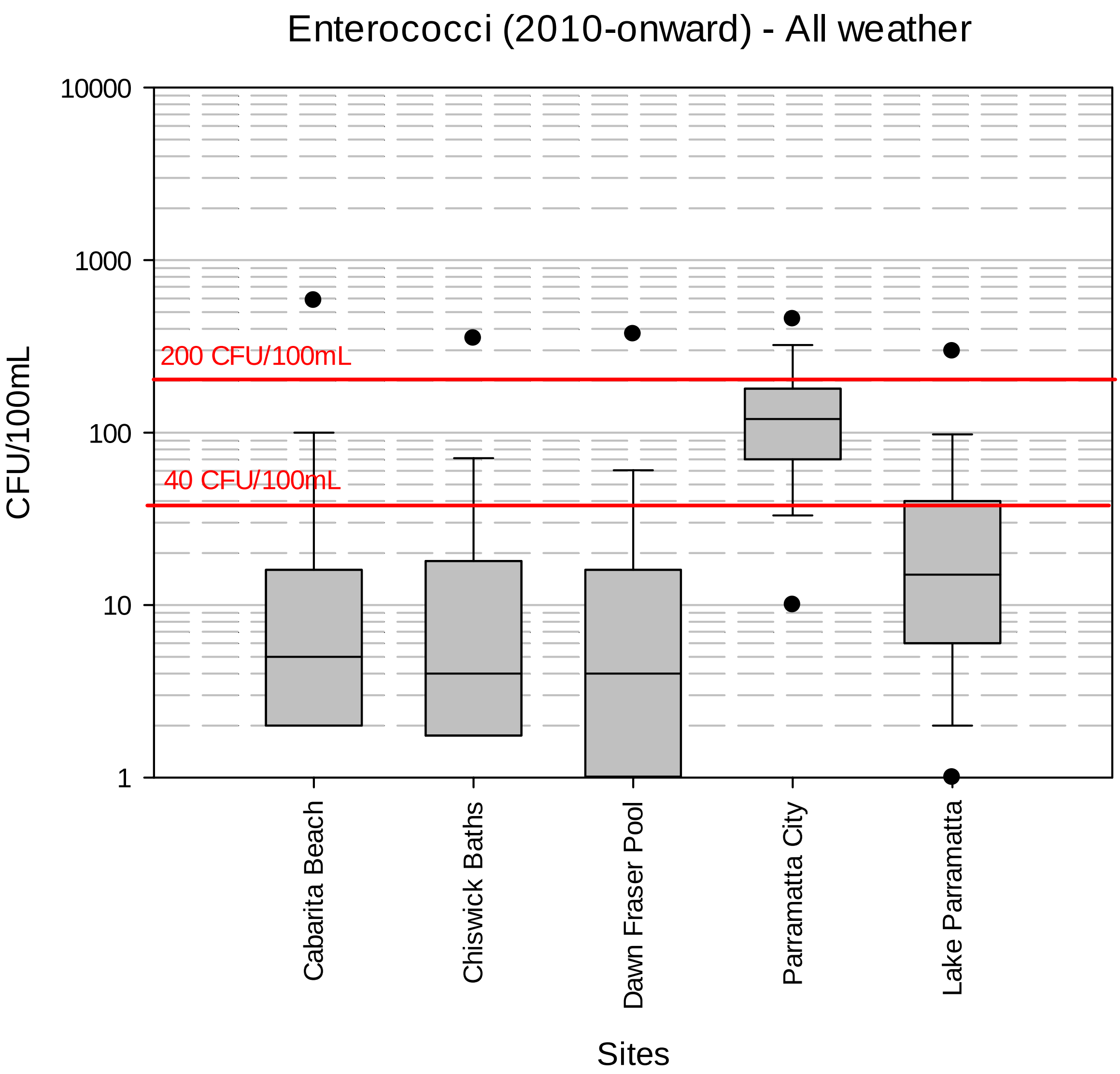


Figure 3-2 Enterococci results (dry and wet weather 2010-2016)

#### 3.1.1 Cabarita Beach (Current swimming site)

Cabarita Beach is a 120m long, narrow beach located on the Parramatta River west of Cabarita Point. It is backed by a large reserve and picnic area, Cabarita Park, which is located within City of Canada Bay Local Government Area (LGA). The LGA covers approximately 1,847ha of the estuary catchment area. Landuse within the area primarily includes low and medium density residential and significant areas dedicated to public recreation (including parks, golf course, wharves and foreshore reserves). The Parramatta River Ferry operates from Cabarita Ferry Wharf, which is located to the immediate west of Cabarita Beach.

Canada Bay LGA maintains over 25 Gross Pollutant Traps (litter traps) throughout the catchment, reducing the amount of litter and sediment pollution entering the river and the harbour. Other projects implemented by Canada Bay LGA to reduce stormwater pollution to the river include the Drummoyne Oval Stormwater Harvesting and Reuse Scheme and the Water for Community Project, which will harvest 180 million litres of stormwater each year for use on irrigating parks and golf courses in Concord.

Water quality of Cabarita Beach is likely to be affected by waters from Hen and Chicken Bay, Upper Parramatta River, sewage overflows, boats and numerous nearby stormwater drains (OEH 2014). Two hundred and ninety two (292) storm water outlets have been identified which discharge directly into the estuary of Canada Bay LGA (AECOM 2010).

Cabarita Beach is a swimming location in Sydney Harbour which has been monitored for enterococci for 20 years as part of the State Government's Beachwatch program. Historically, indicator bacteria concentrations within Cabarita beach have been good, however faecal coliform and enterococci densities generally increase with increasing rainfall and often exceed the median guideline limit in response to 10mm of rainfall or more in the previous 24 hours (OEH 2014). Microbial water quality has generally improved since 2000-2001 owing to licencing of discharges from the sewage system and improved management of storm water (OEH 2014). The data from 2010 has been separated so that the site's suitability for swimming can be assessed under dry weather conditions (Figure 3-1), all weather conditions (Figure 3-2) and following varying rainfall (Figure 3-3).

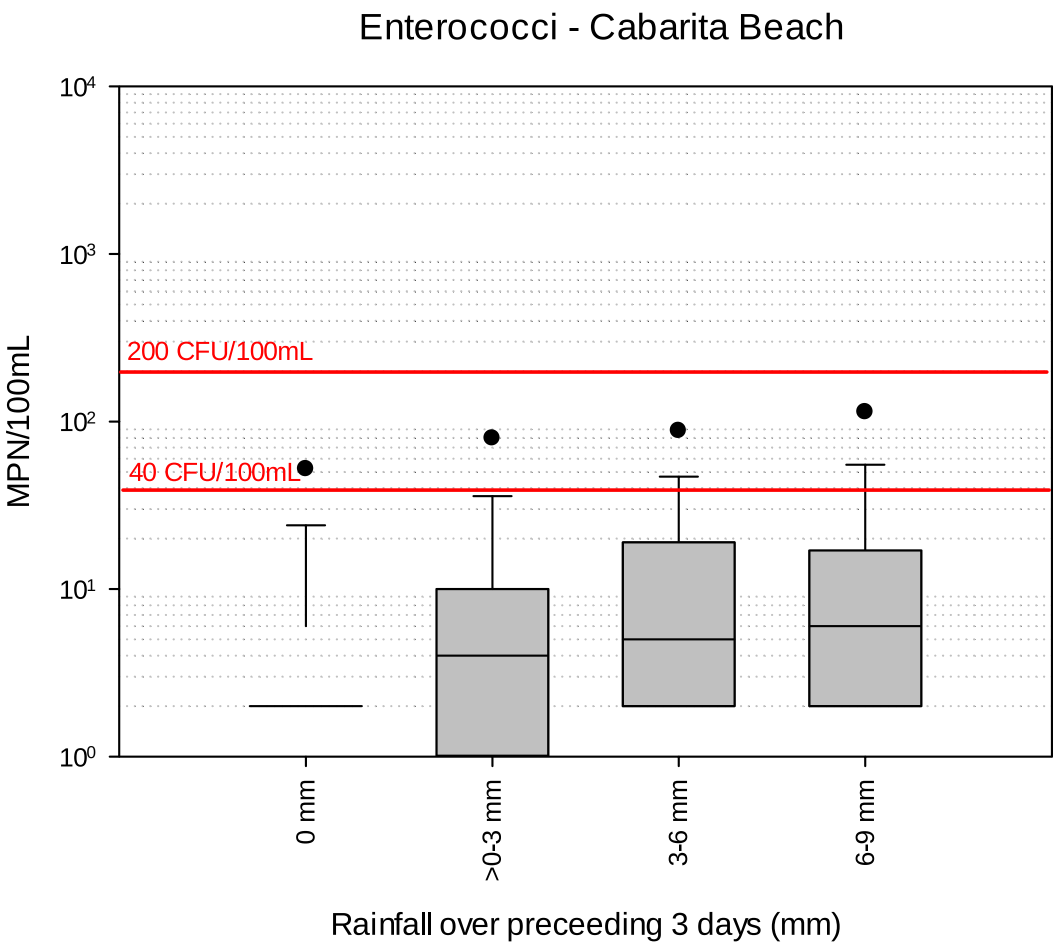


Figure 3-3 Enterococci results Cabarita Beach following varying rainfall

Enterococci numbers are very low during dry weather conditions with a median of 3CFU/100mL and a 95$^{th}$ percentile of 28CFU/100mL which are well below the NHMRC (2008) Microbial Assessment Category (MAC) A limit of 40CFU/100mL and MAC B limit of 200CFU/100mL. Therefore Cabarita Beach could be considered a very good site for swimming during dry weather conditions. When wet weather data are included in the analysis, the number of enterococci increased, inferring that wet weather is a source of bacterial pollution. Median numbers increased to 5CFU/100mL and the 95$^{th}$ percentile value to 582CFU/100mL (Category D). Given that the 95$^{th}$ percentile should be less than 200CFU/100mL, Cabarita Beach could be considered unsuitable for swimming directly following rainfall. This is consistent with the current recommendations made by the Beachwatch program that monitors this site.

Data were combined and segregated into different rainfall amounts up to 9mm (Refer Figure 3-3). Results generally show that enterococci numbers increase as rainfall increases. Compared with other swimming sites, enterococci did not noticeably increase and Cabarita Beach generally maintains relatively compliant levels of enterococci with small amounts of rainfall.

### 3.1.2 Chiswick Baths (Current swimming site)

Chiswick baths are located in Five Dock Bay on the southern side of the Parramatta River. It is a netted enclosure with a small sandy beach and facilities for day visits such as picnic tables and barbecues (Plate 3-1).

Plate 3-1 Chiswick Baths (source the lazy swimmer 2009)

Like other urban areas, the water here is potentially impacted by stormwater and wastewater overflows. Historically the water quality at the baths has been considered poor, with elevated microbial levels, although this has improved since 1998 when Sydney Water's wastewater overflows management changed. The water quality at the baths is also influenced by rainfall, often increasing the microbial levels beyond safe swimming trigger values with as little as 5mm rain.

Chiswick Baths has been monitored for enterococci for 17 years as part of the Beachwatch program. Data collected by OEH from 2010-2016 has been collated and separated so that suitability for swimming can be assessed under dry weather (Figure 3-1) and all weather conditions (Figure 3-2) and following varying rainfall (Figure 3-4).

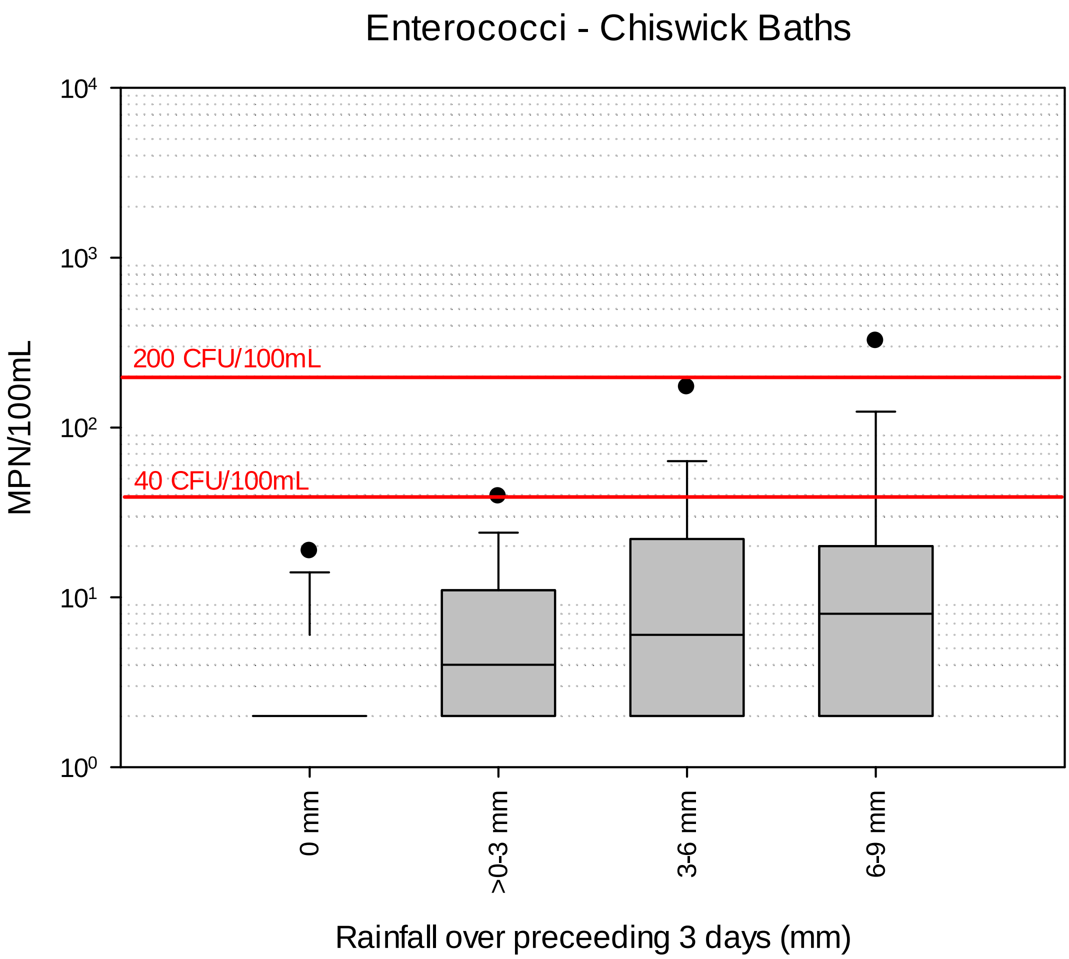


Figure 3-4 Enterococci results Chiswick Baths following varying rainfall

During dry weather, enterococci numbers are very low with a median of 2CFU/100mL and a 95th percentile of ~19CFU/100mL. These results fall below the recommended limit of 40CFU/100mL (category A). Therefore, Chiswick Baths' suitability for swimming could be considered very good. Like other sites, bacterial numbers appear to increase when wet weather data is included in the analysis. Whilst median numbers of enterococci increase slightly to 4CFU/100mL, the 95th percentile shows a more notable increase to ~360CFU/100mL which exceeds the recommended limit of 200CFU/100mL. Therefore, Chiswick Baths could be considered unsuitable for swimming following wet weather. This is consistent with the current recommendations made by the Beachwatch program that monitors this site. The increase in enterococci numbers could be attributable to stormwater runoff and upstream sources in the Parramatta River (including wet weather overflows).

Enterococci numbers increase more notably following varying rainfall amounts at Chiswick Baths, particularly when more than 3mm of rainfall falls (Figure 3-4). The 95th percentile value for enterococci when <3mm of rain falls is ~40CFU/100mL but increased to ~190CFU/100mL with 3-6 mm of rainfall and increases further to ~330 CFU/100mL when 6-9mm of rainfall falls 3 days prior to sampling (including day of sampling).

### 3.1.3 Dawn Fraser Pool (Current swimming site)

Dawn Fraser Pool is located in Balmain. It was built in the 1880s and is on the NSW State Heritage Register as the oldest pool and swimming club in Australia. It is actively managed and opened seasonally between October and April each year (Plate 3-2).


Plate 3-2 Dawn Fraser Pool (source the lazy swimmer 2009)

Balmain's stormwater network, while adequate, has a large number of cracks and displaced joints (Inner West Council, 2013). The clay network which has been in place for almost a century is approaching the end of its life. Therefore stormwater renewal is underway, but in the interim, heavy rainfall can result in excess water travelling overland down roads and through properties. This surface water runoff carries pollutants with it and transports it to the receiving waterways.

The Balmain pool, while not directly in the drainage line of any waterways, may still be influenced indirectly by stormwater and overflows which enter the Parramatta River.

Water quality is generally considered suitable for swimming (based on microbial water quality), however is influenced by upstream sources of pollution, particularly following rainfall. Water quality exceeds the safe limits for swimming with 5mm rainfall. Water quality has improved since 2001 since changes to Sydney Water's wastewater overflows management (OEH 2012)

Dawn Fraser Pool has been monitored since 1994. However, for the purposes of this assessment only, data from 2010 to 2016 has been used to assess the site's suitability for swimming because contemporary data is considered more indicative of current conditions. Similar to other sites, data have been separated into dry weather and all weather. In order to gain an appreciation of the influence of rainfall on bacterial water quality, data has also been analysed under varying rainfall amounts.

Enterococci numbers in the Dawn Fraser Pool during dry weather are very low (median <2CFU/100mL; 95$^{th}$ percentile ~28CFU/100mL) indicating that the water quality is good and suitable for swimming. When data are assessed under all weather conditions, enterococci numbers are generally higher (median ~4CFU/100mL; 95$^{th}$ percentile ~370 CFU/100mL), indicating that wet weather deteriorates the water quality, contributing higher numbers of enterococci and resulting in the Dawn Fraser Pool being unsuitable for swimming. When the data are separated into different rainfall amounts, it becomes clear that as little as 3mm of rainfall can result in higher enterococci levels, and between 6-9 mm of rainfall can result in the site being unsafe for swimming (based on the 95th percentile exceeding 200CFU/100mL) (Figure 3-5). Figure 3-5 shows that as rainfall increases so do enterococci numbers.

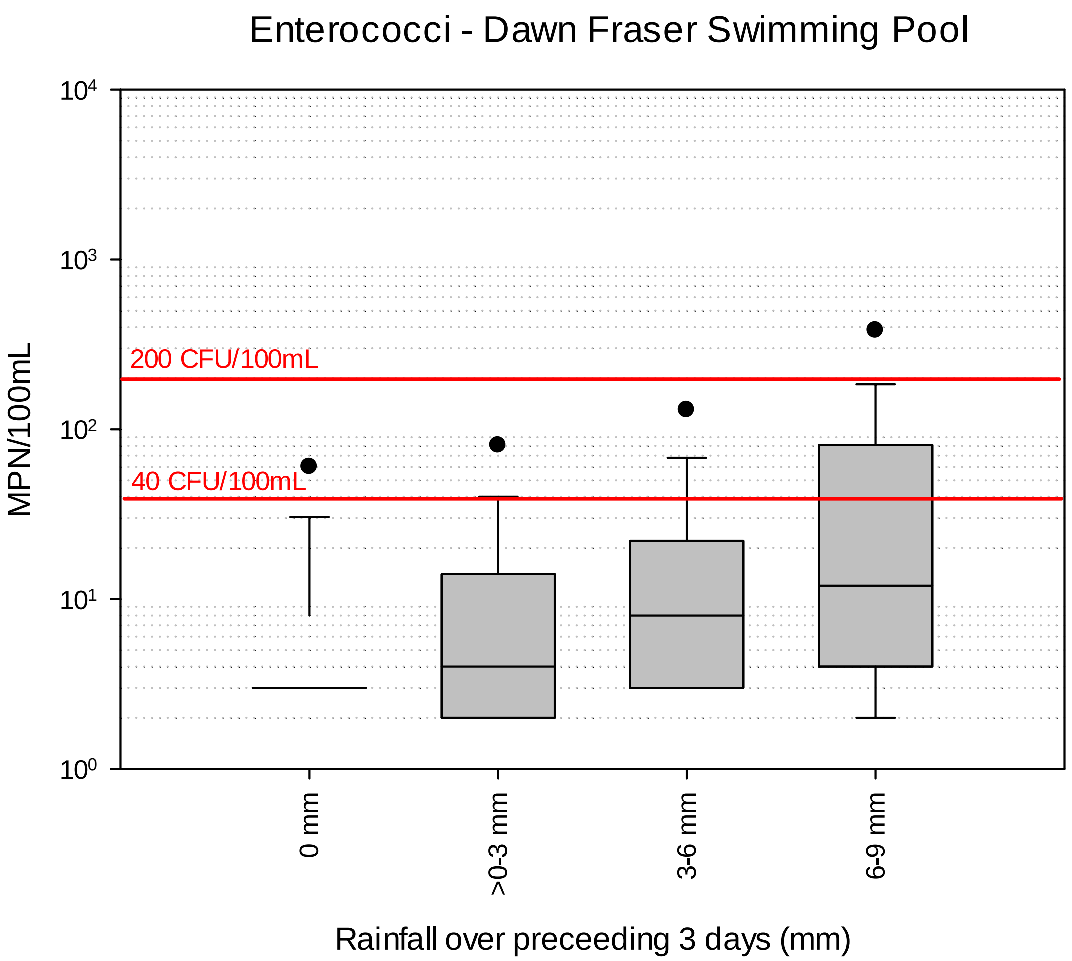


Figure 3-5 Enterococci results Dawn Fraser Pool following varying rainfall

### 3.1.4 Quarantine Reserve (Proposed swimming site)

Quarantine Reserve is a waterfront reserve in Hen and Chicken Bay in Abbotsford, within the City of Canada Bay Local Government Area (LGA). Hen and Chicken Bay catchment was predominately agricultural until after World War II when it changed to medium density housing. The neighbouring catchments (Iron Cove and Homebush Bay) had become increasingly urbanised and industrialised since the early 1900's. Sediments in these estuaries were already moderately contaminated with heavy metals by 1917 (Birch, 2007). Hen and Chicken Bay has been identified as a medium-high priority area of concern where the probability of sediment toxicity is high as are the likelihood of adverse biological effects (Birch & Taylor, 2004). The Bay has also historically been susceptible to poor stormwater quality which has affected seagrass beds in the Bay (Aecom, 2010). Hen and Chicken Bay has been identified as playing an important role in supporting populations of wading birds found in Homebush Bay (Cardno Lawson Treloar, 2008).

Quarantine Reserve is named after its former use as the quarantine station, the land initially purchased for imported animals for Taronga Zoo. Formerly gazetted as a quarantine station in 1920, the site also housed cattle, horses (including valuable racehorses), pigs and dogs. Although briefly closed during World War II, the station continued operating until 1981, after which it was transferred to State ownership and transformed into the existing Quarantine Reserve (Canada Bay Connections, 2013).

A number of facilities are provided at the reserve including bbq's, picnic tables, shaded areas, wheel chair access, tap water, power, toilets and parking (City of Canada Bay, 2013). Quarantine Reserve contains a small beach which supports mangroves (Aecom, 2010).

Water quality data are limited at this site. There are insufficient data to assess the site's suitability for swimming or the ecological health of the site. Despite the limited data, a number of initiatives have been implemented by Council to improve water quality. These include the Barnwell Park Golf Course Stormwater reuse project, the Street Sweeping Program and Gross Pollutant Trap (GPT) maintenance (OEH 2014). Canada Bay Council implemented a sand-filter and re-use system at Barnwell Golfhouse which utilised treated stormwater for irrigation, thereby reducing the amount of stormwater entering Hen and Chicken Bay at Drummoyne on the Parramatta River. The street sweeping program reduces the amount of litter and other pollutants entering the stormwater systems and therefore the receiving waterway. Additionally, Canada Bay Council maintains a number of gross pollutant traps that intercept pollution from the stormwater entering the bays of the Parramatta River (OEH 2014).

### 3.1.5 Bayview Park (Proposed swimming site)

Bayview Park is located in Concord, on the edge of the southern tip of Exile Bay (in Hen and Chicken Bay). Concord is in Canada Bay LGA and follows the same land use history as described above for Quarantine Reserve.

The Park's wharf was historically serviced by various ferry companies until October 2013 when the service was withdrawn due to low patronage. Facilities at the park include sheltered picnic tables, bbq's, public boat ramp, and parking, play equipment, wheelchair access, water and toilet amenities (City of Canada Bay, 2013). Mangroves and patches of seagrass beds are currently present in Exile Bay.

Public Baths were once present at this site which was a popular spot for swimming. Water quality data are limited at this site, although it is known that heavy metals, organic chlorines and polycyclic aromatic hydrocarbons pass through the canals and enter the Bay. To counteract this, stormwater filtration was proposed to be installed on the canals that lead to Exile Bay thereby reducing the flow of pollutants into the receiving waterways. There are insufficient data to assess the site's suitability for swimming or the ecological health of the site.

### 3.1.6 Putney Park (Proposed swimming site)

Putney Park is located in Putney within the City of Ryde LGA. The population of the Ryde LGA is approximately 103,000 (Profile ID, n.d). Land use in Ryde is predominately residential but also has substantial commercial and industrial and institutional areas. Historically, when the first land grants along the northern bank of the Parramatta River were issued in 1792, the land was mainly used for farms and orchards. Subsequent expansion and development of the region occurred after World War II, beginning with industrial, commercial and public housing construction and later rapid growth in apartment construction (Profile ID, n.d).

Like other urban catchments, Ryde faces the challenges of managing impacts to receiving waters from stormwater pollution and wastewater overflows. The catchment characteristics (including the topography and geology) can generate a substantial amount of run-off which can generate water quality impacts in downstream receiving waters. These impacts are being managed through water sensitive urban design and other measures such as raingardens and bio-retention basins, sand filters, swales and buffer strips, constructed wetlands and sedimentation basins (City of Ryde, 2010).

Putney Park is on the Putney Peninsula, an area which was privately owned until the 1840's, when it was subdivided. The land, which comprises much of Putney Park, changed hands several times. In 1928, Ryde Council purchased the lots associated with Putney Park, including the existing mansion, for the purpose of public recreation. Swimming baths were constructed a short time later but the Park and facilities fell into disrepair during World War II. The grounds became a passive recreation Park. The baths were removed, later being filled in and it remains as a grassed area within the Park. The northern section of the Park was purchased and opened as an addition to the park in 1998 (City of Ryde, 2011). The park extends along approximately 720m of the eastern foreshore of Kissing Point Bay on the Parramatta River. The adjacent landuse is mostly residential. The Mortlake Punt Ferry operates across the Parramatta River between Putney and Mortlake, adjacent to Putney Park. Large quantities of organic matter such as leaf litter are sometimes observed in stormwater outflows in Kissing Point Bay. The material settles in nearby mangrove stands or on the shores (Aecom, 2010). No waterways discharge directly into Kissing Point Bay.

Putney Park is part of the recently constructed and opened Ryde Riverwalk. The Riverwalk is a pathway that follows the Parramatta River from Banjo Patterson Park to Wharf Road, West Ryde. The Park is a popular park which is suitable for large groups and can be booked for events such as weddings and parties. The Putney Park Plan of Management (City of Ryde, 2011) outlines the vision for the Park which is broadly to provide recreational opportunities for visitors while maintaining and preserving the natural environment. Facilities include bbq's, picnic areas, cycleway, a large playground with water features and a second playground suitable for younger children, parking and toilets (City of Ryde, 2015).

Water quality data are limited at this site. There are insufficient data to assess the site's suitability for swimming or the ecological health of the site.

### 3.1.7 Kissing Point Park (Proposed swimming site)

Kissing Point Park is located a short distance upstream of Putney Park at Kissing Point and is on the western side of Kissing Point Bay. Kissing Point Park, also within the Ryde LGA, is located directly adjacent to Bennelong Park. Falling within the same catchment as Putney Park, the receiving waters adjacent to Kissing Point Park faces similar potential impacts to those impacts outlined in section 3.1.6 Putney Park, those being stormwater and wastewater overflows. Kissing Point Bay has been impacted by large quantities of organic matter (particularly leaf litter) contained in overflows which are discharging in the near shore environment and being trapped by mangroves growing in close proximity to the site (AECOM 2010).

Kissing Point Park is also part of the Ryde Riverwalk, a walk created to improve the community's enjoyment along the Parramatta River foreshore. The Park has numerous existing facilities, including a bbq, play equipment, cycle and walking paths, parking, toilets and a boat ramp (City of Ryde, 2015). The Parramatta River Ferry Wharf is also attached to the Park.

Water quality data are limited at this site. There are insufficient data to assess the site's suitability for swimming or the ecological health of the site.

### 3.1.8 Meadowbank (Proposed swimming site)

Meadowbank Park is one of the major sporting and recreation areas in Ryde LGA, with more than 10 playing fields. Other features include three playgrounds, walking and cycling paths, bbqs, parking, dog off-leash area and toilets. The Park is also part of the Ryde Riverwalk (City of Ryde, 2015). As per Putney and Kissing Point parks which occur within the Ryde LGA, the catchment history has seen commercial, industrial and more recently residential phases. Typical urban impacts such as stormwater run-off and wastewater overflows are a management challenge for the catchment.

Unlike the other Ryde parks discussed above, Meadowbank Park was previously a landfill site, having been reclaimed and filled with rubbish or other waste materials (Cardno, 2013). Meadowbank Park lies within the Archer Creek subcatchment. Stormwater from the surrounding residential area runs directly into Meadowbank Park. In order to improve the quality of the stormwater entering the Parramatta River at Meadowbank, the Meadowbank Stormwater Treatment System was constructed in 2009 (PRCG, 2011). The system is able to capture and treat the stormwater, in addition to reducing the volume and velocity of the stormwater flowing into the park and waterways. The system improves water quality by reducing pollutants entering the river, with modelling predicting a 39% reduction of Nitrogen, a 63% reduction of Phosphorus and a 78% reduction of Total Suspended Solids (inorganic particles suspended in the water) (PRCG 2011).

Archer Creek flows through the Ryde-Parramatta Golf Course before entering Meadowbank Park and the Parramatta River. Charity Creek runs from west of the Main Northern Railway through Meadowbank Park and to the Parramatta River. Meadowbank Park is part of an extensive wetland system bordering the Parramatta River. The mangroves in the wetland system represent a large proportion of mangroves in the Sydney Region

(Cardno, 2013). Mangroves provide many benefits to the natural environment. In particular they trap and bind sediments, reducing turbidity, which results in cleaner water. They capture effluents from runoff providing a buffer for nutrients, metals and other toxicants entering coastal waters.

Water quality data are limited at this site. There are insufficient data to assess the site's suitability for swimming or the ecological health of the site.

#### 3.1.9 Wilson Park (Proposed swimming site)

Wilson Park is located on the southern bank of the Parramatta River to the east of the Silverwater Road Bridge and just downstream of the confluence between the Parramatta River and Duck River. The Park lies within the new City of Parramatta LGA. The City of Parramatta LGA drains to the Parramatta River via Duck River and Homebush Bay. Land use in the catchment includes residential, business, industrial, special use and recreational. Stormwater management incentives were identified as being warranted for several locations in the Duck River catchment (Aecom, 2010). In Aecom's 2010 report, they observed contaminated stormwater flowing into Duck River (draining the industrial area in Silverwater).

Historically, the Park was natural mangrove and farmland which was developed into a Golf Course in 1920. It was then briefly owned by the Department of Defence from 1930-1946 until it became the site of a chemical factory which, when closed in 1974, left 230,000 tonnes of contaminated soil buried onsite (SOPA, n.d.).

The factory closed down in 1973 and the lands were developed as playing fields by Auburn Council in 1983, although closed in 1993 due to pollution rising to the surface. The site was reopened as playing fields and a public reserve after an extensive clean-up and bioremediation in 2003 (SOPA, n.d.).

A public boat ramp and jetty are located at the western edge of the Park. The park is also connected to Silverwater Park which is to the west of the Silverwater Bridge. The river sediments are a mix of fine sediments and larger cobbles and boulders, and larger items of litter washed into the river. Wash from the Rivercat and other vessels appear to resuspend some of the sediments and increase turbidity (pers. obs., Mirella Verhoeven).

There are currently no contemporary water quality data at this site. Data collected between 2003-2008 showed elevated numbers of enterococci which were rarely below 200CFU/100mL. These numbers indicate that suitability for swimming at Wilsons Park would have been very poor over that timeframe. Contemporary water quality data would need to be collected at this site to determine whether the water quality is acceptable for swimming now and in the future.

#### 3.1.10 Parramatta CBD (Proposed swimming site)

Parramatta CBD is a major business and commercial centre and the second largest CBD in NSW. The Parramatta River flows through the CBD in an easterly direction. Major developments and upgrades have occurred recently in Parramatta including upgrades around the railway station, the expansion of Westfield Parramatta, the creation of a new transport interchange and the ongoing development of the Parramatta Square.

Long term water quality monitoring has been undertaken in the Parramatta River at Marsden Weir. Laxton *et al* (2008) reported the water quality of this site from data collected between 1990 and 2007. The site was generally turbid during dry weather, becoming noticeably more turbid following wet weather, which also correlated with elevated levels of total suspended solid concentrations. Dissolved oxygen levels were highly variable becoming both supersaturated and anoxic at times. Nutrient concentrations were generally always elevated with median concentrations consistently exceeding recommended guidelines. Laxton also correlated the water quality at Marsden weir with influences upstream, noting that the quality of water from Toongabbie Creek and a lesser extent Darlings Mills Creek influenced the quality of water in the Parramatta River at Marsden Weir. This monitoring site at the time was known to be inhabited by exotic ducks, which may have contributed to the poor water quality.

Contemporary water quality data has been collected by the City of Parramatta Council at 3 locations: Lennox Bridge, Elizabeth Street Footbridge and Barry Wilde Bridge. The sites are all in close proximity and data have been combined to assess the swimmability of the Parramatta River at the CBD. Enterococci numbers during dry weather were generally elevated. Median numbers of ~120CFU/100mL (Category B) and a 95$^{th}$ percentile of ~500CFU/100mL (category D) exceeded the NHMRC (2008) Microbial Assessment Category (MAC) A 95$^{th}$ percentile limit of 40CFU/100mL and MAC B of 200CFU/100mL. Therefore, Parramatta River at the CBD would currently be considered unsuitable for swimming. When wet weather data are included in the analysis, the median number of enterococci increased slightly, however the 95$^{th}$ percentile decreased to ~470 CFU/100mL.

#### 3.1.11 MacArthur St Bridge (Proposed swimming site)

MacArthur St Bridge is located on the foreshores of Parramatta River a short distance downstream of the Parramatta River CBD. Mangroves are located at the foreshore edges and the site is a popular spot for waterbirds. The water quality at this site would be influenced by upstream sources including inflows from tributaries, which exhibit poor water quality and runoff from the surrounding heavily urbanised catchment.

Data were limited for this site to determine suitability for swimming. Therefore, the data reported for the Parramatta CBD (which is a combination of 3 sites within 300m of each other) will be used to infer whether MacArthur St Bridge is swimmable. During both dry weather and all weather conditions, enterococci numbers were elevated and exceeded the recommended MAC category for safe swimming. Hence, this site is currently not suitable for swimming, and a more substantial monitoring program would need to be undertaken specifically at this site to gain a better appreciation of enterococci numbers.

#### 3.1.12 Rhodes East (Proposed swimming site)

Rhodes East is located within the City of Canada Bay LGA. The Department of Planning and Environment and Council have identified Rhodes East area as a potential Priority Precinct and are generating a 20 year vision for the area (DoP 2016). Areas between the railway line and Concord Road have been identified as having potential for more open space, home and improved connections to public transport, services and jobs. Redevelopment of Rhodes East would also see improvements to parks, public squares, road, pedestrian and cycle paths and access to the waterfront (Inner West Courier 2016). With the development of Rhodes East comes the proposal for a new ferry wharf and interchange. Additional ferries could result in increases congestion, wash and turbulence that could impact on other waterway users.

The proposed site for swimming is located on the Parramatta River near Concord Road. Whilst there are no contemporary water quality data at this site to determine suitability for swimming, the water quality at this site would largely be influenced from the Parramatta River upstream and runoff from the urban landscape surrounding this site. Urban areas are comprised of hard impervious surfaces that result in increased volume of runoff and large amounts of pollutants being transferred into downstream waterways. To reduce the impact on water quality, the City of Canada Bay has installed numerous stormwater improvement devices and developed biodiversity projects to enhance the natural landscape (City of Canada Bay 2016). Stormwater improvement devices include Gross Pollutant Traps (GPTs) of which council maintain 11 in the Rhodes area. These 11 GPTS currently prevent 34 tonnes of waste entering waterways (City of Canada Bay 2016).

Rhodes Peninsula was the birthplace of Australia’s chemical industry and the site of chemical manufacturing for nearly 60 years. A former Union Carbide site undertook manufacturing and chemical processing operations in the area. Waste containing dioxins (a by-product of the manufacturing process) was used to fill areas across the Peninsula and Homebush Bay (NSW Health 2016). Whilst much of the land has been remediated, there is the potential for sediments along the waterway around Rhodes East to be contaminated.

Water quality data are limited at this site. There are insufficient data to assess the site’s suitability for swimming or the ecological health of the site.

### 3.1.13 Little Coogee, Parramatta Park (Proposed swimming site)

Parramatta Park is located within the Parramatta LGA, in the suburb of Parramatta at the western end of Parramatta River. The Upper Parramatta River Catchment area flows into this site. It has been intensely used throughout history, being a significant location for the Indigenous community but also greatly modified since white settlement. The catchment is mostly urban (94%), most of which is residential. Only 5% of the catchment remains as bushland and major transport corridors transect the catchment.

The health of waterways in the Parramatta River Catchment, like most urban areas, is threatened by stormwater pollution. In recent history, the main sources of pollution in the Parramatta River catchment (particularly upstream of the Parramatta weir) are (but not limited to) nutrients from fertilisers and detergents, wastewater overflows, animal faeces, motor vehicle contaminants (such as oil, grease and heavy metals) and litter (UPRCT, 2001). Significant works have been undertaken in recent years to manage threats and to improve water quality in the catchment, including the construction of pollution control devices, control of point source inputs (through education and enforcement) and the review and improvement of strategic and statutory plans (PCC 2011).

The Park has a rich history and has been identified as a significant cultural heritage location. As such, the Park is listed on the State Heritage Register and the National Heritage Register (Parramatta Park, 2015). The waterways are an integral part of the Park. The Park stretches across both sides of the Parramatta River. Annually it receives over 2 million visitors. The Park's vision for the future is to manage and enhance the biodiversity within the Park while having a multi-use urban park moving forward in the future. One of the objectives is to be home to healthy waterways supporting a diverse array of life (Parramatta Park, 2015). Grant funding in 2010 was used to install sediment erosion control measures and undertake stream bank vegetation works, which has resulted in new habitat and vegetation growth on the River.

Currently, water quality data is not collected at Little Coogee, however, enterococci data has been collected at 3 sites in the Parramatta CBD (1.5km downstream of Little Coogee), which may give some indication about water quality at Little Coogee. The data collected from the Parramatta CBD have been collated and assessed under both dry weather (Figure 3-1) and all weather conditions (Figure 3-2). Whilst numbers appear to be slightly lower on occasion during dry weather, the $95^{th}$ percentile exceeds the recommended limit of 200CFU/100mL and median concentrations of ~120CFU/100mL exceed the recommended dry weather only limit of 40CFU/100mL. Enterococci numbers do not appear to increase substantially when all the data is combined. These data infer that the Parramatta River at the CBD is not suitable for swimming. Contemporary water quality data would need to be collected at Little Coogee to gain a better understanding of this site's suitability for swimming.

### 3.1.14 Lake Parramatta (Current swimming site)

Lake Parramatta is upstream of Parramatta Park within the Parramatta LGA and is an impoundment of Hunts Creek. It has faced many of the same catchment influences on water quality as other urban areas.

Parramatta Lake was artificially created in 1855 as a masonry dam. The Lake holds 485,000 cubic metres of water which is the equivalent to 9,700 backyard swimming pools. The Lake and the surrounding lands became a recreation area in 1909. Consistently poor water quality in the 1970's and 1980's resulted in the erection of signs advising against swimming. Since that time, ongoing management and improvements in water quality resulted in the Lake being officially opened for swimming and recreation on $24^{th}$ of January 2015. The reserve provides a number of facilities over its 73 hectares, including non-motorised boating, playgrounds, walking trails, toilets, café, bbqs and picnic facilities (Parramatta City Council, 2015).

The water quality of Lake Parramatta is influenced by a number factors including:

- Inflow from Hunts Creek, which is a primary source of urban runoff
- Inflow from Kings School Creek
- Runoff from surrounding catchment, which is directed into the lake through a number of smaller inflows
- A wastewater overflow structure that discharges during wet weather (Morison 2003).

Historically, the suitability of recreation (particularly swimming) has been poor due to high levels of pathogens, algal blooms and poor water clarity. At times, secondary recreation activities such as boating have been compromised due to obstruction from macrophytes (Morison 2003).

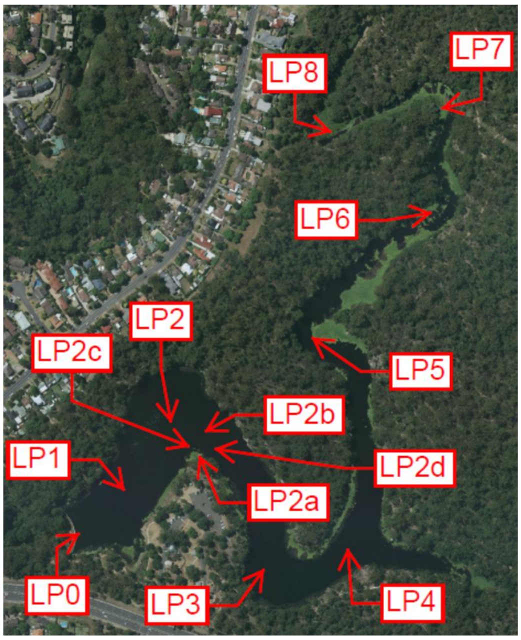


Figure 3-6 Lake Parramatta water quality monitoring sites (Parramatta City Council)

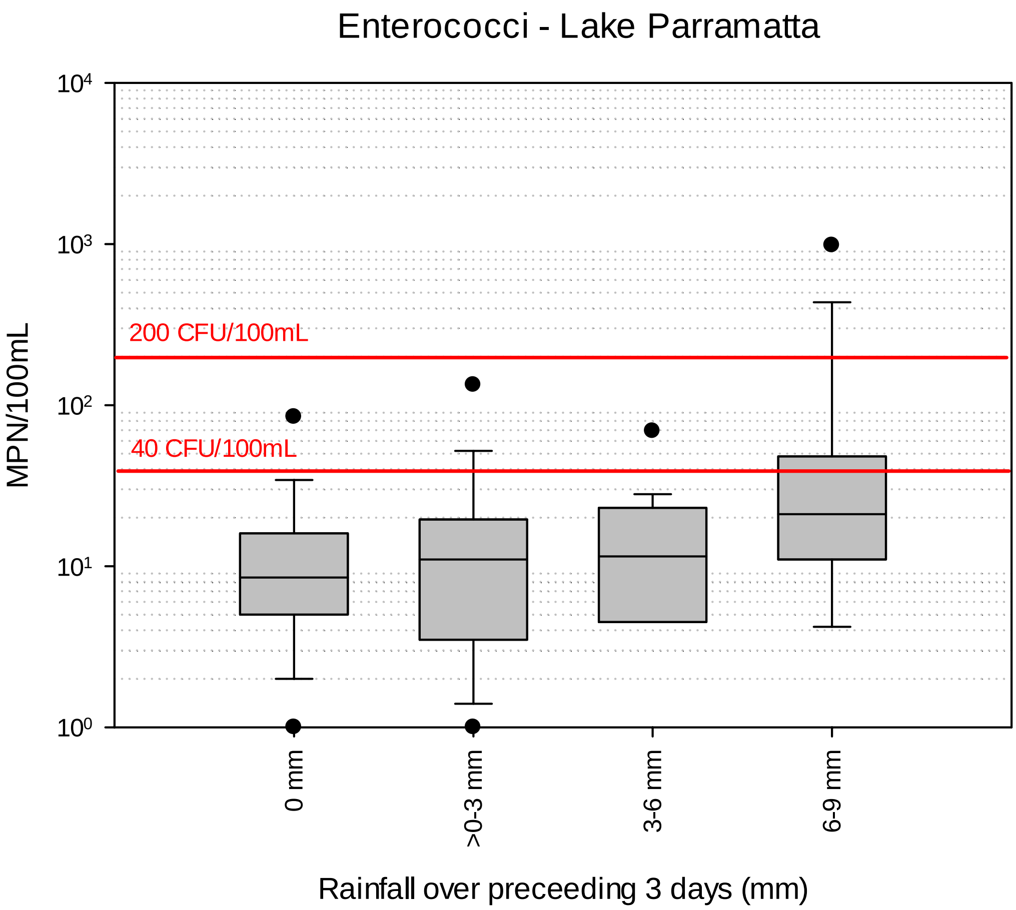


Figure 3-7 Enterococci results Lake Parramatta following varying rainfall

The water quality of Lake Parramatta is routinely monitored by City of Parramatta at numerous sites as shown in Figure 3-6. Sites LP2a, LP2B, LP2C and LP2d are within the swimming area. Enterococci data collected between 2013 and 2016 at these sites has been collated and used to assess the suitability for swimming within the Lake. Data were assessed under all weather conditions (Figure 3-1), for dry weather only (Figure 3-2) and following varying rainfall (Figure 3-7). During dry weather, Lake Parramatta exhibited better recreational water quality with lower numbers of enterococci (<40CFU/100mL) for the majority of time. Median enterococci numbers were ~9 CFU/100mL and the 95$^{th}$ percentile ~35CFU/100mL indicating the microbial water quality is considered suitable for swimming. In comparison, when enterococci data were assessed under all conditions, suitability for primary contact recreation was slightly poorer due to increased numbers (median ~16CFU/100mL, 95$^{th}$ percentile ~300CFU/100mL. This indicates that, at times following rainfall, Lake Parramatta may not be suitable for swimming.

When the data are separated into different rainfall amounts, it becomes clear that as little as 3mm of rainfall can result in higher enterococci, and between 6-9 mm of rainfall can result in the site being unsafe for swimming with the 95$^{th}$ percentile value of ~950 CFU/100mL exceeding the 200CFU/100mL guideline (Figure 3-57).

#### 3.1.15 Henley Baths (Proposed swimming site)

Henley Baths is located on the north shore of the Parramatta River behind a grassy reserve within Hunters Hill Council. This site was once a popular swimming spot, however over the years, visitation decreased and Council removed the shark nets that designated the swimming area. Beachwatch monitoring, which was frequently undertaken within Henley Baths, ceased in 2009, however monitoring data up to that point suggested that water was generally clean enough for people to swim in (with the exception of 2007-2008) (DECCW). The site has been nominated for re-opening as a swimming site.

Water quality at this site is likely to be affected by waters from numerous nearby urban storm water drains, wastewater overflows and the upper Parramatta River. Historical data shows that faecal coliform and enterococci densities generally increased with increasing rainfall, occasionally exceeding the median guideline limits in response to light rain in the previous 24 hours (DECCW 2009). Rainfall greater than 20mm in 24hours would result in frequent exceedances of median guideline limits for bacteria indicators. As a result of this poor water quality, largely due to stormwater, Hunters Hill Council now operates a number of GPTs throughout the catchment reducing the amount of pollution entering the river.

Analysis of the historical dataset collected between 2002 and 2009 indicates that the 95$^{th}$ percentile value for enterococci was generally below 200CFU/100mL (except 2007) and Henley Baths was generally suitable for swimming. Contemporary water quality data would need to be collected at this site to determine whether the water quality is acceptable for swimming now and in the future.

## 3.2 Concentrations and distribution of surficial sediment contaminants in Parramatta River in the upper Sydney Estuary (Authored by Gavin Birch 2016)

The contaminant of major concern in Sydney estuary is heavy metals, which are ubiquitous and at extremely high concentrations in some locations. Birch (2007) refers to the Sydney Estuary to include Central harbour (Circular Quay, Darling Harbour and White, Rozelle and Blackwattle Bays, Middle Harbour, Port Jackson, the Lane Cove and Parramatta Rivers, including Duck River and tributaries up to the fresh water limit and to the weirs on the Duck and Parramatta Rivers. Organochlorine compounds (OCs) and polycyclic aromatic hydrocarbons (PAHs) are also of concern in more restricted parts of the waterway. Concentrations of polychlorinated dibenzo-*p*-dioxins (dioxins) and polychlorinated dibenzofurans (furans) in sediments are highest in un-remediated parts of Homebush Bay, but these chemicals have been dispersed extensively throughout the estuary.

#### 3.2.1 Metals

Sedimentary metal concentrations decline markedly from the upper reaches of Sydney estuary towards the mouth and from the headwaters of offchannel embayments and tributaries in the central estuary towards the central channel. Sediments of the south, central embayments of Iron Cove, Hen and Chicken Bay and Homebush Bay consistently contain the most widespread distribution and highest concentrations of metallic contaminants. Individual embayments have distinctive metal distributions in Sydney estuary. Sediments in

Homebush Bay generally have only moderate concentrations of all metals, except lead in the south east. Surficial sediments in Hen and Chicken Bay have high copper concentrations, whereas sediments of Iron Cove are elevated in lead and cadmium.

#### 3.2.2 Organic contaminants (OCs and PAHs)

High concentrations of many organochlorine compounds occur in sediments in restricted parts of the upper reaches of embayments and tributaries throughout the estuary. Chlordane is the most widespread organochlorine compound and is present in sediments of the south, central embayments, whereas DDT and analogues DDD and DDE are in high concentrations mainly as legacy contaminants in Homebush Bay and is associated with stormwater discharge in Iron Cove and southern embayments of the upper estuary. Other cyclodiene compounds (aldrin, dieldrin, heptachlor and heptachlor-epoxide) are present in sediments at lower concentrations, mainly in Iron Cove and small embayments in the upper estuary. Polychlorinated biphenyls (PCBs) and Hexachlorobenzene (HCBs) are contained in sediments mantling Homebush Bay and the upper reaches of small embayments on the southern shores of central estuary. Total PAHs are elevated in sediments of upper Iron Cove. High concentrations of organic anthropogenic chemicals are mainly as legacy contaminants in Homebush Bay, Blackwattle/Rozelle Bay and other restricted localities, but are associated with stormwater discharge in the upper reaches of less industrialised embayments, e. g. Iron Cove, Hen and Chicken Bay.

Polycyclic aromatic hydrocarbons (PAHs) in sediments of Sydney estuary shows a general trend of increasing concentrations towards bay ends similar to that exhibited by other contaminants, e. g. in Iron Cove, Farm Cove, Homebush Bay and Duck River. Sediment at Mortlake contain extremely high levels of PAHs (240,000 µg/kg and 380,000 µg/kg, respectively), which suggest point sources at these sites. The PAHs are predominately high molecular weight compounds, characteristic of high-temperature combustion suggesting that fuel consumption by internal combustion engine and coal-fired power stations are the likely sources of these chemicals. Sediments in Duck River contained PAHs with a high abundance of low molecular weight compounds indicating a source of un-burnt fuel.

#### 3.2.3 Dioxins and Furans

Concentrations of polychlorinated dibenzo-*p*-dioxins (dioxins) (PCDDs) and polychlorinated dibenzofurans (PCDFs) (furans) in sediments were the highest recorded in Australia and among the highest reported for sediment in the world prior to remediation. Permanent bans were placed on fin fishing and prawn trawling in February, 2006 for the whole estuary, based on dioxin tissue burdens. The ban remains in force to the present day. These chemicals were manufactured by industry on the shores of Homebush Bay and are being dispersed extensively throughout the estuary. Remediation of sediments has been undertaken, however the effect of this work on distributions and in reducing body burdens in fin fish and prawn populations is currently a research gap.

## 3.3 Ecosystem Health

Key indicators measured in waterways for the purpose of monitoring ecosystem health also have the potential to influence the water quality of proposed swimming sites. Where data at swimming sites were not available, data from other waterways in the catchment have been included. These data have been assessed to gain an appreciation of current ecosystem health and likely catchment influences on swimming. The indicators include pH, ammonia, total nitrogen, total phosphorus and chlorophyll-*a*. Only datasets that were current and had an adequate amount of datapoints were included in the assessment. The summary of these results for pH are provided in Figure 3-8, ammonia Figure 3-9, total nitrogen in Figure 3-9, total phosphorus Figure 3-10 and Chlorophyll-a in Figure 3-11.

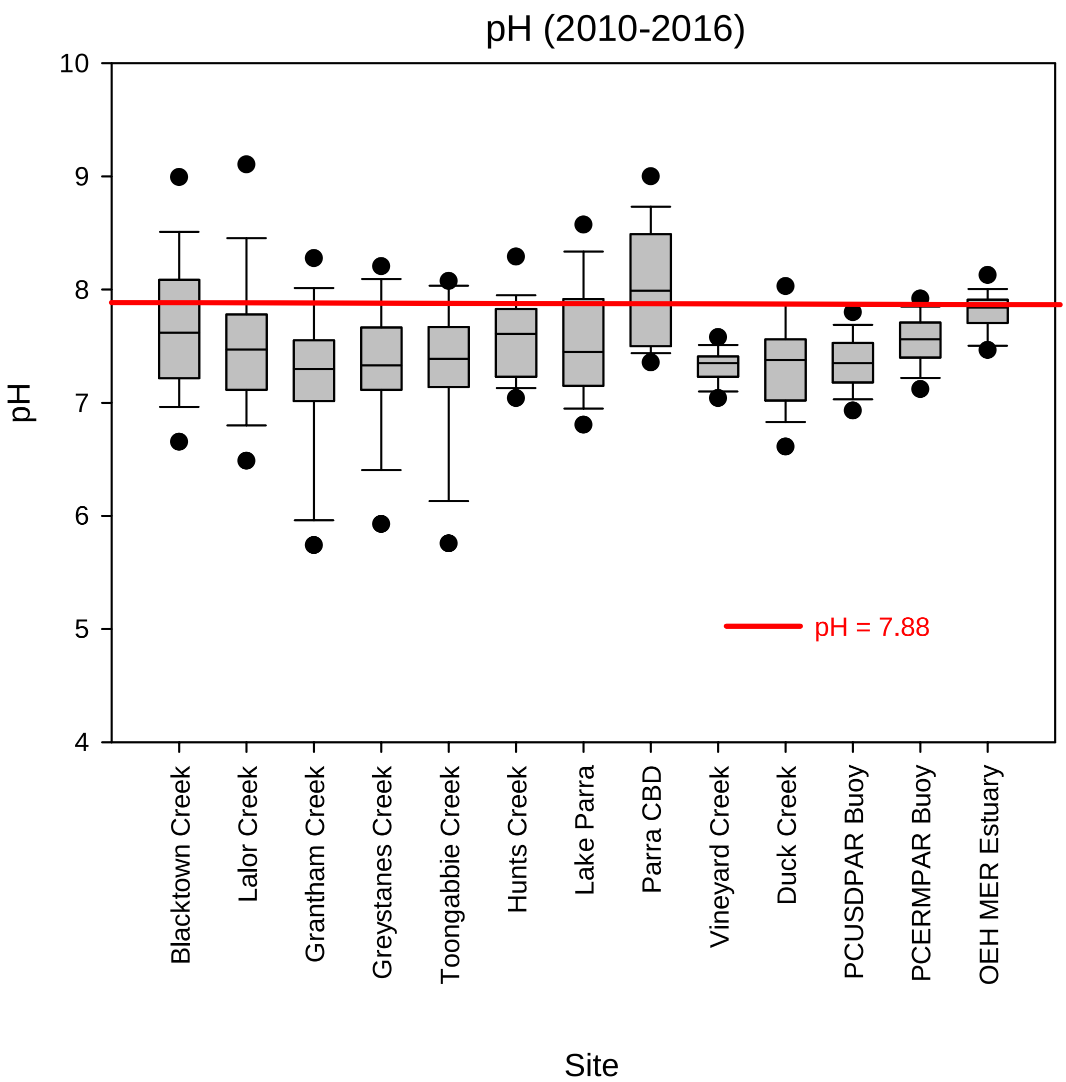


Figure 3-8 pH concentrations in the catchment (2010-2016)

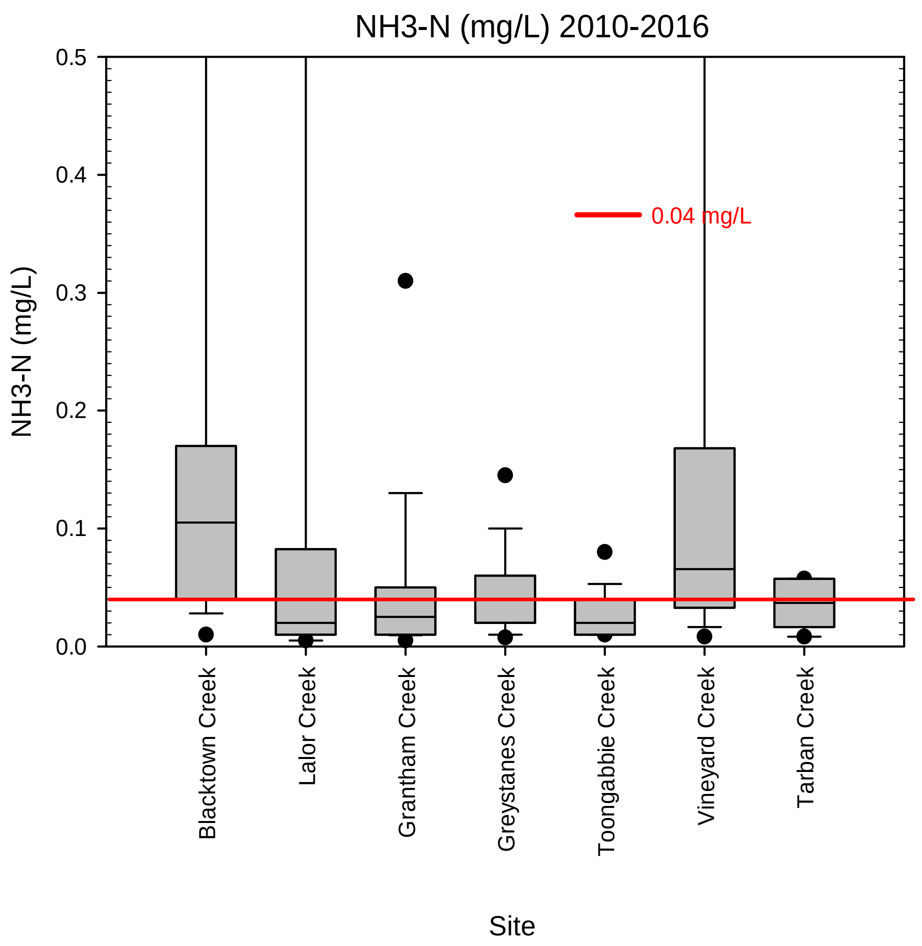


Figure 3-9 Ammonia concentrations in the catchment (2010-2016)

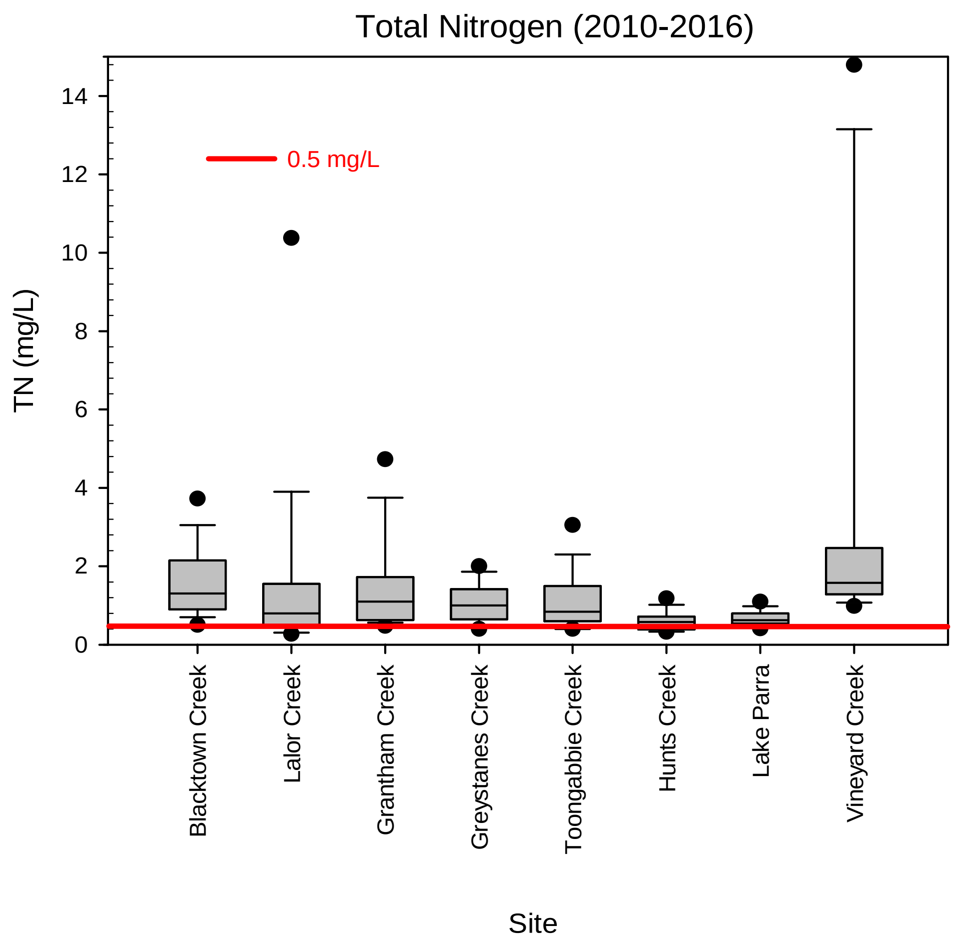


Figure 3-10 Total nitrogen concentrations in the catchment (2010-2016)

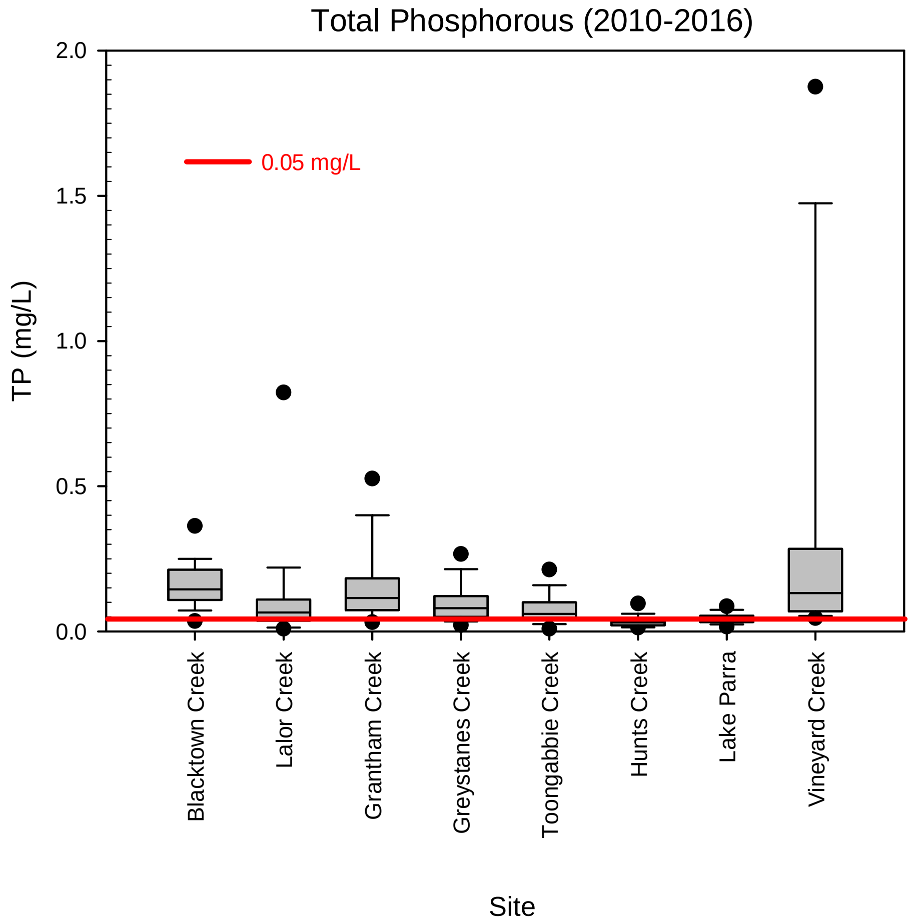


Figure 3-11 Total phosphorus concentrations in the catchment (2010-2016)

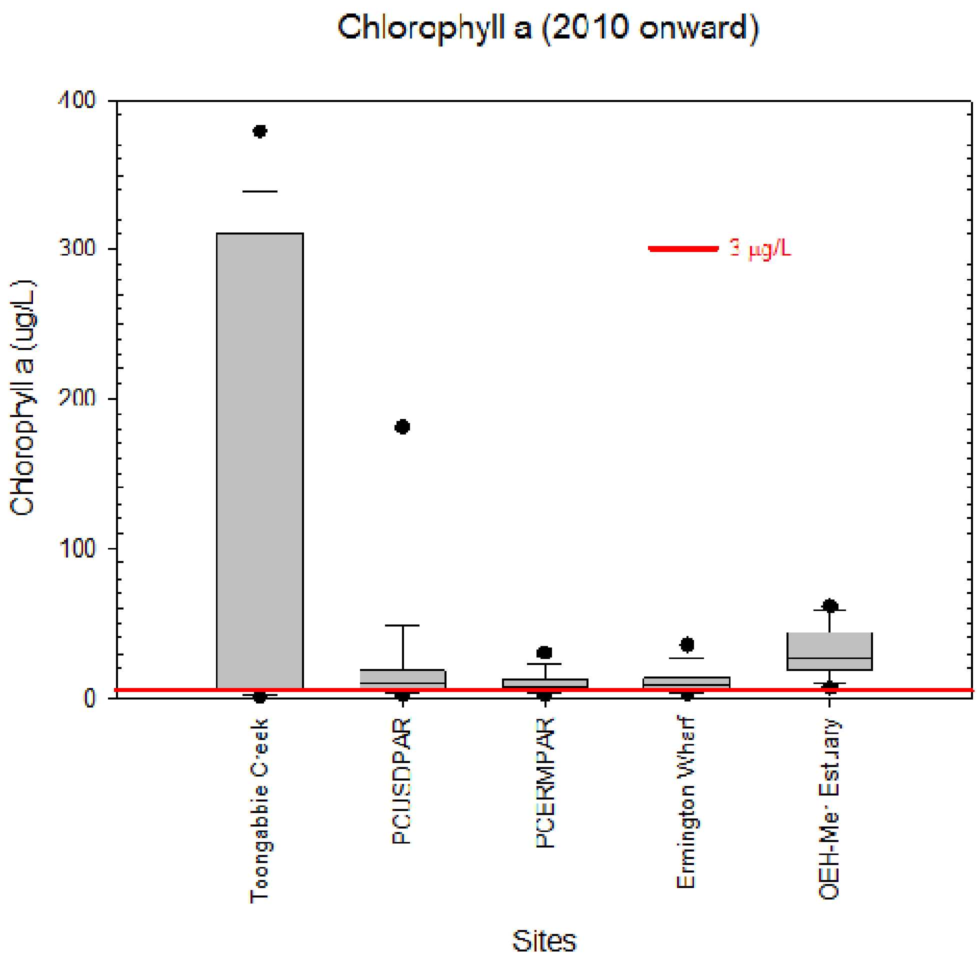


Figure 3-12 Chlorophyll-*a* concentrations in the catchment (2010-2016)

**Blacktown Creek** is located at the upper end of the catchment and drains into Toongabbie Creek. **Lalor Creek** also feeds into Toongabbie Creek at the junction with Blacktown Creek. Landuse within these catchments are largely a combination of residential, commercial and industrial. The water quality of Blacktown Creek and Lalor creek is poor and the creeks are considered eutrophic given the elevated nutrient concentrations. pH levels within the creeks vary. pH is generally higher in Blacktown Creek (median 7.6) than Lalor Creek (median 7.5) and with the exception of the Parramatta River, Blacktown Creek has the poorest pH of the remaining sites with only 59% of samples below the limit of 7.88. Blacktown Creek also exhibits the highest concentrations of ammonia (median 0.11mg/L) of all the tributaries reported. Both Blacktown and Lalor Creek are the receiving waterways for overflows and stormwater which are the most likely cause for the poor water quality. Additionally the creeks are known to suffer from bank erosion, weed proliferation and accumulation of rubbish and sediment during stormwater events.

**Grantham** and **Greystanes Creek** feed into the lower reaches of Toongabbie Creek. Grantham Creek extends from Grantham reserve in Seven Hills to the confluence of Toongabbie Creek. The creek is natural in its upper reaches and semi natural as it flows through Duncan Park. The rest of the creek is largely channelled and concrete lined. Greystanes Creek (also referred to as Girraween Creek) extends from the eastern edge of Prospect Reservoir to its confluence with Toongabbie Creek in McCoy Park. The creek is not in natural condition (aside from a small section), and has been extensively modified for flow mitigation works including realignment, and installation of concrete culverts and gabions. The water quality of these creeks could be considered poor. Whilst median pH levels are below the adopted limit with 85-88% of samples compliant, nutrient concentrations are elevated. In particular, total nitrogen and total phosphorus exceed the adopted limits on more than 80% of sampling occasions. Ammonia concentrations, whilst elevated, were more compliant (56-65% of the time). Median concentrations in Greystanes Creek (0.02mg/L) and median concentrations in Grantham Creek (0.03mg/L) were below the limit. These results infer the water quality of these urban creeks is poor, largely due to increased urban runoff and the resultant discharge of litter, sediment and pollutants from stormwater drains into the creek.

**Toongabbie Creek** flows into the Parramatta River in its upper reaches. Water quality in this creek would be representative of upstream influences which include diffuse pollution in stormwater, run-off from urban areas and wastewater overflows in addition to the inflows from Blacktown and Lalor Creeks. The pH of Toongabbie Creek generally falls below the adopted urban stream limit (79% of the time) and is lower than its inflow streams. Similarly, whilst nutrient concentrations in Toongabbie Creek are high, the concentrations of ammonia, total nitrogen and total phosphorus are generally lower than the inflow streams Blacktown and Lalor Creeks. Chlorophyll-a, a measure of phytoplankton abundance and biomass, is reported in excessive concentrations (median 297.2µg/L). The elevated concentrations of chlorophyll-*a* are reflective of the high nutrient concentrations and eutrophication of this aquatic ecosystem. Overall, the elevated nutrients and chlorophyll-*a* concentrations indicate the water quality of Toongabbie Creek is poor.

The **Hunts Creek** corridor begins in Carlingford and continues to Lake Parramatta Reserve in North Parramatta. The majority of the creek contains remnant bushland, including a large portion within the Kings School. The creek flows through Hawkesbury Sandstone with most of the creek having eroded a steep gully into the base rock. It forms a degraded but continuous corridor of gully forest from Lake Parramatta to Carlingford. The Hunts Creek corridor has retained the most substantial and intact bushland in the Upper Parramatta River Catchment, however the creek still forms a degraded but continuous gully (UPCRT 2001a). This is in part due to the steepness of the terrain which resulted in much later development of residential and industrial areas. Recent developments, upstream in Baulkham Hills and Carlingford, are impacting severely on the lower reaches of the creeks (UPCRT 2001a). The water quality of Hunts Creek is noticeably better than other urban streams in the catchment. pH levels are generally (79%) below the adopted limit of 7.88 and nutrient concentrations are the lowest of all the streams reported. Median total nitrogen concentrations of 0.58mg/L are marginally above the adopted limit of 0.5mg/L and total phosphorus (0.03mg/L) are below the limit of 0.05mg/L. The better quality is likely attributable to a less urbanised catchment and presence of native vegetation.

**Lake Parramatta** Reserve is a 73 hectare bushland and parkland reserve of which approximately 10 hectares is the lake itself. The reserve is located within two kilometres of the Parramatta central business district and is the largest bushland remnant surviving in the Parramatta Local Government Area. As mentioned previously, the water quality of the lake is largely influenced by inflows from Hunts Creeks and Kings School Creek, runoff from the surrounding catchment area and discharge of wastewater from an overflow structure during wet weather. Despite some of these influences, the water quality of the Lake is generally good. pH levels are mostly compliant (73%) and, similar to Hunts Creek, nutrient concentrations are low in comparison to other sites. Concentrations of total nitrogen and total phosphorus show little fluctuation and median concentrations of 0.63mg/L for TN and 0.04mg/L for TP are slightly above and below the adopted limits for urban streams respectively. The good water quality is probably attributable to the greater area of bushland catchment it drains and ongoing improvement works to get the quality of Lake Parramatta back to a level suitable for recreation.

Water quality data (pH only) from three sites in the **Parramatta River** in the CBD were combined to assess the ecosystem health. The water quality of this area is not only influenced by that of the upstream tributaries, which exhibit poor water quality, but also of the surrounding heavily urbanised catchment. The Parramatta River in the CBD generally had higher pH levels than the tributaries, with median levels of 8 greater than the adopted urban stream limit of 7.88. The high pH levels may be attributable to an increase in flow through and from concrete area, including urban concrete stormwater infrastructure. Water coming from these areas is generally higher in calcium and bicarbonate which can increase the pH of water.

**Vineyard Creek** is a tributary of the Parramatta River that drains a relatively small ($5km^2$) but highly modified catchment that discharges into the Parramatta River downstream of the Parramatta River CBD. Parts of Vineyard Creek and its tributaries have been subjected to substantial modification in stream form through the period of European settlement, but particularly during the period of intense urbanisation since 1970. The catchment is almost fully developed and is composed of low-medium density urban precincts, a Golf Course adjacent to the creek line, significant areas of parkland throughout and light to medium industrial zones in the southern part of the catchment (PCC 2003). Despite compliant pH levels (100%), the water quality of this creek could be considered poor and eutrophied. This is due to the excessive nutrient loads that enter the creek via stormwater and wastewater outlets and runoff. The concentrations of total nitrogen and phosphorus exceed the adopted limits for urban streams at all times for TN and 94% of the time for TP. Ammonia concentrations whilst elevated, comply on occasion (31%).

The **Duck River** discharges just upstream of the proposed swimming site at Wilsons Park and it is tidal in its downstream reaches. Several sites have been monitored in the Duck River, including the Botanical Gardens, Mona Bridge, Princess Road West (weir) and the Golfcourse (Wellington Road). Additionally, a water quality monitoring buoy was deployed in the Duck River to measure pH and chlorophyll-*a*. pH levels were below the adopted limit 97% of the time from the buoy and 92% of the time from other sites. There are no nutrient data for Duck River, however elevated chlorophyll-*a* concentrations (median 8.8µg/L) infer that nutrient concentrations are also likely to be high. The eutrophied state of Duck River is largely due to the highly industrialised and urbanised catchments surrounding this River. Council have identified many sites adjacent to the River containing unhealthy landfill and there are known sites of contamination in close proximity to Duck River.

**Ermington Bay** is located between Wilsons Park and Meadowbank, both sites nominated as proposed swimming locations. A monitoring buoy was deployed here to continually measure pH and chlorophyll-*a*. Chlorophyll-*a* samples were also collected at the wharf. Ermington Bay is estuarine and the water quality is not only influenced tidally, but also from runoff from a largely residential catchment with some industrial landuse. Monitoring results indicate that the pH levels are mostly compliant and less than the adopted limit of 7.88. Chlorophyll-*a* concentrations are elevated and exceed the ANZECC/ARMCANZ (2000) default limit of 4µg/L for estuarine ecosystems at most times (80%).

Monitoring of the estuary itself has also been undertaken. Several sites were monitored between the Parramatta River downstream of its confluence with Duck River to Cabarita Point for both pH and chlorophyll-*a*. The data from these sites have been combined to provide an overview of the water quality of the estuary. pH levels are typically higher in saline waters. Consistent with this, whilst pH levels are generally good, they are higher than the upstream freshwater tributaries of the Parramatta River Catchment. Chlorophyll-*a* concentrations are also elevated (median 25.7µg/L) and exceed the ANZECC/ARMCANZ limit at all times inferring that nutrient levels are also likely to be high.

# 4. Data Gaps and recommendations

The review of existing data at proposed swimming sites has identified that there are large gaps in information relating to the current water quality of the proposed swimming sites. The recommended indicators and methodology for assessing recreational water quality in the Parramatta River were identified and discussed extensively in the literature review (see Appendix A). Recommended indicators included heavy metals (surface sediment), dioxins (surface sediment and water), cyanobacteria, enterococci, bacteroides and faecal bacteriophages (PCC 2016). Table 4-1 displays the proposed and current swimming sites and current data gaps with respect to the above-mentioned indicators.

Table 4-1 Current data gaps for recreational water quality

| Site | Heavy Metals | Dioxins | Cyanobacteria | Enterococci | Bacteroides | Faecal Bacteriophages |
|---|---|---|---|---|---|---|
| Cabarita Beach | ✘ | ✘ | ✘ | ✓ | ✘ | ✘ |
| Chiswick Baths | ✘ | ✘ | ✘ | ✓ | ✘ | ✘ |
| Dawn Fraser Pool | ✘ | ✘ | ✘ | ✓ | ✘ | ✘ |
| Quarantine Reserve | ✓ | ✘ | ✘ | ✘ | ✘ | ✘ |
| Bayview Park | ✓ | ✘ | ✘ | ✘ | ✘ | ✘ |
| Putney Park | ✘ | ✘ | ✘ | ✘ | ✘ | ✘ |
| Kissing Point Park | ✘ | ✘ | ✘ | ✘ | ✘ | ✘ |
| Meadowbank | ✓ | ✘ | ✘ | ✘ | ✘ | ✘ |
| Wilson Park | ✘ | ✘ | ✘ | ✘ | ✘ | ✘ |
| Little Coogee (Parramatta Park) | ✘ | ✘ | ✘ | ✘ | ✘ | ✘ |
| Lake Parramatta | ✘ | ✘ | ✘ | ✓ | ✘ | ✘ |
| Henley Baths | ✘ | ✘ | ✘ | ✘ | ✘ | ✘ |
| Parramatta CBD | ✘ | ✘ | ✘ | ✓ | ✘ | ✘ |
| MacArthur St Bridge | ✘ | ✘ | ✘ | ✓ | ✘ | ✘ |
| Rhodes East | ✘ | ✘ | ✘ | ✘ | ✘ | ✘ |

✘ = Data Gap
✓= Current data

Collection of water quality data under different conditions (wet and dry) is important, however, it is only one step in assessing a site's suitability for swimming. For each site, a detailed risk assessment should be undertaken as per the NHMRC (2008) *Guidelines for Managing Risks in Recreational Waters.* The approach to assessing risks and managing hazards in recreational water is based on a preventative strategy which focuses on developing a) an understanding of all potential influences on a recreational water body and b) monitoring programs that can provide a real time indication of water quality (NHMRC 2008). A preventative approach focuses on assessing and managing hazards (a biological, chemical, physical or radiological agent that has the potential to cause harm) and hazardous events (an incident that can lead to the presence of a hazard) within a risk management framework. The risk is the likelihood of the identified hazard causing harm.

Potential hazards that require management in recreational waters, with particular reference to the Parramatta River Catchment include:

- Incidents and physical hazards (stormwater rubbish, mangroves, variable water depth)
- Heat, cold and ultraviolet radiations
- Microbial contamination (pathogens from wastewater and stormwater inputs, animal droppings)
- Toxic algae and cyanobacteria (eutrophied waterways which may lead to algal blooms)
- Chemical contamination (stormwater, resuspension of contaminant sediments)
- Dangerous or venomous organisms (bull sharks known to occur in Parramatta River).

# 5. Conclusion

This technical analysis is an early stepping stone in understanding the water quality of key sites in the Parramatta River with respect to their suitability for swimming, while also identifying some of the critical data gaps and risks which need to be addressed to help enable the PRCG to achieve their objective to make sites in the Parramatta River swimmable by 2025.

Overall, sites display water quality indicative of the catchment history and current land use. Sediment contamination has been reported at several sites within the river, and many sites are affected by nutrients from wastewater overflows and stormwater runoff. Nevertheless, water quality appears to be improving as a result of catchment management measures. For the first time in decades, Lake Parramatta was officially opened again for swimming in 2015, one of the 16 sites identified as proposed or current swimming sites by the PRCG.

Water quality data collated for many sites is patchy or inconsistent, so it is difficult to rigorously asses the sites for their suitability for swimming. Of the five locations monitored for recreational water quality (i.e. with sufficient enterococci data), all sites except Parramatta CBD can be considered suitable for swimming during dry weather. Following wet weather, when receiving waters are often affected by wastewater and stormwater, sites are not suitable for primary contact recreation. The time it takes for a site to be suitable for swimming following rainfall varies depending on the amount of rainfall and the location of the site itself. Given the results show an increase in enterococci numbers 3 days after rainfall, it would be considered that swimming would not be suitable for 3 days following rainfall. This approach is consistent with current Beachwatch advice for harbour swimming sites.

This analysis has found that almost all sites require further monitoring in order to understand the existing environment, but also to enable a measure of change over time resulting from investment and management actions. Although some historical data are available for recreational water quality, these data can only be used to describe the general patterns in the past and are not a reliable source for which to base future decisions. Sites such as Bayview Park, Quarantine Reserve, Putney Park, Kissing Point Park and Meadowbank have little to no available information to understand the recreational or ecological health of the site.

The water quality parameters recommended for recreational monitoring in Appendix A: *How should recreational water quality in the Parramatta River be assessed? A review of current literature* have not been monitored at the sites, with the exception of enterococci, as discussed in this report.

This technical analysis completes phase three of the project, entitled *Strategic Analysis of Water Quality Monitoring in the Parramatta River Catchment.* The next and final phase of this project is the preparation of a business case for the development and implementation of a monitoring program, tailored to recreational water quality at the nominated swimming sites in the Parramatta River.

# 6. References


Aecom (2010). Parramatta River Estuary Processes Study. Prepared for the Parramatta River Estuary Committee.

Birch, G.F. (2016). Concentrations and distributions of Surficial Sediment Contaminants in Parramatta River in the upper Sydney estuary. (provided by G Birch for this report).

Birch, G. F. (2007). A short geological and environmental history of the Sydney estuary, Australia, pp 217-246. In: Water, Wind, Art and Debate. Ed. G. F. Birch, Sydney University Press, The Sydney University, Australia. 433p.

Canada Bay Connections (2013). Animal Quarantine Station. Available at https://canadabayconnections.wordpress.com/2013/05/14/animal-quarantine-station/. Accessed 11 April 2016.

Cardno Lawson Treloar (2008). Parramatta River Estuary Data Compilation and Review Study. Prepared for the Parramatta City Council, Department of Environment and Climate Change & Sydney Metropolitan Catchment Management Authority on behalf of the Parramatta River Estuary Management Committee.

Cardno (NSW/ACT) Pty Ltd (2013). Parramatta River Estuary Coastal Zone Management Plan. St Leonards NSW 2065.

City of Canada Bay (2013). Parks. Available at http://www.canadabay.nsw.gov.au/parks---main-page.html#acctab1. Accessed 11 April 2016.

City of Canada Bay (2016) Water. Available at http://www.canadabay.nsw.gov.au/water----main-page.html#acctab1. Accessed 3 August 2016.

City of Ryde (2010). Local Planning Study. City of Ryde.

City of Ryde (2011). Putney Park Plan of Management. City of Ryde. Prepared by Open Space, Community Life.

City of Ryde (2015). Parks and Playgrounds. . Available at http://www.ryde.nsw.gov.au/Recreation/Parks-and-Sportsgrounds . Accessed 11 April 2016.

DoP (2016). *Rhodes East Priority Precinct Investigation Area Workshops Outcomes Report.* Department of Planning and Environment June 2016.

DSEWPaC (2013). *Characterising the Relationship between Water Quality and Water Quantity.* Department of Sustainability, Environment, Water, Population and Communities.

Inner West Council (2013) Stormwater Drains. Available at http://www.leichhardt.nsw.gov.au/Community-Issues/Other-Issues/Our-Future/What-Must-Be-Funded/Stormwater-Drains. Accessed 20 July 2016

Inner West Courier (2016). *Rhodes East to become vibrant community precinct for growing Sydney.* Available at http://www.dailytelegraph.com.au/newslocal/inner-west/rhodes-east-to-become-vibrant-community-precinct-for-growing-sydney/news-story/24770075fd53093cbd450f88b3d1491b. Accessed on 3 August 2016.

Morison, Peter (2003). Revision of Lake Parramatta Water Quality Management Plan

NSW Health (2016). *Rhodes Peninsula Remediation.* Available at http://www.health.nsw.gov.au/environment/hazard/rhodes/Pages/default.aspx. Accessed 3 August 2016

OEH (2012). *State of the Beaches Report 2011-2012: Sydney Estuarine Beaches region*. Office of Environment and Heritage NSW.

OEH (2014) *Sydney Harbour – Lower Parramatta River.* Available at http://www.environment.nsw.gov.au/beach/ar0708/lowerparramatta.htm. Accessed 20 July 2016.

Parramatta City Council (2003). Vineyard Creek Waterways Maintenance and Rehabilitation Masterplan. Volume 1, Issue 1. 2003

Parramatta City Council (2011). Waterways and Catchment Management. Available at http://www.parracity.nsw.gov.au/live/my_environment/water_and_waterways/waterways_management. Accessed on 20 July 2016

Parramatta City Council (2015). Swimming at Lake Parramatta. Available here http://www.parracity.nsw.gov.au/play/sports_and_recreation/swimming_at_lake_parramatta. Accessed 12 April 2016.

Parramatta City Council (2016) *How should recreational water quality in the Parramatta River be assessed? A review of current literature,* compiled by the Stuart Khan, University of NSW, in conjunction with Jacobs Consulting.

Parramatta Park (2015). Biodiversity Strategy. Available at https://www.parrapark.com.au/assets/Uploads/Resources/plans-of-management/PPT-Parramatta-Park-Biodiversity-Strategy.pdf. Accessed 12 April 2016.

Pers.obs. Personal observation by Mirella Verhoeven, Senior Environmental Scientist at Jacobs Group (Australia) Pty Ltd in April 2016.

Profile ID (n.d.). Community Profile. ID The population experts. Available at http://profile.id.com.au/. Accessed 12 April 2016.

PRCG (2011). Demonstration Case Study. Working Together to Sustain the Parramatta River. Available at http://parramattariver.org.au/wp-content/uploads/Meadowbank-Park2.pdf. Accessed 12 April 2016.

SOPA (n.d.). Case Study – Wilson Park. Sydney Olympic Park Authority. Available at http://www.sopa.nsw.gov.au/media/pdfs/publications/case_studies/case_study_-_wilson_park. Accessed 12 April 2016. .

The Lazy Swimmer (2009). Available at https://sites.google.com/site/thelazyswimmer/day-3, Accessed 20 July 2016

Tippler, C., Wright, I.A., Davies, P.J. and Hanlon, A. (2013). *Ecosystem Guidelines for the Conservation of Aquatic Ecosystems of the Georges River Catchment: A Method Applicable to the Sydney Basin.* Proceedings from the 6th State of Australian Cities Conference, Sydney, 26-29 November 2013.

UPRCT (2001). Upper Parramatta River Catchment Education Resource Kit, 2002. Information Sheet (environmental issues) E7 – Water Pollution. Available here http://www.uprct.nsw.gov.au/HTML/Info%20Sheets/Enviro%20Issues/E7%20Water%20Pollution.htm. Accessed 12 April 2016.

UPRCT (2001a). Upper Parramatta River Catchment Education Resource Kit, 2002. S6 – Hunts Creek Sub-catchment. Available here http://www.uprct.nsw.gov.au/PDF/Info%20Sheets/Sub-catchment/S6%20-%20Hunts%20Creek.pdf. Accessed 3 May 2016

# Appendix A. Literature Review

Lake Parramatta, 2015. Photograph by Chris Frape.

# Strategic Analysis of Water Quality in the Parramatta River

Parramatta River Catchment Group

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## How should recreational water quality in the Parramatta River be assessed? A Review of Current Literature.

Parramatta City Council | FINAL

10 May 2016

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## Strategic Analysis of Water Quality in the Parramatta River

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| Final | 10 May 2016 | Literature Review | S Khan (UNSW) | K Byrnes | Parramatta City Council |

# Contents

# Executive Summary

A review of current scientific literature was undertaken with the following key aims:

- To identify current knowledge regarding water quality in the Parramatta River with direct relevance to potential increased primary contact recreational activities such as swimming.
- To consider potential future approaches to monitoring recreational water quality in the Parramatta River to assess the public health safety for potential increased primary contact recreational uses.

The Parramatta River has a long history of contamination, primarily related to urban and industrial activities which have taken place in the river's catchment throughout the last two centuries. Research conducted since the 1990s has established a relatively clear picture of spatial and temporal patterns of contamination for a range of chemical contaminants including metals, nutrients, halogenated organic compounds and polycyclic aromatic hydrocarbons.

Information relating to cyanobacteria and pathogenic microbial contaminants (bacteria, viruses and protozoa) are much sparser. Some bacterial monitoring (for faecal indicator bacteria) has been undertaken at a limited number of sites over an extensive period of time. While this monitoring has been undertaken with the aim of providing an indication of likely faecal contamination –and hence the presences of a potentially wider range of organisms – there are limitations to the ability to draw such connections.

A detailed understanding of recreational water quality risks in the Parramatta River will require comprehensive risk assessment. Suitable established frameworks are identified to undertake the necessary risk assessment for chemical contaminants. While a number of limitations are identified for current approaches to water quality monitoring for microbial risks in Australian recreational waters, a general approach to developing a suitable strategy is proposed.

However, it is concluded that the establishment of an effective ongoing monitoring strategy will require efforts to understand the observable relationships between potential indicators of faecal microbial contamination and risks associated with the actual presence of pathogenic organisms. Quantitative Microbial Risk Assessment (QMRA) is identified as a tool which can be used to facilitate the development of this understanding.

It is proposed that a number of contaminants and indicators should be monitored at specific locations proposed for future recreational water use. Due to the nature of the contaminants of concern, and whether they present acute or chronic health risks, there are significant differences in appropriate monitoring frequencies. Furthermore, it is essential to consider the appropriate sites for sample collection, including whether they include sediment, the pelagic zone or the water surface.

Monitoring data should be used in association with a conceptual recreational exposure assessment to identify levels of chemical and microbial health risk posed to recreational water users at individual proposed sites.

Note that these recommendations follow a thorough review of the scientific literature and are considered to provide a scientifically-informed assessment of recreational water quality. However, this process has not included a cost/benefit analysis since that is to be undertaken separately.

## Heavy metals in surface sediment

A small suite of heavy metals (most notably mercury, cadmium and lead) should be assessed in sediment at each proposed swimming location. Since these contaminants present chronic (as opposed to acute) human health risks, monitoring could be done well in advance of any recreational use and updated periodically (eg. Once per year at the beginning of each swimming season).

## Dioxins in surface sediment and aqueous samples

Key dioxins that have previously been detected in significant concentrations in the Parramatta River should be assessed in each proposed swimming location. Analytical methods that target dioxins concentrations commonly target a suite of these chemicals, enabling a weighted sum of the results to give a toxic equivalency

(TEQ) value, representing the overall toxicity as a single value. The TEQ should be measured for sediment and aqueous samples on an annual basis at the start of each swimming season.

## Cyanobacteria

The presence of severe cyanobacterial blooms can be detected visually and regular (eg, weekly) inspections should be made at various locations on the river. A clear protocol for detecting and identifying a potential cyanobacterial bloom should be developed. In circumstances where a bloom is detected as affecting, or potentially affecting a swimming site, a number of actions could be taken. One option may be to close the site for recreational use as a precautionary measure. Alternatively, samples could be genetically analysed for specific species in order to determine whether they are potentially toxin-producing.

## Enterococci

As the current international standard for monitoring recreational water quality in marine waters, regular monitoring (during the swimming season) for enterococci is warranted. Although significant background concentrations can be anticipated, and the usefulness as an indicator of human faecal contamination is limited, monitoring will strengthen the overall evidence-base and ability to understand changing water quality. A once-off period of intensive monitoring (eg, daily for 3-6 months) would provide a strong basis for understanding trends. It would then be anticipated the ongoing regular testing could be less frequent and possibly event-driven.

## Bacteroides

Monitoring of *Bacteroides* is undertaken using molecular methods (as opposed to culture-based methods). It has the advantages that these bacteria are excreted in very high numbers and that a range of host-specific organisms provides excellent opportunities to distinguish various sources of bacterial contamination in water. Human-specific *Bacteroides* should be tested, potentially along with other strains which may indicate sources from birds and other species. Analysis should be undertaken with the same frequency as analysis for enterococci.

## Faecal bacteriophages

Faecal bacteriophages (such as coliphages) should be tested since they are believed to represent the fate of enteric viruses, much more effectively than bacterial monitoring. An appropriate faecal bacteriophage species (and hence method) will need further consideration. Analysis should be undertaken with the same frequency as analysis for enterococci.

## Direct pathogen monitoring

Some direct pathogen monitoring, for non-faecally derived pathogenic organisms, such as pathogenic *Vibrio Spp.* may be warranted. Following a satisfactory research period, it may be possible to develop sufficient understanding of the spatial and temporal variability, that other non-microbial measures may become sufficient to inform risk assessments for these organisms.

## Spill detection

Careful consideration should be given for how best to detect a diverse range of spills that may occur and pose risks to recreational water quality. Some water quality monitoring (e.g. for BTEX chemicals) may be effective. However, other useful approaches could include visual inspections, combined with a compulsory reporting-based regulatory system, or a well organised community reporting system.

# 1. Introduction

The Parramatta River extends from Blacktown Creek in the west to the confluence of the Lane Cove River in the east. It is the largest river entering Port Jackson (Sydney Harbour). The river is tidal to the Charles Street Weir in Parramatta, some 30 km upstream from Sydney Heads. The Parramatta River below the weir is, in fact, an estuary and not a river, whereas (Upper) Parramatta River above the weir is a river.

The Parramatta River is 19 km in length, but has around 220 km of waterways in its catchment, including a number of significant tributaries (Parramatta River Catchment Group, 2016). These include Subiaco Creek, Tarban Creek, Duck River, Duck Creek, Haslams Creek, Iron Cove Creek, Hawthorne Canal and Powells Creek.

The estuary itself covers 12 square kilometres and is in a constant state of flux with tidal movements and freshwater from the river's tributaries changing the chemical composition of the water on a daily basis (Parramatta River Catchment Group, 2016). Tidal flushing for complete water exchange takes 3-4 months.

The total area of the catchment is 257 $km^2$ and the majority is managed by local government, including the Local Government Areas of Ashfield, Auburn, Bankstown, Blacktown, Burwood, Canada Bay, The Hills, Hunters Hill, Holroyd, Leichhardt, Parramatta, Ryde and Strathfield. Other major land managers include Sydney Olympic Park Authority, Bidjigal Reserve and Shell Oil Clyde Refinery (Parramatta River Catchment Group, 2016).

Catchment management oversight is provided by the Parramatta River Catchment Group (PRCG), which is composed of Local Government and other agencies (PRCG 2016). The current management strategy for the river is outlined in The Parramatta River Estuary Coastal Zone Management Plan, which was prepared on behalf of the PRCG (Cardno Pty Ltd 2013). The Sydney Coastal Councils Group have also recently reported the outcomes of a Sydney Harbour Coastal Zone Management Plan Scoping Study (GHD, 2015)

The Parramatta River and the Sydney estuary, to which it drains, have a long history of anthropogenic contamination by chemical and microbial substances, stretching back to European colonisation in 1788 (Davies & Wright, 2014; Birch *et al.*, 2015c). Together, they form one of the most modified waterways in Australia due to a highly urbanised catchment and a high population (Birch *et al.*, 2015c).

Industries were first established on the banks of Darling Harbour in 1800, from where they gradually spread along the southern shore of the River (Birch *et al.*, 2015b). While regulatory reforms were introduced in the 1940s and 1950s to address pollution of the Harbour, it wasn't until the Clean Waters Act 1970 that pollution levels entering the Harbour began to decline (Montoya, 2015).

Many parts of the estuary have been subject to land reclamation, and in many cases these reclaimed lands have been filled with municipal or other waste materials (Birch *et al.*, 2009). This reclamation has been shown to have detrimentally impacted water quality in the Parramatta River and its tributaries in a number of circumstances (Suh *et al.*, 2003; Suh *et al.*, 2004). Industrial activities throughout the 20$^{th}$ century, along the shores and within the catchment of the River (Birch *et al.*, 2015c), have resulted in a large store of legacy chemicals in sediments (Birch & Taylor, 1999; Birch & Taylor, 2000).

However, the greatest contemporary source of contaminants is believed to be stormwater, particularly from highly urbanised catchments on the southern side of the river (Beck & Birch, 2012). Evidence for this includes a strong spatial relationship between major stormwater outlets and distribution of metals in Sydney Harbour sediment (Birch & McCready, 2009; Birch & Rochford, 2010). Stormwater modelling reported in 2009 indicated an average annual discharge to Sydney Harbour of 215 GL (Birch & Rochford, 2010), much of which is delivered to the lower reaches of the estuary via the Parramatta River.

Urban stormwater often conveys a high load of human pathogens (disease-causing microorganisms) including viruses, bacteria and protozoa (Jiang *et al.*, 2015; Lim *et al.*, 2015; Page *et al.*, 2015). Many of these pathogens originate from municipal sewage and are transferred from sewers to stormwater systems by leakage or wet-weather overflows designed into the sewage system (Passerat *et al.*, 2011; Khan *et al.*, 2014). Consequently, increased rainfall, runoff and stormwater overflow lead to more events carrying peak concentrations of waterborne pathogens in surface water (Schijven & de Roda Husman, 2005; Schijven *et al.*, 2013). This can lead to the exposure of recreational water users to pathogens responsible for a range of illnesses, including gastrointestinal disease, skin infections and ear infections (Stewart *et al.*, 2008).

A review of water quality data collected for the upper Parramatta River between 1990 and 2007 was commissioned by Parramatta Council (Laxton *et al.*, 2008). This review reported a number of indicators of generally poor water quality including elevated nutrient concentrations, turbidity, and –following wet weather – faecal coliforms. Salinity concentrations exhibited a large range from 0.06 ppt to 31ppt, depending on runoff and tidal movements. Large seasonal variations were observed in surface temperature and dissolved oxygen concentrations. While the ecology of the upper-Parramatta River was found to be very productive and dynamic, the water quality failed to meet most of the relevant criteria for primary contact recreation, secondary contact recreation, or passive recreation.

A number of sites on the lower Parramatta River are currently monitored for recreational water quality, most notably Cabarita Beach (Cabarita), Chiswick Baths (Five Dock Bay) and the Dawn Fraser Pool (Balmain). During 2014-2015, these sites were assessed as having water quality that was safe for swimming most of the time but could be susceptible to pollution after heavy rainfall (10 mm or more) (OEH NSW 2015). However, the river west of Cabarita is not currently considered to be swimmable due to poor water quality, including the assumed presence of pathogenic microorganisms.

Community consultation undertaken in preparation of The Parramatta River Estuary Coastal Zone Management Plan highlighted "*water quality suitable for recreational usage*" as a contemporary community value (Cardno Pty Ltd 2013). Consequently, a key management aim identified in the Plan is "*to improve water quality in the estuary such that it is suitable for a range of environmental functions and recreational uses*" (Cardno Pty Ltd 2013).

As a first step toward an improved understanding of recreational water quality, a review of existing published literature pertaining to chemical and microbial contaminants within the river has been undertaken. It is intended that this review will provide a basis for informed discussion and future planning.

# 2. Chemical Contaminants

Research undertaken since the 1990s has established a relatively detailed knowledge base for the spatial and temporal distribution of a range of chemical contaminants in the Parramatta River. Most attention has been focused on metals, nutrients, halogenated organic compounds and polycyclic aromatic hydrocarbons. More recently, a survey of water soluble trace organic contaminants was published, highlighting the continuing flux of contaminants to the river from stormwater and sewage systems that leak or overflow to stormwater.

## 2.1 Metals and metalloids

Sediments in Sydney Harbour, including the Parramatta River and its tributaries are contaminated with a range of inorganic substances, including heavy metals and metalloids (Birch & Taylor, 1999; McCready *et al.*, 2006a; Ying *et al.*, 2009; Birch, 2011). Widely detected metals and metalloids include antimony, arsenic, cadmium, chromium, copper, iron, lead, manganese, mercury, nickel, silver, and zinc (McCready *et al.*, 2006a). In particular, severe enrichments (above historic concentrations) of copper, lead and zinc have been reported (Irvine & Birch, 1998; Nath *et al.*, 2014).

Many of the metals detected in sediment are also measurable as dissolved (or suspended) substances in the water column, including cadmium, copper, nickel, manganese and zinc (Hatje *et al.*, 2001; Hatje *et al.*, 2003). The partitioning of metals between precipitated and dissolved forms depends on local geochemical factors including pH and redox conditions (Simpson *et al.*, 2002). Sediment contamination around Iron Cove was found to be greatest near a stormwater canal, where sediments were anoxic and contained high concentrations of sulfide in the pore-water (Simpson *et al.*, 2002).

Since metals concentrations (copper, lead and zinc) in the water column have been found to be associated with total suspended solids (TSS) concentrations, monitoring TSS has been proposed as a surrogate for estimating metal loading in real time under some conditions (Beck & Birch, 2011). Research has shown that TSS and associated metal loads are elevated in Parramatta River water column during heavy rainfall and high-wind conditions (Birch & O'Hea, 2007).

Surficial sediments covering the bathymetry of the parts of the Parramatta River contain some of the highest concentrations of metals reported in Australia, and globally (Birch *et al.*, 2013). Of six embayments of Sydney Harbour recently studied, sedimentary metal concentrations were highest in Rozelle and Blackwattle Bays, followed closely by Iron Cove, for both total and size-normalised sediments (Birch *et al.*, 2013). Lower concentrations were observed in Hen and Chicken Bay, Homebush Bay, Lane Cove estuary and Central Middle Harbour (with the latter two external to the Parramatta River estuary).

Sediment cores taken adjacent to long-term industrial sites have shown that past industrial practices contributed significantly to contamination of estuarine sediment (Taylor *et al.*, 2004; Birch *et al.*, 2015b). Further analysis of vintage surficial sediment and sediment cores has revealed that metal concentrations in surficial sediment have declined in many areas since about the early 1990s (Birch *et al.*, 2013). The decline was reported to have been extensive in the upper and central parts of the estuary, but accompanied by smaller increases in the lower estuary, due mainly to a down-estuary shift in industry and urbanisation.

Mangrove systems, and the fine sediments that provide their root rhizosphere, play an important role influencing the fate of trace metals in the Parramatta River. Although they have a large potential to sequester trace metals, thus reducing pollution in the marine environment, changes in physico-chemical conditions may trigger release of accumulated trace metals to the sediment–water interface (Chaudhuri *et al.*, 2014). The ability to detect heavy metal concentrations in mangrove pneumatophore (aerial root) tissues has led to suggestions that these may play a useful role as a bio-indicator of estuarine metal contamination (Nath *et al.*, 2014).

The majority (>90%) of contemporary metal (copper, lead and zinc) and total suspended solid annual loads are believed to be contributed during high stormwater-flow conditions (>50 mm rainfall day) (Beck & Birch, 2012). There is evidence to indicate that commercial and industrial discharges to the stormwater system are current major contributors to overall metal discharged to the river and that significant improvements could be achieved by targeting these sources (Beck & Birch, 2014). A further minor source of metals is from surface runoff from previously contaminated sites on the river foreshore (Birch *et al.*, 2013). In particular, soil concentrations of copper, lead and zinc are known to be elevated throughout large areas of the previously industrialised catchment (Snowdon & Birch, 2004; Birch *et al.*, 2010b). As such, managing catchment condition to prevent particulate transport from sources such as soils, road dust and drainage canals may provide a further effective control on the quality of riverine sediment (Birch & McCready, 2009).

## 2.2 Halogenated organic compounds and polycyclic aromatic hydrocarbons

Parramatta River sediments are contaminated in many areas with organochlorine compounds (Birch & Taylor, 2000). Some of the most prominent organochlorine contaminants include pesticides (chlordane, DDT/DDD/DDE, Aldrin, dieldrin, endrin, heptachlor, heptachlor epoxide and hexachlorbenzene) and polychlorinated biphenyls (PCBs) (Birch & Taylor, 2000; McCready *et al.*, 2006a; Ying *et al.*, 2009).

Analytical assessment of the onset of organochlorine compound contamination of estuarine sediment closely agrees with the record of industrialisation in the catchment of each embayment (Taylor *et al.*, 2004). PCBs, chlordane, and to a lesser extent dieldrin, are most elevated in sediment in creeks on the southern shores of the estuary, suggesting sources within older, highly urbanised/industrialised catchments of western-central Sydney (Birch & Taylor, 2000). There are high concentrations of total DDT and hexachlorbenzene in sediments of the upper harbour and Homebush Bay suggesting that (previous) chemical industries on the shores of the estuary in this area are sources of these contaminants (Birch & Taylor, 2000).

Most notoriously, a range of dioxin compounds are known to contaminate sediment throughout the Parramatta River, with the most intense contamination in and around Homebush Bay (Mueller *et al.*, 2004; Birch *et al.*, 2007; Ying *et al.*, 2009). The term 'dioxins' is used to refer to two main groups of polychlorinated hydrocarbons. These are polychlorinated dibenzo para dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs). Certain dioxin-like PCBs with similar toxic properties are also commonly included under the term 'dioxins'.

Between 1928 and 1985, Timbrol (later known as Union Carbide) manufactured a variety of chemicals on the Rhodes Peninsula. Dioxins were released in industrial effluent disposed of in part in Homebush Bay (Montoya, 2015). An Environmental Impact Statement prepared prior to remediation of the Timbrol site and parts of Homebush Bay reported the detection of some of the highest surface and subsurface sediment dioxin concentrations in the world, as well as significant aqueous concentrations (Parsons Brinckerhoff Australia & Thiess Serivces, 2002). A distinct congener profile corresponded to the chemicals known to have been produced at the Timbrol site (Birch *et al.*, 2007). The Timbrol site and adjacent Homebush Bay sediments were partially remediated between 2005 and 2011, but as of 2014, the effectiveness of the remediation program was unknown (Montoya, 2015).

In addition to the high sediment loads of dioxins, passive samplers have been used to assess dioxin concentrations in the pelagic zone of the river (Roach *et al.*, 2009). Highest concentrations were measured in Homebush Bay and concentrations generally declined with distance from Homebush Bay. Higher daily concentrations were detected in summer compared to winter, which may reflect higher rates of solubilisation in warmer water.

Polybrominated diphenyl ethers (PBDEs) and hexabromocyclododecane (HBCDs) have been used extensively as brominated flame retardants worldwide. Stormwater is a recognised potential source of brominated flame retardants to the aquatic environment (Richman *et al.*, 2013). These hydrophobic compounds are resistant to many common biodegradation processes, rendering them likely to accumulate in estuarine sediment (Richman *et al.*, 2013).

A range of PBDEs and HBCDs have been reported in sediment cores from the Sydney estuary, including sites on the Parramatta River, taken from locations close to stormwater drains (Drage *et al.*, 2015). Large increases in concentrations were observed for all compounds between 1980 and 2014 (Drage *et al.*, 2015). PBDE concentrations in surficial sediments were relatively high when compared with those presented in the available international literature, suggesting that their input into the estuary has not decreased since their bans almost a decade earlier. HBCD concentrations exhibited a sharp increase during the 1990s and with global legislation allowing its usage for the next 10 years, it is expected that its input into the estuary is likely to continue.

Perfluorinated compounds including perfluorooctane sulphonate (PFOS) and perfluorooctanoate (PFOA) are persistent environmental pollutants which have become of concern worldwide in recent years following their detection in the general population of several countries, and in the global environment (Chang *et al.*, 2014;

MiraIles-Marco & Harrad, 2015; Wang *et al.*, 2015). PFOS and PFOA have been reported in water and surface sediment samples collected from around Homebush Bay, in the upper reaches of the Parramatta River estuary (Thompson *et al.*, 2011; Kaserzon *et al.*, 2012).

The river sediments also contain a range of polycyclic aromatic hydrocarbons (PAHs) including acenaphthene, acenaphthylene, anthracene, benz(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(ghi)perylene, benzo(a)pyrene, benzo(e)pyrene, coronene, chrysene, dibenz(ah)anthracene, fluoranthene, fluorene, indeno(1,2,3-cd)pyrene, 2-methylnaphthalene, naphthalene, perylene, phenanthrene, and pyrene (McCready *et al.*, 2000; McCready *et al.*, 2006a). The spatial distribution of PAHs indicates that they derive predominantly from urban run-off (McCready *et al.*, 2000). The relative abundance of individual PAH compounds indicates that high temperature combustion processes are the predominant source of PAH contamination (McCready *et al.*, 2000; Ying *et al.*, 2009).

## 2.3 Nutrients

Nutrients, including nitrogen and phosphorus are transported to the river by urban stormwater (Beck & Birch, 2012). Modelling nutrient loads from stormwater to the Parramatta River (using MUSIC) has indicated that the majority is delivered during moderate rainfall (5–50 mm $day^{-1}$) conditions and accumulates close to discharge points and remains in the estuary (Birch *et al.*, 2010a). In contrast to metals, considerable loads of nitrogen (up to 55%) and phosphorus (up to 21%) appear to be transported to the River during dry weather base-flow conditions (Beck & Birch, 2012).

Under high-rainfall conditions (>50 mm $day^{-1}$), the estuary becomes stratified and nutrients are either removed directly in a plume or indirectly by advective/dispersive remobilisation (Birch *et al.*, 2010a).

Nutrients have accumulated in bottom sediments in concentrations up to 50 times greater than pre-anthropogenic levels (Birch *et al.*, 1999).

## 2.4 Water soluble trace organic contaminants

A survey of trace organic contaminants in various locations of the Parramatta River was recently reported (Birch *et al.*, 2015a). The contaminants detected included pharmaceuticals, personal care products, a food additive (acesulfame) and pesticides. Anthropogenic organic chemicals such the pharmaceuticals and acesulfame are increasingly used as indicators of domestic sewage since there are usually no other significant sources to the environment (Gasser *et al.*, 2014; Tran *et al.*, 2014; Jekel *et al.*, 2015; Lee *et al.*, 2015a). Since there are no sewage treatment plants discharging to the Parramatta River, the most viable sources for these chemicals are leakage from sewerage systems and occasional sewage overflows to the stormwater system during intense wet weather events.

This survey reported that acesulfame and a number of the pharmaceuticals were widely detected, even in the absence of significant recent rainfall (Birch *et al.*, 2015a). This is suggestive of a continuous source from leaking sewers. The major source for a number of pesticides detected was proposed to be after environmental application and wash-off to stormwater (Birch *et al.*, 2015a). However, it should be noted that most of the reported pesticides are also known to occur in municipal sewage (Ratola *et al.*, 2012; Pal *et al.*, 2014; Margot *et al.*, 2015).

## 2.5 Surfactants

Municipal sewage typically contains high concentrations of a range of surfactants including linear alkylbenzene sulfonate, quaternary ammonium compounds, alkylphenol ethoxylates, and alcohol ethoxylates (Jardak *et al,* 2016). Although many of these surfactants are relatively biodegradable, high concentrations in sewage can lead to relatively high concentrations in surface waters (Jardak *et al,* 2016). At sufficiently high concentrations, this may present environmental risks including aquatic toxicity and foaming, which may lead to reduced oxygen concentrations (Jardak *et al,* 2016).

# 3. Microbial Contaminants and Indicators

In contrast to chemical contaminants, microbial water quality contaminants are generally regarded as posing greater risks to human health than to aquatic ecosystems. Important microbial contaminants which may present health risks to recreational water users include bacteria, viruses, protozoa and cyanobacteria.

Throughout the last century, the Parramatta River has generally been regarded as a contaminated waterway and this has resulted in minimal use involving primary recreational contact (eg, swimming). As a consequence, microbial monitoring has been minimal, other than that undertaken by the NSW Office of Environment and Heritage (OEH) under the Beachwatch program (Hose *et al.*, 2005).

## 3.1 Bacteria

The NSW OEH has routinely monitored faecal contamination at a number of Sydney Harbour sites as part of the Beachwatch program since 1994 (Hose *et al.*, 2005). This monitoring is based on a single water sample collected from each site by boat every six days during summer season (October to April) and monthly surveillance sampling undertaken during the winter period (May to September). Samples are analysed for enterococci using culture-based methods following the Australian standard method (Standards Australia & Standards New Zealand, 2007). Three of the monitored sites are on the Parramatta River at Cabarita Beach (Cabarita), Chiswick Baths (Five Dock Bay) and the Dawn Fraser Pool (Balmain).

Spatial and rainfall related patterns of faecal coliform and enterococci densities in Sydney Harbour estuary have been reported (Hose *et al.*, 2005). Unsurprisingly, sites to the west and along the Parramatta River exhibited much greater bacterial densities than eastern sites, closer to the mouth of the Harbour. This was attributed to greater tidal flushing at sites closer to the harbour mouth. At particular locations, it was determined that rainfall accounted for between 15-66% of the observed temporal variability in bacterial densities, with the strongest relationships for the Parramatta River sites. The findings of this research indicate that simple rainfall-based regression models are appropriate for predicting bacterial indicator concentrations when flushing at a site is limited.

*Vibrio* are a genus of naturally occurring marine bacteria that have substantial environmental and human health importance. A number of sites within the Parramatta River were recently investigated for the presence of *Vibrio Spp*. (Siboni *et al.*, 2016). Significant spatial and seasonal variation were observed with abundance higher during late summer than winter and within locations with mid-range salinity (5–26 ppt). While toxigenic strains of *V. cholerae* were not detected in any samples, non-toxigenic strains were detected in 71% of samples. In contrast, pathogenic *V. vulnificus* was only detected in 14% of samples, with its occurrence restricted to the late summer.

High water temperature is a strong predictor for the presence of *Vibrio spp.* and they are mainly detected in warmer waters (above 15°C) (Lutz *et al.*, 2013; Vezzulli *et al.*, 2013). Many studies have demonstrated that the abundance of *Vibrio spp.* follows a seasonal pattern, largely dictated by temperature (Lutz *et al.*, 2013; Rashid *et al.*, 2013). It is believed that warmer temperatures enhance the persistence of *Vibrio spp.* by promoting biofilm formation and colonisation of environmental surfaces such as chitin (Stauder *et al.*, 2010). The effect of increased ocean surface temperatures in promoting spread of *Vibrio spp.* in coastal and brackish waters has been considered as a possible causal factor explaining observed increases in *Vibrio* illnesses in many parts of the world (Vezzulli *et al.*, 2013).

Several QMRAs have suggested that bacteria, -most notably Campylobacter - are significant sources of health risk from some urban rivers and freshwater lakes (Oster *et al.*, 2014; Corsi *et al.*, 2016).

## 3.2 Viruses

No published reports of virus densities in the Parramatta River have been identified. However, pathogenic human viruses are believed to cause over half of gastroenteritis cases associated with recreational water use worldwide (Ahmed *et al.*, 2015a).

## 3.3 Protozoa

Cryptosporidium and Giardia are intestinal protozoan parasites, which are excreted by infected hosts in large numbers, hence are commonly present in untreated sewage (Li *et al.*, 2012; Tonani *et al.*, 2013; Taran-Benshoshan *et al.*, 2015). Furthermore, these parasites are environmentally robust, which facilitates transmission (Cacciò *et al.*, 2005). In circumstances where recreational marine waters are contaminated with domestic sewage, there may be considerable risk of infection and disease caused by these organisms (Betancourt *et al.*, 2014).

No published reports of protozoan densities in the Parramatta River have been identified.

## 3.4 Cyanobacteria

No published reports of cyanobacterial populations in the Parramatta River have been identified. Nonetheless, it is known that cyanobacteria blooms do occur in the upper reaches of the river from time-to-time and this should be considered for primary recreational contact.

# 4. Recreational Water Quality Risks

Australian guidelines for managing risks in recreational water identify a diverse range of physical, chemical and biological hazards to which swimmers may be exposed (NHMRC 2008). These include water depth, currents, UV radiation, water temperature, snags, venomous species and other dangerous animals. Each of these would need to be considered for a comprehensive risk assessment of future potential recreational water use. However, in the current circumstance, only chemical and microbial water quality contaminants are discussed.

## 4.1 Risks from recreational exposure to chemical contaminants

Many of the contaminants reported in sediments and the water column of the Parramatta River may pose toxicity risks to the aquatic system and biota (Birch & Taylor, 2002a; Birch & Taylor, 2002b; McCready *et al.*, 2004; Birch *et al.*, 2008). Indeed, correlations between measures of ecological toxicity and concentrations of some chemical contaminants in surficial sediments have been observed (McCready *et al.*, 2005; McCready *et al.*, 2006b).

Furthermore, many heavy metals and lipophilic organic chemicals (such as dioxins and many pesticides) are known to accumulate in fish and other aquatic organisms (Hellou *et al.*, 2013; Lehnherr, 2014; Cruz *et al.*, 2015). Examples of this accumulation or 'biomagnification' have been reported for various chemicals in the Parramatta River. These include metals (Birch *et al.*, 2014; Lee *et al.*, 2015b), chlorinated hydrocarbons (Roach & Runcie, 1998), brominated hydrocarbons (Losada *et al.*, 2009), and perfluorinated hydrocarbons (Thompson *et al.*, 2011). As a consequence of biomagnification of dioxins in various fish species, the NSW Government have imposed a ban commercial fishing in Sydney Harbour and advise against the consumption of fish caught by recreational fishing west of the Sydney Harbour Bridge (NSW DPI 2016).

In addition to the movement of industry from the upper-catchment, metal concentration declines have been partially attributed to the introduction of regulation, which prevents pollutants being discharged directly to the river (Birch *et al.*, 2013). Relevant legislation have included the State Pollution Control Commission Act 1970, the CleanWaters Act 1978, the Coastal Protection Act 1979 and the Catchment Management Act 1989, which have prohibited the dumping of waste, reformed pollution licensing and enforced control procedures (Smith, 1997). Nonetheless, since high stormwater metal concentrations persist, it is proposed that stormwater remediation will be required for further rapid improvement (Birch *et al.*, 2013).

Cyanobacterial-derived water quality impairment issues are a growing concern worldwide, including health risks from recreational water exposure (Otten & Paerl, 2015). These organisms can produce a range of bioactive metabolites, many of which are known human toxins. The occurrence and characterisation of cyanobacterial organisms –and the metabolites that they may exude- appears to be a current knowledge gap for the Parramatta River.

In the late 1990s, Sydney Water undertook a risk assessment to assess the risks of chemical contaminants to human health (and aquatic organisms) in creeks, rivers, estuaries and ocean waters affected by wet weather discharges (Bickford *et al.*, 1999). This work included assessment of chemicals in stormwater and sewage overflows (as well as sewage treatment plant discharges). The risk assessment methodology was based on comparison of measured and predicted concentrations of chemicals with toxicity reference values. While various risks to human health were identified (primarily from the consumption of contaminated fish), no significant risks from chemicals to people engaged in recreational water use were identified.

## 4.2 Risks from recreational exposure to microbial contaminants

Recreational water use commonly involves exposure to pathogenic organisms and is associated with increased levels of illnesses including gastrointestinal illness respiratory illness, as well as ear, eye and skin infections (Collier *et al.*, 2015). Epidemiological studies have shown that risks of these infections in swimmers increases with either exposure to urban runoff or declining water quality due to pollution or sewage (Stewart *et al.*, 2008). Based on risk assessments, it has been estimated that globally, each year, there are in excess of 120 million cases of gastrointestinal disease and in excess of 50 million cases of more severe respiratory diseases caused by swimming and bathing in wastewater-polluted coastal waters (Shuval, 2003).

Despite the apparent lack of historic monitoring data, there is compelling evidence that a variety of pathogenic microorganisms may present some risks to people engaging in primary recreational contact with Parramatta River water. This is because the chemical monitoring data (see previous section), undertaken over decades, has confirmed that stormwater is a major source of pollution to the river. Stormwater is a well-established source of pathogen risk to recreational water environments (Stewart *et al.*, 2008).

Following a large storm, large volumes of stormwater flow into the upper Parramatta River and cause significant stratification (Wolanski, 1977). Such circumstances could lead to significant exposure to pathogens by swimmers. Recent investigations have revealed that these stratified stormwater plumes are relatively short-lived and generally not effective for rapidly transporting contaminants outside the Sydney estuary (Lee *et al.*, 2011). Thus the major mechanisms for recovery of microbial water quality will be dilution and gradual environmental inactivation of pathogens. The frequent stratification of the river greatly affects the fate and transport of contaminants and pathogens in the water column as well as the ability to assess the associated risks.

Numerical modelling has been employed to determine stormwater runoff volumes and establish an appropriate rainfall/runoff relationship capable of replicating fresh-water discharge due to the full range of precipitation conditions in the Parramatta River (Lee & Birch, 2012). International research has demonstrated that even relatively small drains can lead to localised high levels of faecal indicator bacteria at enclosed beaches (Rippy *et al.*, 2014).

In addition to fresh inputs of contaminants to the river, recreational users may be exposed to contaminants that are resuspended from the bottom sediment to the water column by a variety of processes. These include natural processes such as wind, waves or tidal movements, or anthropogenic processes including the effect of watercraft (Bishop, 2007).

Recreational activity itself can lead to increased concentrations of some contaminants including human waterborne pathogens, and faecal indicator bacteria in marine recreational beach water. For example, it is believed that re-suspension of bottom sediments by bathers may cause elevated levels of enterococci and waterborne parasites (Graczyk *et al.*, 2010). Swimmers may themselves be sources of microorganisms in water including enterococci and *Staphylococcus aureus* (Elmir *et al.*, 2007; Stewart *et al.*, 2008). Consequently, human pathogens can be present in beach water on days deemed acceptable for bathing according to faecal bacterial standards (Graczyk *et al.*, 2010).

A number of naturally occurring Vibrio spp. are pathogenic to humans (Baker-Austin *et al.*, 2013; Matteucci *et al.*, 2015). Consequently, an understanding of the spatiotemporal dynamics of *Vibrios* and their potential to bloom and cause disease outbreaks has become increasingly important (Oberbeckmann *et al.*, 2011; Takemura *et al.*, 2014). The spatiotemporal dynamics of *Vibrio Spp.* and the occurrence of bloom events have been linked to several environmental drivers, including temperature, salinity, turbidity, dissolved oxygen, pH, chlorophyll, and nutrients, as well as associations with potential host organisms (Takemura *et al.*, 2014).

# 5. Future Water Quality Risks and Management

Prior to declaring new sites on the Parramatta River as being safe for swimming (including under any specific limited circumstances), a number of risk assessment and ongoing monitoring activities should be undertaken. Principal guidance for this risk assessment should come from the Australian guidelines for managing risks in recreational water (NHMRC 2008). However, due to the historically degraded water quality of the river, and its vulnerability to a wide range of contaminant sources, a number of additional factors should be considered.

Many chemical contaminants pose predominantly chronic risks, as opposed to acute risks, to the health of recreational water users. Examples include heavy metals and halogenated organic chemicals such as dioxins (Nau, 2006; Bensefa-Colas *et al.*, 2011). An advantage for the assessment of these types of risks is that short-term exposure variations are much less significant than long-term exposure trends (enHealth Council, 2012). This means that effective risk assessment could be undertaken well in advance of potential recreational contact and need only be updated periodically (eg, annually).

Based on the information collected in this review, site-specific risk assessment should be undertaken for exposure to a range of chronic risk chemicals including heavy metals, halogenated organic compounds and polycyclic aromatic hydrocarbons.

In 1983, the US National Research Council published what became known as the 'red book' (NRC 1983), which provided a formalised set of steps to be taken for assessing risks to human health by chemicals from environmental and other sources. These were:

1. Problem Formulation and Hazard Identification—to describe the human health effects derived from any particular hazard (for example, acute toxicity, carcinogenicity)
2. Exposure Assessment—to determine the size and characteristics of the population exposed and the route, amount, and duration of exposure
3. Dose-Response Assessment—to characterise the relationship between the dose exposure and the incidence of identified health impacts
4. Risk Characterisation—to integrate the information from exposure, dose response, and health interventions in order to estimate the magnitude of the public health impact and to evaluate variability and uncertainty.

These steps have evolved into a general framework now used by environmental health agencies throughout the world to assess risks posed by environmental human health hazards. An Australian version is described in detail in the important document *Environmental Health Risk Assessment: Guidelines for Assessing Human Health Risks from Environmental Hazards* (enHealth Council, 2012). The systematic approach described in this document is appropriate for the assessment of chronic exposure risks to chemical contaminants in the Parramatta River.

Some potential chemical contaminants to the Parramatta River may be associated with possible short-term extreme exposure. Examples include those resulting from large chemical spills (from within the catchment, direct industrial releases, or from ships). Such circumstances could lead to acute health risks to recreational water users. Similarly, cyanobacterial growth could lead to rapid production and release of chemicals posing health risks to swimmers. These types of acute health risks, resulting from short-term exposure may be overlooked when focussing risk assessment on the enHealth Council (2012) framework. This is because that document does not explicitly emphasise the need to consider potential 'hazardous events' which may drastically alter short-term exposure conditions. For a more systematic consideration of the role of hazardous events in risk assessment, Australian guidelines for managing risks in recreational water (NHMRC 2008), or even the Australian Drinking Water Guidelines (NHMRC & NRMMC 2011) should be referred to.

Pathogenic microbial organisms (including viruses, bacteria and protozoa) present predominantly acute risks to public health. Consequently, short-term fluctuations in pathogen densities can be highly significant in terms of changing health risks to recreational water users.

Management approaches for recreational water quality currently focus on sampling recreational waters and returning a water quality statistic possessing many uncertainties, days after swimmer exposure has occurred or averaging samples collected over multiple dates to generally characterise a bathing site (Ashbolt *et al.*, 2010).

The NSW Government Beachwatch program (OEH NSW 2015) grades swimming sites as Very Good, Good, Fair, Poor or Very Poor in accordance with the Australian Guidelines for Managing Risks in Recreational Water (NHMRC 2008). These grades provide a long-term assessment of how suitable a beach is for swimming. The grades are determined from the most recent 100 water quality results (two to four years' worth of data depending on the sampling frequency) and a risk assessment of potential pollution sources. Water quality results are based primarily on enterococci monitoring. The risk assessment is based on sanitary surveys considering potential pathogen sources including bathers, animals, toilet facilities, sewage overflows, sewer chokes, stormwater discharges and other local features (OEH NSW 2015). Beachwatch also issues daily beach pollution forecasts for swimming sites in Sydney, Central Coast, Hunter and Illawarra regions. The likelihood of pollution is predicted using rainfall data. Rainfall thresholds have been determined for each swimming location by analysing rainfall and bacterial data collected over the last five years. Managers at some swimming sites, including Dawn Fraser Pool, use this information to close the baths when pollution is likely.

Scientific evidence supporting recreational water quality benchmarks primarily stems from epidemiological studies conducted at beaches impacted by human faecal sources. The human illness potential from a recreational exposure to freshwater impacted by rainfall-induced runoff containing non-human animal faecal material may be at least an order of magnitude lower than the benchmark level of public health protection associated with current US recreational water quality criteria, which are based on contamination from human sewage sources (Soller *et al.*, 2014; Soller *et al.*, 2015).

Nonetheless, a range of human pathogenic (and indicator) microorganisms have been detected in the faeces of domestic animals and wildlife in the Sydney region (Cox *et al.*, 2005). Of particular relevance to the Parramatta River may be birds, some species of which are known to be sources of pathogenic bacteria including Salmonella and Campylobacter (Antilles *et al.*, 2015; Cody *et al.*, 2015; Ramonaite *et al.*, 2015).

Current technology for water-quality monitoring is based on frequent sampling and culturing methods which are time-consuming and do not allow a rapid decision making process (Amini & Kraatz, 2015). However, during the last few decades, a range of 'molecular methods' such as polymerase chain reaction (PCR)-based methods, DNA sequencing and immuno-fluorescence methods have been developed, and offer promising strategies for more rapid and cost-effective pathogen detection (Amini & Kraatz, 2015).

Compared to culture-based methods, which can take between 18 and 96 hours for sample processing, molecular methods can be applied in just a couple of hours (Raith *et al.*, 2014). Thus, molecular methods offer an opportunity to provide a more meaningful statement of microbial risk to water-users by providing near-real-time information enabling potentially more informed decision-making with regard to recreational water use (Mendes Silva & Domingues, 2015; Oliver *et al.*, 2016).

Furthermore, the potential use of a suite of molecular methods would facilitate monitoring of some indigenous organisms, which are not directly associated with faecal indicators, such as pathogenic *Vibrio Spp.* (Siboni *et al.*, 2016).

However, the use of molecular methods, compared with traditional culture-based methods for quantifying microbial parameters in recreational waters generates considerable ongoing debate at the science-policy interface (Oliver *et al.*, 2016). Regulators and researchers have highlighted a number of technical and logistical issues associated with the emerging use of molecular methods for recreational water quality assessment (Oliver *et al.*, 2014). For example, the practical benefit of rapid analysis can be limited by centralised laboratory infrastructure, implying long transit times for some locations. There also remain uncertainties regarding the robustness of the epidemiological evidence-base for results obtained from molecular method quantitation (Oliver *et al.*, 2014).

For comparing faecal indicator monitoring data with acceptable guideline levels, some agencies have chosen the 95th percentile (WHO 2003; NHMRC 2008). However, it is well known that these kinds of data do not display a normal distribution and several alternative distributional forms have been proposed and are in use for estimating the percentile (Laura Patat *et al.*, 2015).

To facilitate and standardise the process, a Microsoft Excel template (the EnteroTester) has been developed for generating workbooks that estimate the infection risk (according to formula used in the above guidelines) for any given enterococcal distribution, and calculate a 95th percentile standardised to that of the reference distribution with the same risk (Lugg *et al.*, 2012). A similar statistical decision support tool 'EnterosisA' was recently developed to facilitate the analysis of microbial water quality data for the purposes of classifying recreational waterways in south-east Queensland (Xie *et al.*, 2015). Other approaches, such as the use of a Tweedie distribution have also been proposed (Laura Patat *et al.*, 2015).

An alternative (or complimentary) approach for the rapid assessment of water quality may be achieved by the development of an understanding of the relationships between pathogen (or indicator) organism densities and rapidly observable factors that influence their occurrence. It is this type of observation that has led to recommendations to avoid swimming at Sydney beaches for one to three days following rainfall events (OEH NSW 2015).

In a recent study from Germany, multiple linear regression models were developed in order to predict the abundance of the faecal indicator organisms *E. coli*, intestinal enterococci and somatic coliphages in a freshwater river (Herrig *et al.*, 2015). Useful predictive variables were found to include ammonia concentration, turbidity, global solar irradiance, chlorophyll a content, rainfall, oxygen concentration and pH. It was reported that these models could explain around 70% of the observed variance in faecal indicator concentrations. Site-specific efficiencies were around 80%.

Predictive empirical modelling has been used at a number of Great Lakes beaches in Chicago to develop a fully automated water quality management system (Shively *et al.*, 2016). In that study, data from water quality buoys and weather stations were transmitted to a web hosting service. An executable program simultaneously retrieved and aggregated data for regression equations and calculated empirical modelling results each morning. In that case, solar radiation, rainfall, and wind direction were common model regressors. A decision-making tool for beach management has also been described, based on (up to 5-day) advance predictions of bathing water quality, which is in-turn derived from weather forecasts (Bedri *et al.*, 2016).

A range of calculation and modelling techniques are available for estimating annual stormwater contaminant loadings to the Parramatta River. These include calculations based on measured event mean concentrations (EMCs), pollutant load/runoff relationship calculations and the use of the computer modelling application ‘Model of Urban Stormwater Infrastructure Conceptualisation’ (MUSIC). However, a recent assessment of the use of these techniques to estimate annual TSS, TN, TP and metals loadings to the Parramatta River revealed high degrees of inconsistencies among predictions (Beck & Birch, 2013). Consequently, it was concluded that some or all of the methods used were likely to be inaccurate and unreliable for this application.

Quantitative Microbial Risk Assessment (QMRA) has been an increasingly important tool for assessing risks from recreational water exposure to pathogenic microbial organisms (Oster *et al.*, 2014; Fewtrell & Kay, 2015; Soller *et al.*, 2015; Sunger & Haas, 2015). The use of QMRA for modelling (and thus predicting) pathogens and indicators has numerous potential advantages (Ashbolt *et al.*, 2010). For example, it can facilitate the exploration of a large diversity of scenarios for faecal contamination and hydrologic events, such as from waterfowl, agricultural animals, resuspended sediments and from the bathers themselves (Ashbolt *et al.*, 2010).

Epidemiological studies show a generally elevated risk of gastrointestinal illness in bathers compared to non-bathers but often no clear association with water quality as measured by faecal indicator bacteria; this is especially true where study sites are impacted by non-point source pollution (Fewtrell & Kay, 2015). Evidence from QMRAs support the lack of a consistent water quality association for non-point source-impacted beaches. It has been suggested that source attribution, through quantified microbial source apportionment, linked with appropriate use of microbial source tracking methods should be employed as an integral part of future epidemiological surveys (Fewtrell & Kay, 2015).

## 5.1 Indications of faecal contamination and associated pathogens

Most contemporary recreational water quality monitoring practices are focused on concentrations of faecal indicator bacteria such as *total and faecal coliforms, Clostridium perfringens, Escherichia coli, and faecal enterococci* (Field & Samadpour, 2007; Bennell *et al.*, 2015; Cheung *et al.*, 2015; Fan *et al.*, 2015).

However, monitoring for these indicators is not always effective for determining when streams and coastal waters are contaminated with sewage because faecal indicator bacteria can reside in the environment and may even multiply under certain conditions (Field & Samadpour, 2007; Stewart *et al.*, 2008; Boehm *et al.*, 2009a). For example, these indicators have been consistently reported from beach sands and sediments from freshwater and marine beaches, even in the absence of any known sources of human/animal waste (Stewart *et al.*, 2008; Cloutier *et al.*, 2015; Halliday *et al.*, 2015). Since these "extra-enteric" bacteria multiplied in environmental habitats, such as soil rather than intestinal habitats of humans or animals, these bacteria are not indicators of faecal contamination (Fujioka *et al.*, 2015).

In some cases, constant background levels of faecal indicator bacteria are present due to the presence of birds and wildlife. This was the case for Lake Parramatta, for which background *E. coli* and enterococci contamination were detected due to waterfowl (Roser *et al.*, 2006).

Furthermore, faecal indicator bacteria are known to differ in their environmental fate and transport characteristics compared to some important pathogens. For example, indicator bacteria have been shown to be more sensitive to inactivation by sunlight than some important waterborne human viruses (Fujioka & Yoneyama, 2002; Boehm *et al.*, 2009b; Carratala *et al.*, 2013). Consequently, the concentrations of faecal indicator bacteria measured in environmental waters are not always reliable –or even conservative- assurances that human pathogens are below levels that may cause infections in swimmers (Field & Samadpour, 2007; Fujioka *et al.*, 2015).

Consequently, there are limitations to determining risks to recreational water users based only on monitoring data for established faecal indicator bacteria. Promising more sewage-specific markers have been identified including *C. perfringens*, various bacteriophages, *Bacteroides*, as well as human enteric viruses (Boehm *et al.*, 2009a; Fujioka *et al.*, 2015). Ecology and physiology of indicator bacteria varies vastly from those of many pathogens, such as viruses and protozoa. Therefore, there is a need for supplemental indicator organisms that would be indicative of risk for a wide array of human pathogens and to provide better protection of public health (Fujioka *et al.*, 2015).

### 5.1.1 E. Coli

*Escherichia coli* (*E. coli*), is a member of the coliform group of bacteria, but unlike the general coliform group, *E. coli* are almost exclusively of faecal origin and their presence is thus an effective confirmation of faecal contamination. However, *E. coli* are not specific to humans and are excreted by many species including birds. Most strains of *E. coli* are harmless, but some can cause serious illness in humans.

*E. coli* is used as a faecal indicator for fresh water (but not marine) systems in the USA as described by the US EPA Recreational Water Quality Criteria (US EPA 2012). In that document, local authorities are provided two alternative recommended levels of health protection that they may work to. Recommendation 1 is applied at an estimated illness rate of 36/1000 and is based on exceeding *E. coli* densities with a geometric mean of 126 cfu/100 mL or statistical threshold value of 410 cfu/100 mL. Recommendation 2 is applied at an estimated illness rate of 32/1000 and is based on exceeding *E. coli* densities with a geometric mean of 100 cfu/100 mL or statistical threshold value of 320 cfu/100 mL. The statistical threshold value approximates the 90th percentile of the water quality distribution and is intended to be a value that should not be exceeded by more than 10 percent of the samples taken.

### 5.1.2 Enterococci

Enterococci are facultative anaerobic organisms (that is, they are capable of cellular respiration in both oxic and anoxic environments). Though they are not capable of forming spores, enterococci are tolerant of a wide range of environmental conditions including temperature (10-45°C), pH (4.5-10.0) and high sodium chloride concentrations (Fisher & Phillips, 2009).

Enterococci are excreted in faeces and are rarely present in unpolluted waters. International agencies including the US EPA (US EPA 2012) and the World Health Organization (WHO 2003) now generally use enterococci as the single preferred faecal indicator in marine waters.

Australian guidelines for recreational water quality monitoring do not dictate the use of enterococci monitoring (NHMRC 2008). However, they do refer explicitly to WHO recommendations for the use of enterococci as a faecal indicator in marine waters (WHO 2003).

The WHO Guidelines describe an assessment approach based on a combination of a sanitary inspection (to identify susceptibility to faecal influence) and microbial water quality assessment (WHO 2003). The microbial water quality assessment is used to categorise recreational water quality based on measurements of the 95$^{th}$ percentile intestinal enterococci densities. The applied microbial water quality assessment categories are “A” (≤40 cfu/100mL), “B” (41-200 cfu/100mL), “C” (201-500 cfu/100 mL) and “D” (>500 cfu/100 mL).

The WHO Guidelines also refer to 95th percentile value of intestinal enterococci/100ml greater than 500 (or greater than 200 if source mainly human faecal pollution) in consecutive samples as one of a number of conditions that may merit intervention by public health authorities (WHO 2003).

Analogous to the use of *E. coli* for fresh water quality criteria, the US EPA provides two recommendations for enterococci limits in marine and fresh waters, relating to estimated illness rates of 36/1000 (Recommendation 1) and 32/1000 (Recommendation 2) (US EPA 2012). Recommendation 1 is based on exceeding enterococci densities with a geometric mean of 35 cfu/100 mL or statistical threshold value of 130 cfu/100 mL. Recommendation 2 is based on exceeding enterococci densities with a geometric mean of 30 cfu/100 mL or statistical threshold value of 110 cfu/100 mL.

#### 5.1.3 Clostridium perfringens

*Clostridium perfringens* is an anaerobic, spore-forming pathogenic bacterium. *C. perfringens* is ever-present in nature and can be found as a normal component of decaying vegetation, soil, marine sediment, and in the intestinal tract of humans and other species.

In Hawaii, due to ambient growth and high elevated concentrations of faecal indicator bacteria in soil and streams, *C. perfringens* is used as a secondary water quality standard because it is a more reliable marker of sewage contamination than the conventional faecal indicator bacteria (Viau *et al.*, 2011b; Fujioka *et al.*, 2015). This practice was adopted because monitoring data had shown that the ambient and daily concentrations of conventional faecal indicator bacteria in the major streams of Oahu, Hawaii greatly exceeded the (now defunct) faecal coliform standard (Fujioka *et al.*, 1988) and the US EPA *E. coli* and enterococci standards (Luther & Fujioka, 2004). Widespread occurrence and growth of the conventional faecal indicator bacteria in the soil environment of Hawaii was determined to be the reason for high levels of these bacteria in freshwater streams and rivers (Fujioka *et al.*, 2015). Consequently, it was not possible to determine when streams and coastal waters were contaminated with sewage or other human faecal sources.

In contrast to conventional faecal indicator bacteria, concentrations of *C. perfringens* were consistently low in streams but increased during a sewage contamination event (Fujioka *et al.*, 2015). As a result, the state of Hawaii adopted *C. perfringens* as a state recreational water quality standard (HIDOH 2014). However, the US EPA questioned the use of *C. perfringens* for this purpose and recommended that Hawaii maintain enterococci as the primary faecal indicator and use *C. perfringens* as a secondary tracer (Fujioka *et al.*, 2015).

#### 5.1.4 Bacteroides

*Bacteroides* is a genus of obligate anaerobic bacteria, making up a substantial portion of the mammalian gastrointestinal flora. As many as $10^{10}$ cells per gram of human faeces (dry weight) have been reported (Franks *et al.*, 1998).

*Bacteroides* species have a high degree of host specificity that reflects differences in the digestive system of the host animal (Bernhard & Field, 2000). The use of molecular methods, instead of culture methods, to measure *Bacteroides* densities allows quantification of genetic markers that are specific to the host of the bacteria (Gómez-Doñate *et al.*, 2015). In this way, it is possible to distinguish between multiple bacterial sources, such as by human-*Bacteroides*, pig-*Bacteroides*, and bovine-*Bacteroides* (Viau *et al.*, 2011a). A number of specific *Bacteroides* assays are now available to identify faecal sources such as human, cattle, dogs and other animals (Fujioka *et al.*, 2015).

Since *Bacteroides* have a small potential to grow in the environment, they have been increasingly touted as an alternative or complimentary sewage-specific faecal indicator bacteria (Bell *et al.*, 2009; Ahmed *et al.*, 2015b; Byappanahalli *et al.*, 2015; Verhougstraete *et al.*, 2015). Epidemiological studies have demonstrated that human-specific *Bacetroides* densities correlate well with illness rates, supporting the use of these bacteria as reliable indicators of human health risks in recreational waters (Wade *et al.*, 2006).

### 5.1.5 Bacteriophages

A bacteriophage is a virus that infects and replicates within a bacterium. "Coliphage" is used to describe bacteriophage that infect coliform bacteria, such as *E. coli* (Eg., Bacteriophage lambda and Leviviridae). Another common term is faecal bacteriophage, to describe bacteriophage known to occur in faecal material (Ashbolt *et al.*, 2010).

Coliphages have been studied as pollution indicators since the early 1960s (Fujioka *et al.*, 2015). Municipal sewage contains high concentrations of bacteriophages and, since they multiply in specific bacterial strains found in sewage, monitoring recreational waters for coliphages is an alternative indicator for sewage pollution (Ashbolt *et al.*, 2010). More recently, other bacteriophages , such as those that infect enterococci (enterophages) and those that infect *Bacteroide*s bacteria, have been considered as alternative sewage-specific indicators (Fujioka *et al.*, 2015).

Since bacteriophages closely resemble human viruses (but are not infective to human cells), they are conceptually better models of human enteric virus behaviour in the environment than faecal indicator bacteria (Ashbolt *et al.*, 2010). This is significant since enteric viruses are commonly thought to be the major causative agents for observed recreator gastroenteritis in waters impacted by human sources (Sinclair *et al.*, 2009; Schoen & Ashbolt, 2010; Soller *et al.*, 2010).

### 5.1.6 Direct monitoring of pathogens

Given that presence and prevalence of indicators does not often correlate well with risk of infection from environmental pathogens, direct monitoring for pathogens is often suggested. Detection of pathogens from environmental samples is increasingly viable through the development of molecular methods such as PCR. While the detection of pathogen molecular material is not necessarily indicative of viability or even infectivity, it does represent a rapid and specific method. New molecular assays have been introduced for detection of bacterial, viral and protozoan pathogens (Stewart *et al.*, 2008). Furthermore, recent improvements in detection technologies are allowing simultaneous detection of multiple targets in a single assay from the same sample (Stewart *et al.*, 2008).

Quantitative assessment of bacterial pathogens was recently reported from Great Lakes beaches in North America (Oster *et al.*, 2014). Quantitative PCR was used to test for genes from E. coli O157:H7, shiga-toxin producing *E. coli*, *Campylobacter jejuni*, *Shigella spp*., and a *Salmonella enterica*-specific DNA sequence in algae, water, and sediment. Subsequent QMRA, based on the detected pathogen densities indicated a moderate probability of illness for *Campylobacter jejuni* at the sites investigated.

Methicillin-resistant Staphylococcus aureus (MRSA) have also been detected in fresh and marine recreational water bodies (Fogarty *et al.*, 2015). Since this and other non-faecal derived bacteria have been observed not to be related to faecal indicator presence, direct monitoring of recreational waters for non-faecal bacteria such as staphylococci and/or Staphylococcus aureus has been suggested (Stewart *et al.*, 2008; Fogarty *et al.*, 2015).

Following this logic, it has been proposed that a range of microbial measurements could also be applied as indicators of disease transmitted via other routes of infection, including respiratory routes (e.g. adenovirus, Legionella) and oral ingestion or wound infections from indigenous microbes such as *Vibrio Spp.* (Stewart *et al.*, 2008).

Direct monitoring of human pathogenic viruses in recreational waters has shown that the presence of these pathogens may be poorly represented by faecal indicator bacteria (Prez *et al.*, 2015; Updyke *et al.*, 2015). Consequently, enteric viruses have been widely recommended (but yet to be successfully implemented on a large scale) in routine monitoring of water quality (Prez *et al.*, 2015; Updyke *et al.*, 2015).

Despite the advances in detection technologies, a major limitation for direct pathogen monitoring has been the low concentrations in environmental waters (Ahmed *et al.*, 2015a). For appropriately sensitive analysis, it is necessary to effectively concentrate and recover pathogens such as viruses from large volumes of water (eg. >10L) (Ahmed *et al.*, 2015a). Many of the reported methods to concentrate pathogens are complex, costly and/or of low efficiency (Fujioka *et al.*, 2015).

# 6. Conclusions

The Parramatta River is an iconic waterway in Australia's largest city. An opportunity to improve water quality suitable for (primary contact) recreational usage appears to have growing community and other stakeholder support. However, there are a number of water quality issues that require improved understanding and risk management before widespread recreational use of some parts of the river can be advised.

A variety of chemical contaminants are known to be present in suspended and surface sediment, as well as in the pelagic zone. While previous assessments have not identified significant risks to recreational water users from chemical contaminants, such risks should be carefully re-examined on a site-by-site basis. Human health risk assessments from exposure to known contaminants such as heavy metals, halogenated organic compounds, polycyclic aromatic hydrocarbons and surfactants should be undertaken at specific sites proposed for recreational activities. Australian environmental health risk assessment guidelines (enHealth Council, 2012) provide an appropriate framework for this assessment.

Additional consideration should be given to the potential for hazardous events, such as spills, to lead to short-term elevated exposure of chemicals which may present acute health risks. Australian guidelines for managing risks in recreational water (NHMRC 2008) and the Australian Drinking Water Guidelines (NHMRC & NRMMC 2011) provide an appropriate framework for this type of risk assessment.

Pathogens, such as viruses, bacteria and protozoa have a number of potential sources in the river. The most significant of these is expected to be stormwater, which is commonly contaminated with raw (untreated) municipal sewage. Since these organisms present predominantly acute health risks, short-term water quality fluctuations can be highly significant in terms of the risks they present to human health. Indigenous pathogenic bacteria, including *Vibrio Spp*. may also present health risks to recreational water users, yet the spatial and temporal variability in their occurrence is currently only poorly understood.

Existing approaches in Australia for microbial monitoring in recreational water are based almost exclusively on monitoring the faecal indicator bacteria enterococci. However, there are a number of limitations with this approach. These include the occurrence of organisms from sources other human faeces or sewage. Indeed, constant background detections of *E. coli* and enterococci (believed to have originated from waterfowl) were reported from risk assessment work undertaken for Lake Parramatta (Roser *et al.*, 2006). A similar outcome might be expected for the Parramatta River. Pathogenic *Vibrio Spp.* have also been shown to be indigenous to the river (Siboni *et al.*, 2016). A further limitation of faecal indicator bacteria monitoring is that they are not believed to be conservative indicators for some of the most important sewage-derived pathogens including a number of enteric viruses (Field & Samadpour, 2007; Fujioka *et al.*, 2015).

Internationally, a tiered monitoring strategy has been proposed as potentially viable option for future recreational water quality (Boehm *et al.*, 2003; Stewart *et al.*, 2008). In a tiered approach, the first step could involve using the simplest and most practical tests for contamination, perhaps using a rapid molecular test for faecal indicators. Tier two may involve adding methods to differentiate human from animal sources of pollution, and the tier three test, if necessary, would measure for specific pathogens.

A similar approach proposed for future review of US Recreational Water Quality Criteria may be worth investigating (Fujioka *et al.*, 2015). This involves routine monitoring for culturable levels of *C. perfringens* (considered to be the most conservative assay for sewage-borne bacteria) and for human specific *Bacteroides* (highly sensitive and specific assay for human faecal contamination). A water sample with minimal *C. perfringens* density would be interpreted as having minimal sewage contamination. However, since *C. perfringens* is not specific to human sewage, elevated concentrations could indicate either human or animal faecal contamination. Therefore, by also assaying the water sample for human specific *Bacteroides*, it can be determined whether the source of *C. perfringens* was human. Additional *Bacteroides* assays can be used to determine the specific animal faecal sources.

Prior to the development of an on-going routine monitoring program for the Parramatta River, it will be necessary to characterise the observable relationships between potential indicators of faecal microbial contamination and the actual presence of pathogenic organisms. QMRA can be used to facilitate an understanding of risks associated with specific pathogenic substances and a wide range of circumstances including the occurrence of hazardous events which may lead to elevated level of exposure to pathogens.

Monitoring, especially for pathogens and organic contaminants, is expensive and interpreting results can be complex. While comprehensive monitoring is required in the short-term to understand spatial and temporal patterns of contamination, longer-term solutions may benefit from a greater focus on predictive modelling.

# 7. References

Ahmed, W., Harwood, V. J., Gyawali, P., Sidhu, J. P. S. and Toze, S. (2015a) Comparison of Concentration Methods for Quantitative Detection of Sewage-Associated Viral Markers in Environmental Waters. *Appl Environ Microbiol,* **81**(6)*,* 2042-2049.

Ahmed, W., Sidhu, J. P., Smith, K., Beale, D. J., Gyawali, P. and Toze, S. (2015b) Distributions of Fecal Markers in Wastewater from Different Climatic Zones for Human Fecal Pollution Tracking in Australian Surface Waters. *Appl Environ Microbiol,* **82**(4)*,* 1316-23.

Amini, K. and Kraatz, H.-B. (2015) Recent advances and developments in monitoring biological agents in water samples. *Reviews in Environmental Science and Bio-Technology,* **14**(1)*,* 23-48.

Antilles, N., Sanglas, A. and Cerda-Cuellar, M. (2015) Free-living Waterfowl as a Source of Zoonotic Bacteria in a Dense Wild Bird Population Area in Northeastern Spain. *Transboundary and Emerging Diseases,* **62**(5)*,* 516-521.

Ashbolt, N. J., Schoen, M. E., Soller, J. A. and Roser, D. J. (2010) Predicting pathogen risks to aid beach management: The real value of quantitative microbial risk assessment (QMRA). *Water Res.,* **44**(16)*,* 4692-4703.

Baker-Austin, C., Trinanes, J. A., Taylor, N. G. H., Hartnell, R., Siitonen, A. and Martinez-Urtaza, J. (2013) Emerging Vibrio risk at high latitudes in response to ocean warming. *Nature Clim. Change,* **3**(1)*,* 73-77.

Beck, H. J. and Birch, G. F. (2011) Spatial and temporal variance of metal and suspended solids relationships in urban stormwater—Implications for monitoring. *Water, Air, & Soil Pollution,* **223**(3)*,* 1005-1015.

Beck, H. J. and Birch, G. F. (2012) Metals, nutrients and total suspended solids discharged during different flow conditions in highly urbanised catchments. *Environmental Monitoring and Assessment,* **184**(2)*,* 637-653.

Beck, H. J. and Birch, G. F. (2013) The magnitude of variability produced by methods used to estimate annual stormwater contaminant loads for highly urbanised catchments. *Environ Monit Assess,* **185**(6)*,* 5209-20.

Beck, H. J. and Birch, G. F. (2014) The nature and source of irregular discharges to stormwater entering Sydney estuary, Australia. *Environmental pollution (Barking, Essex : 1987),* **188***,* 172-6.

Bedri, Z., Corkery, A., O'Sullivan, J. J., Deering, L. A., Demeter, K., Meijer, W. G., O'Hare, G. and Masterson, B. (2016) Evaluating a microbial water quality prediction model for beach management under the revised EU Bathing Water Directive. *Journal of environmental management,* **167***,* 49-58.

Bell, A., Layton, A. C., McKay, L., Williams, D., Gentry, R. and Sayler, G. S. (2009) Factors Influencing the Persistence of Fecal Bacteroides in Stream Water All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. *J. Environ. Qual.,* **38**(3).

Bennell, M. C., Joyce, A., Gardner, E. and Majury, A. (2015) An Evaluation of Southeastern Ontario Recreational Water Quality. *J. Environ. Health,* **77**(10)*,* 26-33.

Bensefa-Colas, L., Andujar, P. and Descatha, A. (2011) Mercury poisoning. *Revue De Medecine Interne,* **32**(7)*,* 416-424.

Bernhard, A. E. and Field, K. G. (2000) A PCR Assay To Discriminate Human and Ruminant Feces on the Basis of Host Differences in Bacteroides-Prevotella Genes Encoding 16S rRNA. *Appl Environ Microbiol,* **66**(10)*,* 4571-4574.

Betancourt, W. Q., Duarte, D. C., Vasquez, R. C. and Gurian, P. L. (2014) Cryptosporidium and Giardia in tropical recreational marine waters contaminated with domestic sewage: estimation of bathing-associated disease risks. *Mar Pollut Bull,* **85**(1)*,* 268-73.

Bickford, G., Toll, J., Hansen, J., Baker, E. and Keessen, R. (1999) Aquatic Ecological and Human Health Risk Assessment of Chemicals in Wet Weather Discharges in the Sydney Region, New South Wales, Australia. *Mar. Pollut. Bull.,* **39**(1–12)*,* 335-345.

Birch, G. and O'Hea, L. (2007) The chemistry of suspended particulate material in a highly contaminated embayment of Port Jackson (Australia) under quiescent, high-wind and heavy-rainfall conditions. *Environ. Geol.,* **53**(3)*,* 501-516.

Birch, G. and Taylor, S. (1999) Source of heavy metals in sediments of the Port Jackson estuary, Australia. *Sci. Total Environ.,* **227**(2-3)*,* 123-138.

Birch, G. and Taylor, S. (2002a) Possible biological significance of contaminated sediments in Port Jackson, Sydney, Australia. *Environmental Monitoring and Assessment,* **77**(2)*,* 179-190.

Birch, G. F. (2011) Contaminated soil and sediments in a highly developed catchment-estuary system (Sydney estuary, Australia): an innovative stormwater remediation strategy. *Journal of Soils and Sediments,* **11**(1)*,* 194-208.

Birch, G. F., Chang, C. H., Lee, J. H. and Churchill, L. J. (2013) The use of vintage surficial sediment data and sedimentary cores to determine past and future trends in estuarine metal contamination (Sydney estuary, Australia). *Sci Total Environ,* **454-455***,* 542-61.

Birch, G. F., Cruickshank, B. and Davis, B. (2010a) Modelling nutrient loads to Sydney estuary (Australia). *Environmental Monitoring and Assessment,* **167**(1-4)*,* 333-348.

Birch, G. F., Drage, D. S., Thompson, K., Eaglesham, G. and Mueller, J. F. (2015a) Emerging contaminants (pharmaceuticals, personal care products, a food additive and pesticides) in waters of Sydney estuary, Australia. *Mar Pollut Bull,* **97**(1-2)*,* 56-66.

Birch, G. F., Eyre, B. and Taylor, S. E. (1999) The distribution of nutrients in bottom sediments of Port Jackson (Sydney Harbour), Australia. *Mar. Pollut. Bull.,* **38**(12)*,* 1247-1251.

Birch, G. F., Harrington, C., Symons, R. K. and Hunt, J. W. (2007) The source and distribution of polychlorinated dibenzo-p-dioxin and polychlorinated dibenzofurans in sediments of Port Jackson, Australia. *Mar. Pollut. Bull.,* **54**(3)*,* 295-308.

Birch, G. F., Lean, J. and Gunns, T. (2015b) Growth and decline of shoreline industry in Sydney estuary (Australia) and influence on adjacent estuarine sediments. *Environmental Monitoring and Assessment,* **187**(6).

Birch, G. F., Lean, J. and Gunns, T. (2015c) Historic change in catchment land use and metal loading to Sydney estuary, Australia (1788-2010). *Environ Monit Assess,* **187**(9)*,* 594.

Birch, G. F. and McCready, S. (2009) Catchment condition as a major control on the quality of receiving basin sediments (Sydney Harbour, Australia). *Sci. Total Environ.,* **407**(8)*,* 2820-2835.

Birch, G. F., McCready, S., Long, E. R., Taylor, S. S. and Spyrakis, G. (2008) Contaminant chemistry and toxicity of sediments in Sydney Harbour, Australia: spatial extent and chemistry-toxicity relationships. *Marine Ecology Progress Series,* **363***,* 71-87.

Birch, G. F., Melwani, A., Lee, J. H. and Apostolatos, C. (2014) The discrepancy in concentration of metals (Cu, Pb and Zn) in oyster tissue (Saccostrea glomerata) and ambient bottom sediment (Sydney estuary, Australia). *Mar. Pollut. Bull.,* **80**(1–2)*,* 263-274.

Birch, G. F., Murray, O., Johnson, I. and Wilson, A. (2009) Reclamation in Sydney Estuary, 1788-2002. *Australian Geographer,* **40**(3)*,* 347-368.

Birch, G. F. and Rochford, L. (2010) Stormwater metal loading to a well-mixed/stratified estuary (Sydney Estuary, Australia) and management implications. *Environmental Monitoring and Assessment,* **169**(1-4)*,* 531-551.

Birch, G. F. and Taylor, S. E. (2000) Distribution and possible sources of organochlorine residues in sediments of a large urban estuary, Port Jackson, Sydney. *Australian Journal of Earth Sciences,* **47**(4)*,* 749-756.

Birch, G. F. and Taylor, S. E. (2002b) Application of sediment quality guidelines in the assessment and management of contaminated surficial sediments in Port Jackson (Sydney Harbour), Australia. *Environmental Management,* **29**(6)*,* 860-870.

Birch, G. F., Vanderhayden, M. and Olmos, M. (2010b) The Nature and Distribution of Metals in Soils of the Sydney Estuary Catchment, Australia. *Water, Air, & Soil Pollution,* **216**(1)*,* 581-604.

Bishop, M. J. (2007) Impacts of boat-generated waves on macroinfauna: Towards a mechanistic understanding. *J. Exp. Mar. Biol. Ecol.,* **343**(2)*,* 187-196.

Boehm, A. B., Ashbolt, N. J., Colford, J. M., Dunbar, L. E., Fleming, L. E., Gold, M. A., Hansel, J. A., Hunter, P. R., Ichida, A. M., McGee, C. D., Soller, J. A. and Weisberg, S. B. (2009a) A sea change ahead for recreational water quality criteria. *Journal of Water and Health,* **7**(1)*,* 9-20.

Boehm, A. B., Fuhrman, J. A., Mrse, R. D. and Grant, S. B. (2003) Tiered approach for identification of a human fecal pollution source at a recreational beach: case study at Avalon Bay, Catalina Island, California. *Environ Sci Technol,* **37**(4)*,* 673-80.

Boehm, A. B., Yamahara, K. M., Love, D. C., Peterson, B. M., McNeill, K. and Nelson, K. L. (2009b) Covariation and Photoinactivation of Traditional and Novel Indicator Organisms and Human Viruses at a Sewage-Impacted Marine Beach. *Environ. Sci. Technol.,* **43**(21)*,* 8046-8052.

Byappanahalli, M. N., Nevers, M. B., Whitman, R. L., Ge, Z., Shively, D., Spoljaric, A. and Przybyla-Kelly, K. (2015) Wildlife, urban inputs, and landscape configuration are responsible for degraded swimming water quality at an embayed beach. *Journal of Great Lakes Research,* **41**(1)*,* 156-163.

Cacciò, S. M., Thompson, R. C. A., McLauchlin, J. and Smith, H. V. (2005) Unravelling Cryptosporidium and Giardia epidemiology. *Trends in Parasitology,* **21**(9)*,* 430-437.

Cardno (NSW/ACT) Pty Ltd (2013) Parramatta River Estuary Coastal Zone Management Plan, LJ2929/R2701v3. Prepared for Parramatta River Estuary Management Committee.

Carratala, A., Rusinol, M., Rodriguez-Manzano, J., Guerrero-Latorre, L., Sommer, R. and Girones, R. (2013) Environmental Effectors on the Inactivation of Human Adenoviruses in Water. *Food and Environmental Virology,* **5**(4)*,* 203-214.

Chang, E. T., Adami, H. O., Boffetta, P., Cole, P., Starr, T. B. and Mandel, J. S. (2014) A critical review of perfluorooctanoate and perfluorooctanesulfonate exposure and cancer risk in humans. *Crit. Rev. Toxicol.,* **44***,* 1-81.

Chaudhuri, P., Nath, B. and Birch, G. (2014) Accumulation of trace metals in grey mangrove Avicennia marina fine nutritive roots: The role of rhizosphere processes. *Mar. Pollut. Bull.,* **79**(1–2)*,* 284-292.

Cheung, P. K., Yuen, K. L., Li, P. F., Lau, W. H., Chiu, C. M., Yuen, S. W. and Baker, D. M. (2015) To swim or not to swim? A disagreement between microbial indicators on beach water quality assessment in Hong Kong. *Mar. Pollut. Bull.,* **101**(1)*,* 53-60.

Cloutier, D. D., Alm, E. W. and McLellan, S. L. (2015) Influence of Land Use, Nutrients, and Geography on Microbial Communities and Fecal Indicator Abundance at Lake Michigan Beaches. *Appl Environ Microbiol,* **81**(15)*,* 4904-4913.

Cody, A. J., McCarthy, N. D., Bray, J. E., Wimalarathna, H. M. L., Colles, F. M., van Rensburg, M. J. J., Dingle, K. E., Waldenstrom, J. and Maiden, M. C. J. (2015) Wild bird-associated Campylobacter jejuni isolates are a consistent source of human disease, in Oxfordshire, United Kingdom. *Environmental Microbiology Reports,* **7**(5)*,* 782-788.

Collier, S. A., Wade, T. J., Sams, E. A., Hlavsa, M. C., Dufour, A. P. and Beach, M. J. (2015) Swimming in the USA: beachgoer characteristics and health outcomes at US marine and freshwater beaches. *Journal of Water and Health,* **13**(2)*,* 531-543.

Corsi, S. R., Borchardt, M. A., Carvin, R. B., Burch, T. R., Spencer, S. K., Lutz, M. A., McDermott, C. M., Busse, K. M., Kleinheinz, G. T., Feng, X. and Zhu, J. (2016) Human and Bovine Viruses and Bacteria at Three Great Lakes Beaches: Environmental Variable Associations and Health Risk. *Environ. Sci. Technol.,* **50**(2)*,* 987-995.

Cox, P., Griffith, M., Angles, M., Deere, D. and Ferguson, C. (2005) Concentrations of pathogens and indicators in animal feces in the Sydney watershed. *Appl Environ Microbiol,* **71**(10)*,* 5929-5934.

Cruz, R., Cunha, S. C. and Casal, S. (2015) Brominated flame retardants and seafood safety: A review. *Environ. Int.,* **77***,* 116-131.

Davies, P. J. and Wright, I. A. (2014) A review of policy, legal, land use and social change in the management of urban water resources in Sydney, Australia: A brief reflection of challenges and lessons from the last 200 years. *Land Use Policy,* **36***,* 450-460.

Drage, D., Mueller, J. F., Birch, G., Eaglesham, G., Hearn, L. K. and Harrad, S. (2015) Historical trends of PBDEs and HBCDs in sediment cores from Sydney estuary, Australia. *Sci Total Environ,* **512-513***,* 177-84.

Elmir, S. M., Wright, M. E., Abdelzaher, A., Solo-Gabriele, H. M., Fleming, L. E., Miller, G., Rybolowik, M., Peter Shih, M. T., Pillai, S. P., Cooper, J. A. and Quaye, E. A. (2007) Quantitative evaluation of bacteria released by bathers in a marine water. *Water Res,* **41**(1)*,* 3-10.
enHealth Council (2012) Environmental Health Risk Assessment: Guidelines for assessing human health risks from environmental hazards, Department of Health and Ageing and enHealth Council, Canberra.
Fan, J., Ming, H., Li, L. and Su, J. (2015) Evaluating spatial-temporal variations and correlation between fecal indicator bacteria (FIB) in marine bathing beaches. *Journal of water and health,* **13**(4)*,* 1029-38.
Fewtrell, L. and Kay, D. (2015) Recreational Water and Infection: A Review of Recent Findings. *Current environmental health reports,* **2**(1)*,* 85-94.
Field, K. G. and Samadpour, M. (2007) Fecal source tracking, the indicator paradigm, and managing water quality. *Water Res.,* **41**(16)*,* 3517-3538.
Fisher, K. and Phillips, C. (2009) The ecology, epidemiology and virulence of Enterococcus. *Microbiology,* **155**(6)*,* 1749-1757.
Fogarty, L. R., Haack, S. K., Johnson, H. E., Brennan, A. K., Isaacs, N. M. and Spencer, C. (2015) Staphylococcus aureus and methicillin-resistant S. aureus (MRSA) at ambient freshwater beaches. *Journal of Water and Health,* **13**(3)*,* 680-692.
Franks, A. H., Harmsen, H. J., Raangs, G. C., Jansen, G. J., Schut, F. and Welling, G. W. (1998) Variations of bacterial populations in human feces measured by fluorescent in situ hybridization with group-specific 16S rRNA-targeted oligonucleotide probes. *Appl Environ Microbiol,* **64**(9)*,* 3336-45.
Fujioka, R. S., Solo-Gabriele, H. M., Byappanahalli, M. N. and Kirs, M. (2015) US Recreational Water Quality Criteria: A Vision for the Future. *International Journal of Environmental Research and Public Health,* **12**(7)*,* 7752-7776.
Fujioka, R. S., Tenno, K. and Kansako, S. (1988) Naturally occurring fecal coliforms and fecal streptococci in Hawaii's freshwater streams. *Toxicity Assessment,* **3**(5)*,* 613-630.
Fujioka, R. S. and Yoneyama, B. S. (2002) Sunlight inactivation of human enteric viruses and fecal bacteria. *Water Sci. Technol.,* **46**(11-12)*,* 291-295.
Gasser, G., Pankratov, I., Elhanany, S., Glazman, H. and Lev, O. (2014) Calculation of wastewater effluent leakage to pristine water sources by the weighted average of multiple tracer approach. *Water Resources Research,* **50**(5)*,* 4269-4282.
GHD (2015) Sydney Coastal Councils Group Sydney Harbour Coastal Zone Management Plan Scoping Study.
Gómez-Doñate, M., Casanovas-Massana, A., Muniesa, M. and Blanch, A. R. (2015) Development of new host-specific Bacteroides qPCRs for the identification of fecal contamination sources in water. *MicrobiologyOpen,* n/a-n/a.
Graczyk, T. K., Sunderland, D., Awantang, G. N., Mashinski, Y., Lucy, F. E., Graczyk, Z., Chomicz, L. and Breysse, P. N. (2010) Relationships among bather density, levels of human waterborne pathogens, and fecal coliform counts in marine recreational beach water. *Parasitology research,* **106**(5)*,* 1103-8.
Halliday, E., Ralston, D. K. and Gast, R. J. (2015) Contribution of Sand-Associated Enterococci to Dry Weather Water Quality. *Environ. Sci. Technol.,* **49**(1)*,* 451-458.
Hatje, V., Apte, S. C., Hales, L. T. and Birch, G. F. (2003) Dissolved trace metal distributions in Port Jackson estuary (Sydney Harbour), Australia. *Mar. Pollut. Bull.,* **46**(6)*,* 719-730.
Hatje, V., Rae, K. and Birch, G. F. (2001) Trace metal and total suspended solids concentrations in freshwater: the importance of small-scale temporal variation. *Journal of environmental monitoring : JEM,* **3**(2)*,* 251-6.
Hawaii State Department of Health (HIDOH) (2014) Title 11 Department of Health. In Hawaii Administrative Rules; Chapter 54 Water Quality Standards; HIDOH: Honolulu, HI, USA.
Hellou, J., Lebeuf, M. and Rudi, M. (2013) Review on DDT and metabolites in birds and mammals of aquatic ecosystems. *Environ. Rev.,* **21**(1)*,* 53-69.
Herrig, I. M., Boeer, S. I., Brennholt, N. and Manz, W. (2015) Development of multiple linear regression models as predictive tools for fecal indicator concentrations in a stretch of the lower Lahn River, Germany. *Water Res.,* **85***,* 148-157.

Hose, G. C., Gordon, G., McCullough, F. E., Pulver, N. and Murray, B. R. (2005) Spatial and rainfall related patterns of bacterial contamination in Sydney Harbour estuary. *Journal of water and health,* **3**(4)*,* 349-58.

Irvine, I. and Birch, G. F. (1998) Distribution of heavy metals in surficial sediments of Port Jackson, Sydney, New South Wales. *Australian Journal of Earth Sciences,* **45**(2)*,* 297-304.

Jardak, K., Drogui, P. and Daghrir, R. (2016) Surfactants in aquatic and terrestrial environment: occurrence, behavior, and treatment processes. *Environ. Sci. Pollut. Res.,* **23**(4)*,* 3195-3216.

Jekel, M., Dott, W., Bergmann, A., Dunnbier, U., Gnirss, R., Haist-Gulde, B., Hamscher, G., Letzel, M., Licha, T., Lyko, S., Miehe, U., Sacher, F., Scheurer, M., Schmidt, C. K., Reemtsma, T. and Ruhl, A. S. (2015) Selection of organic process and source indicator substances for the anthropogenically influenced water cycle. *Chemosphere,* **125***,* 155-167.

Jiang, S. C., Lim, K. Y., Huang, X., McCarthy, D. and Hamilton, A. J. (2015) Human and environmental health risks and benefits associated with use of urban stormwater. *Wiley Interdisciplinary Reviews-Water,* **2**(6)*,* 683-699.

Kaserzon, S. L., Kennedy, K., Hawker, D. W., Thompson, J., Carter, S., Roach, A. C., Booij, K. and Mueller, J. F. (2012) Development and Calibration of a Passive Sampler for Perfluorinated Alkyl Carboxylates and Sulfonates in Water. *Environ. Sci. Technol.,* **46**(9)*,* 4985-4993.

Khan, S. J., Wang, L. L., Hashim, N. H. and McDonald, J. A. (2014) Distinct Enantiomeric Signals of Ibuprofen and Naproxen in Treated Wastewater and Sewer Overflow. *Chirality,* **26**(11)*,* 739-746.

Laura Patat, M., Ricci, L., Paula Comino, A. and Scagliola, M. (2015) Estimating Percentiles of Bacteriological Counts of Recreational Water Quality Using Tweedie Models. *Water Quality Exposure and Health,* **7**(2)*,* 227-231.

Laxton, J. H., Laxton, E. and Gittins, R. (2008) Water Quality of Upper Parramatta River: Analysis of Data Collected between 1990 and 2007. Parramatta Council.

Lee, D. G., Roehrdanz, P. R., Feraud, M., Ervin, J., Anumol, T., Jia, A., Park, M., Tamez, C., Morelius, E. W., Gardea-Torresdey, J. L., Izbicki, J., Means, J. C., Snyder, S. A. and Holden, P. A. (2015a) Wastewater compounds in urban shallow groundwater wells correspond to exfiltration probabilities of nearby sewers. *Water Res.,* **85***,* 467-475.

Lee, J. H., Birch, G. F., Cresswell, T., Johansen, M. P., Adams, M. S. and Simpson, S. L. (2015b) Dietary ingestion of fine sediments and microalgae represent the dominant route of exposure and metal accumulation for Sydney rock oyster (Saccostrea glomerata): A biokinetic model for zinc. *Aquatic toxicology (Amsterdam, Netherlands),* **167***,* 46-54.

Lee, S. B. and Birch, G. F. (2012) Utilising monitoring and modelling of estuarine environments to investigate catchment conditions responsible for stratification events in a typically well-mixed urbanised estuary. *Estuarine Coastal and Shelf Science,* **111***,* 1-16.

Lee, S. B., Birch, G. F. and Lemckert, C. J. (2011) Field and modelling investigations of fresh-water plume behaviour in response to infrequent high-precipitation events, Sydney Estuary, Australia. *Estuarine Coastal and Shelf Science,* **92**(3)*,* 389-402.

Lehnherr, I. (2014) Methylmercury biogeochemistry: a review with special reference to Arctic aquatic ecosystems. *Environ. Rev.,* **22**(3)*,* 229-243.

Li, N., Xiao, L. H., Wang, L., Zhao, S. M., Zhao, X. K., Duan, L. P., Guo, M. J., Liu, L. L. and Feng, Y. Y. (2012) Molecular Surveillance of Cryptosporidium spp., Giardia duodenalis, and Enterocytozoon bieneusi by Genotyping and Subtyping Parasites in Wastewater. *Plos Neglected Tropical Diseases,* **6**(9).

Lim, K. Y., Hamilton, A. J. and Jiang, S. C. (2015) Assessment of public health risk associated with viral contamination in harvested urban stormwater for domestic applications. *Sci. Total Environ.,* **523***,* 95-108.

Losada, S., Roach, A., Roosens, L., Santos, F. J., Galceran, M. T., Vetter, W., Neels, H. and Covaci, A. (2009) Biomagnification of anthropogenic and naturally-produced organobrominated compounds in a marine food web from Sydney Harbour, Australia. *Environ. Int.,* **35**(8)*,* 1142-1149.

Lugg, R. S. W., Cook, A. and Devine, B. (2012) Estimating 95th Percentiles from Microbial Sampling: A Novel Approach to Standardising their Application to Recreational Waters. In: The Significance of Faecal Indicators in Water: A Global Perspective The Royal Society of Chemistry, 62-71.

Luther, K. and Fujioka, R. (2004) Usefulness of monitoring tropical streams for male-specific RNA coliphages. *J Water Health,* **2**(3)*,* 171-81.

Lutz, C., Erken, M., Noorian, P., Sun, S. Y. and McDougald, D. (2013) Environmental reservoirs and mechanisms of persistence of Vibrio cholerae. *Frontiers in Microbiology,* **4**.

Margot, J., Rossi, L., Barry, D. A. and Holliger, C. (2015) A review of the fate of micropollutants in wastewater treatment plants. *Wiley Interdisciplinary Reviews-Water,* **2**(5)*,* 457-487.

Matteucci, G., Schippa, S., Lallo, G., Migliore, L. and Thaller, M. C. (2015) Species diversity, spatial distribution, and virulence associated genes of culturable vibrios in a brackish coastal Mediterranean environment. *Annals of Microbiology,* **65**(4)*,* 2311-2321.

McCready, S., Birch, G. F. and Long, E. R. (2006a) Metallic and organic contaminants in sediments of Sydney Harbour, Australia and vicinity - A chemical dataset for evaluating sediment quality guidelines. *Environ. Int.,* **32**(4)*,* 455-465.

McCready, S., Birch, G. F., Long, E. R., Spyrakis, G. and Greely, C. R. (2006b) Relationships between toxicity and concentrations of chemical contaminants in sediments from Sydney Harbour, Australia, and vicinity. *Environmental Monitoring and Assessment,* **120**(1-3)*,* 187-220.

McCready, S., Greely, C. R., Hyne, R. V., Birch, G. F. and Long, E. R. (2005) Sensitivity of an indigenous amphipod (Corophium colo) to chemical contaminants in laboratory toxicity tests conducted with sediments from Sydney Harbor, Australia, and vicinity. *Environ. Toxicol. Chem.,* **24**(10)*,* 2545-2552.

McCready, S., Slee, D. J., Birch, G. F. and Taylor, S. E. (2000) The Distribution of Polycyclic Aromatic Hydrocarbons in Surficial Sediments of Sydney Harbour, Australia. *Mar. Pollut. Bull.,* **40**(11)*,* 999-1006.

McCready, S., Spyrakis, G., Greely, C. R., Birch, G. F. and Long, E. R. (2004) Toxicity of surficial sediments from Sydney Harbour and vicinity, Australia. *Environmental Monitoring and Assessment,* **96**(1-3)*,* 53-83.

Mendes Silva, D. and Domingues, L. (2015) On the track for an efficient detection of Escherichia coli in water: A review on PCR-based methods. *Ecotoxicol Environ Saf,* **113***,* 400-11.

Miralles-Marco, A. and Harrad, S. (2015) Perfluorooctane sulfonate: A review of human exposure, biomonitoring and the environmental forensics utility of its chirality and isomer distribution. *Environ. Int.,* **77***,* 148-159.

Montoya, D. (2015) Pollution in Sydney Harbour: sewage, toxic chemicals and microplastics. NSW Parliamentary Research Service Briefing Paper No 03/2015.

Mueller, J., Muller, R., Goudkamp, K., Shaw, M., Mortimer, M., Haynes, D., Paxman, C. J., Hyne, R., McTaggart, A., Burniston, D., Symons, R. and Moore, M. R. (2004) Dioxins in Aquatic Environments in Australia - National Dioxins Program Technical Report No. 6, Australian Government Department of the Environment and Heritage, Canberra. .

Nath, B., Birch, G. and Chaudhuri, P. (2014) Assessment of sediment quality in Avicennia marina-dominated embayments of Sydney Estuary: the potential use of pneumatophores (aerial roots) as a bio-indicator of trace metal contamination. *Sci Total Environ,* **472***,* 1010-22.

National Health and Medical Research Council - Government of Australia (2008) Guidelines for Managing Risks in Recreational Water.

National Health and Medical Research Council and Natural Resource Management Ministerial Council (2011) Australian Drinking Water Guidelines. Government of Australia, Canberra.

National Research Council (1983) Risk Assessment in the Federal Government: Managing the Process. National Academy Press, Washington, DC.

Nau, H. (2006) Effects and toxicity mechanisms of "dioxins" in humans and animals. *Dtsch. Tierarztl. Wochenschr.,* **113**(8)*,* 292-297.

NSW Department of Primary Industries (2016) Fishing in Sydney Harbour. .Website: http://www.dpi.nsw.gov.au/fisheries/recreational/info/syd-harbour Accessed: *28/1/2016*.

Oberbeckmann, S., Fuchs, B. M., Meiners, M., Wichels, A., Wiltshire, K. H. and Gerdts, G. (2011) Seasonal Dynamics and Modeling of a Vibrio Community in Coastal Waters of the North Sea. *Microbial Ecology,* **63**(3)*,* 543-551.

Office of Environment & Heritage NSW (2015) State of the Beaches 2014–2015, Sydney Region New South Wales.

Oliver, D. M., Hanley, N. D., van Niekerk, M., Kay, D., Heathwaite, A. L., Rabinovici, S. J. M., Kinzelman, J. L., Fleming, L. E., Porter, J., Shaikh, S., Fish, R., Chilton, S., Hewitt, J., Connolly, E., Cummins, A., Glenk, K., McPhail, C., McRory, E., McVittie, A., Giles, A., Roberts, S., Simpson, K., Tinch, D., Thairs, T., Avery, L. M., Vinten, A. J. A., Watts, B. D. and Quilliam, R. S. (2016) Molecular tools for bathing water assessment in Europe: Balancing social science research with a rapidly developing environmental science evidence-base. *Ambio,* **45**(1)*,* 52-62.

Oliver, D. M., van Niekerk, M., Kay, D., Heathwaite, A. L., Porter, J., Fleming, L. E., Kinzelman, J. L., Connolly, E., Cummins, A., McPhail, C., Rahman, A., Thairs, T., de Roda Husman, A. M., Hanley, N. D., Dunhill, I., Globevnik, L., Harwood, V. J., Hodgson, C. J., Lees, D. N., Nichols, G. L., Nocker, A., Schets, C. and Quilliam, R. S. (2014) Opportunities and limitations of molecular methods for quantifying microbial compliance parameters in EU bathing waters. *Environ. Int.,* **64***,* 124-128.

Oster, R. J., Wijesinghe, R. U., Haack, S. K., Fogarty, L. R., Tucker, T. R. and Riley, S. C. (2014) Bacterial Pathogen Gene Abundance and Relation to Recreational Water Quality at Seven Great Lakes Beaches. *Environ. Sci. Technol.,* **48**(24)*,* 14148-14157.

Otten, T. G. and Paerl, H. W. (2015) Health Effects of Toxic Cyanobacteria in U.S. Drinking and Recreational Waters: Our Current Understanding and Proposed Direction. *Current environmental health reports,* **2**(1)*,* 75-84.

Page, D., Gonzalez, D., Torkzaban, S., Toze, S., Sidhu, J., Miotlinski, K., Barry, K. and Dillon, P. (2015) Microbiological risks of recycling urban stormwater via aquifers for various uses in Adelaide, Australia. *Environmental Earth Sciences,* **73**(12)*,* 7733-7737.

Pal, A., He, Y. L., Jekel, M., Reinhard, M. and Gin, K. Y. H. (2014) Emerging contaminants of public health significance as water quality indicator compounds in the urban water cycle. *Environ. Int.,* **71***,* 46-62.

Parramatta River Catchment Group (2016) Parramatta River Catchment Group. http://www.parramattariver.org.au/.

Parsons Brinckerhoff Australia and Thiess Serivces (2002) Remediation of Lednez Site, Rhodes and Homebush Bay : environmental impact statement.

Passerat, J., Ouattara, N. K., Mouchel, J.-M., Vincent, R. and Servais, P. (2011) Impact of an intense combined sewer overflow event on the microbiological water quality of the Seine River. *Water Res.,* **45**(2)*,* 893-903.

Prez, V. E., Gil, P. I., Temprana, C. F., Cuadrado, P. R., Martinez, L. C., Giordano, M. O., Masachessi, G., Isa, M. B., Re, V. E., Pavan, J. V., Nates, S. V. and Barril, P. A. (2015) Quantification of human infection risk caused by rotavirus in surface waters from Cordoba, Argentina. *Sci. Total Environ.,* **538***,* 220-229.

Raith, M. R., Ebentier, D. L., Cao, Y., Griffith, J. F. and Weisberg, S. B. (2014) Factors affecting the relationship between quantitative polymerase chain reaction (qPCR) and culture-based enumeration of Enterococcus in environmental waters. *J Appl Microbiol,* **116**(3)*,* 737-46.

Ramonaite, S., Novoslavskij, A., Zakariene, G., Aksomaitiene, J. and Malakauskas, M. (2015) High Prevalence and Genetic Diversity of Campylobacter jejuni in Wild Crows and Pigeons. *Current Microbiology,* **71**(5)*,* 559-565.

Rashid, A., Haley, B. J., Rajabov, M., Ahmadova, S., Gurbanov, S., Colwell, R. R. and Huq, A. (2013) Detection of Vibrio cholerae in environmental waters including drinking water reservoirs of Azerbaijan. *Environmental Microbiology Reports,* **5**(1)*,* 30-38.

Ratola, N., Cincinelli, A., Alves, A. and Katsoyiannis, A. (2012) Occurrence of organic microcontaminants in the wastewater treatment process. A mini review. *J. Haz. Mat.,* **239***,* 1-18.

Richman, L. A., Kolic, T., MacPherson, K., Fayez, L. and Reiner, E. (2013) Polybrominated diphenyl ethers in sediment and caged mussels (Elliptio complanata) deployed in the Niagara River. *Chemosphere,* **92**(7)*,* 778-786.

Rippy, M. A., Stein, R., Sanders, B. F., Davis, K., McLaughlin, K., Skinner, J. F., Kappeler, J. and Grant, S. B. (2014) Small Drains, Big Problems: The Impact of Dry Weather Runoff on Shoreline Water Quality at Enclosed Beaches. *Environ. Sci. Technol.,* **48**(24)*,* 14168-14177.

Roach, A. C., Muller, R., Komarova, T., Symons, R., Stevenson, G. J. and Mueller, J. F. (2009) Using SPMDs to monitor water column concentrations of PCDDs, PCDFs and dioxin-like PCBs in Port Jackson (Sydney Harbour), Australia. *Chemosphere,* **75**(9)*,* 1243-1251.

Roach, A. C. and Runcie, J. (1998) Levels of selected chlorinated hydrocarbons in edible fish tissues from polluted areas in the Georges/Cooks Rivers and Sydney Harbour, New South Wales, Australia. *Mar. Pollut. Bull.,* **36**(5)*,* 323-344.

Roser, D. J., Davies, C. M., Ashbolt, N. J. and Morison, P. (2006) Microbial exposure assessment of an urban recreational lake: a case study of the application of new risk-based guidelines. *Water Sci Technol,* **54**(3)*,* 245-52.

Schijven, J., Bouwknegt, M., Husman, A. M. D., Rutjes, S., Sudre, B., Suk, J. E. and Semenza, J. C. (2013) A Decision Support Tool to Compare Waterborne and Foodborne Infection and/or Illness Risks Associated with Climate Change. *Risk Anal.,* **33**(12)*,* 2154-2167.

Schijven, J. F. and de Roda Husman, A. M. (2005) Effect of climate changes on waterborne disease in The Netherlands. *Water Sci Technol,* **51**(5)*,* 79-87.

Schoen, M. E. and Ashbolt, N. J. (2010) Assessing Pathogen Risk to Swimmers at Non-Sewage Impacted Recreational Beaches. *Environ. Sci. Technol.,* **44**(7)*,* 2286-2291.

Shively, D. A., Nevers, M. B., Breitenbach, C., Phanikumar, M. S., Przybyla-Kelly, K., Spoljaric, A. M. and Whitman, R. L. (2016) Prototypic automated continuous recreational water quality monitoring of nine Chicago beaches. *Journal of Environmental Management,* **166***,* 285-293.

Shuval, H. (2003) Estimating the global burden of thalassogenic diseases: human infectious diseases caused by wastewater pollution of the marine environment. *J Water Health,* **1**(2)*,* 53-64.

Siboni, N., Balaraju, V., Carney, R., Labbate, M. and Seymour, J. R. (2016) Spatiotemporal dynamics of Vibrio spp. within the Sydney Harbour estuary. *Frontiers in Microbiology,* **7**.

Simpson, S. L., Rochford, L. and Birch, G. F. (2002) Geochemical influences on metal partitioning in contaminated estuarine sediments. *Mar. Freshw. Res.,* **53**(1)*,* 9-17.

Sinclair, R. G., Jones, E. L. and Gerba, C. P. (2009) Viruses in recreational water-borne disease outbreaks: a review. *Journal of Applied Microbiology,* **107**(6)*,* 1769-1780.

Smith, S. (1997) Proposed New Pollution Control Legislation in NSW: Background and Commentary. Briefing Paper No 5/97. NSW Parliamentary Library Research Service. ISSN 1325-5142.

Snowdon, R. and Birch, G. F. (2004) The nature and distribution of copper, lead, and zinc in soils of a highly urbanised sub-catchment (Iron Cove) of Port Jackson, Sydney. *Soil Research,* **42**(3)*,* 329-338.

Soller, J., Bartrand, T., Ravenscroft, J., Molina, M., Whelan, G., Schoen, M. and Ashbolt, N. (2015) Estimated human health risks from recreational exposures to stormwater runoff containing animal faecal material. *Environmental Modelling & Software,* **72***,* 21-32.

Soller, J. A., Schoen, M. E., Bartrand, T., Ravenscroft, J. E. and Ashbolt, N. J. (2010) Estimated human health risks from exposure to recreational waters impacted by human and non-human sources of faecal contamination. *Water Res.,* **44**(16)*,* 4674-4691.

Soller, J. A., Schoen, M. E., Varghese, A., Ichida, A. M., Boehm, A. B., Eftim, S., Ashbolt, N. J. and Ravenscroft, J. E. (2014) Human health risk implications of multiple sources of faecal indicator bacteria in a recreational waterbody. *Water Res.,* **66***,* 254-264.

Standards Australia and Standards New Zealand (2007) AS/NZS 4276.9:2007 Water microbiology. Method 9: Enterococci—Membrane filtration method (ISO 7899-2:2000, MOD).

Stauder, M., Vezzulli, L., Pezzati, E., Repetto, B. and Pruzzo, C. (2010) Temperature affects Vibrio cholerae O1 El Tor persistence in the aquatic environment via an enhanced expression of GbpA and MSHA adhesins. *Environmental Microbiology Reports,* **2**(1)*,* 140-144.

Stewart, J. R., Gast, R. J., Fujioka, R. S., Solo-Gabriele, H. M., Meschke, J. S., Amaral-Zettler, L. A., del Castillo, E., Polz, M. F., Collier, T. K., Strom, M. S., Sinigalliano, C. D., Moeller, P. D. R. and Holland, A. F. (2008) The coastal environment and human health: microbial indicators, pathogens, sentinels and reservoirs. *Environ. Health,* **7**(Suppl 2)*,* S3-S3.

Suh, J. Y., Birch, G. F. and Hughes, K. (2004) Hydrochemistry in reclaimed lands of the 2000 Olympic games site, Sydney, Australia. *Journal of Coastal Research,* **20**(3)*,* 709-721.

Suh, J. Y., Brown, P. L. and Virch, G. F. (2003) Hydrogeochemical characteristics and importance of natural and anthropogenic influences on soil and groundwater in reclaimed land adjacent to Port Jackson, Sydney, Australia. *Mar. Freshw. Res.,* **54**(6)*,* 767-779.

Sunger, N. and Haas, C. N. (2015) Quantitative Microbial Risk Assessment for Recreational Exposure to Water Bodies in Philadelphia. *Water Environ. Res.,* **87**(3)*,* 211-222.

Takemura, A. F., Chien, D. M. and Polz, M. F. (2014) Associations and dynamics of Vibrionaceae in the environment, from the genus to the population level. *Frontiers in Microbiology,* **5**.

Taran-Benshoshan, M., Ofer, N., Dalit, V. O., Aharoni, A., Revhun, M., Nitzan, Y. and Nasser, A. M. (2015) Cryptosporidium and Giardia removal by secondary and tertiary wastewater treatment. *J. Environ. Sci. Heal. A,* **50**(12)*,* 1265-1273.

Taylor, S. E., Birch, G. F. and Links, F. (2004) Historical catchment changes and temporal impact on sediment of the receiving basin, Port Jackson, New South Wales. *Australian Journal of Earth Sciences,* **51**(2)*,* 233-246.

The World Health Organization (2003) Guidelines for safe recreational water environments. Volume 1: Coastal and fresh waters.

Thompson, J., Roach, A., Eaglesham, G., Bartkow, M. E., Edge, K. and Mueller, J. F. (2011) Perfluorinated alkyl acids in water, sediment and wildlife from Sydney Harbour and surroundings. *Mar. Pollut. Bull.,* **62**(12)*,* 2869-2875.

Tonani, K. A. A., Padula, J. A., Juliao, F. C., Fregonesi, B. M., Alves, R. I. S., Sampaio, C. F., Beda, C. F., Hachich, E. M. and Segura-Munoz, S. I. (2013) Persistence of Giardia, Cryptosporidium, Rotavirus, and Adenovirus in Treated Sewage in Sao Paulo State, Brazil. *Journal of Parasitology,* **99**(6)*,* 1144-1147.

Tran, N. H., Hu, J. Y., Li, J. H. and Ong, S. L. (2014) Suitability of artificial sweeteners as indicators of raw wastewater contamination in surface water and groundwater. *Water Res.,* **48***,* 443-456.

Updyke, E. A., Wang, Z., Sun, S., Connell, C., Kirs, M., Wong, M. and Lu, Y. (2015) Human enteric viruses - potential indicators for enhanced monitoring of recreational water quality. *Virologica Sinica,* **30**(5)*,* 344-353.

US Environmental Protection Agency (2012) Recreational Water Quality Criteria. Office of Water 820-F-12-058.

Verhougstraete, M. P., Martin, S. L., Kendall, A. D., Hyndman, D. W. and Rose, J. B. (2015) Linking fecal bacteria in rivers to landscape, geochemical, and hydrologic factors and sources at the basin scale. *Proceedings of the National Academy of Sciences of the United States of America,* **112**(33)*,* 10419-10424.

Vezzulli, L., Colwell, R. R. and Pruzzo, C. (2013) Ocean Warming and Spread of Pathogenic Vibrios in the Aquatic Environment. *Microbial Ecology,* **65**(4)*,* 817-825.

Viau, E. J., Goodwin, K. D., Yamahara, K. M., Layton, B. A., Sassoubre, L. M., Burns, S. L., Tong, H.-I., Wong, S. H. C., Lu, Y. and Boehm, A. B. (2011a) Bacterial pathogens in Hawaiian coastal streams—Associations with fecal indicators, land cover, and water quality. *Water Res.,* **45**(11)*,* 3279-3290.

Viau, E. J., Lee, D. and Boehm, A. B. (2011b) Swimmer risk of gastrointestinal illness from exposure to tropical coastal waters impacted by terrestrial dry-weather runoff. *Environ Sci Technol,* **45**(17)*,* 7158-65.

Wade, T. J., Calderon, R. L., Sams, E., Beach, M., Brenner, K. P., Williams, A. H. and Dufour, A. P. (2006) Rapidly measured indicators of recreational water quality are predictive of swimming-associated gastrointestinal illness. *Environ Health Perspect,* **114**(1)*,* 24-8.

Wang, T. Y., Wang, P., Meng, J., Liu, S. J., Lu, Y. L., Khim, J. S. and Giesy, J. P. (2015) A review of sources, multimedia distribution and health risks of perfluoroalkyl acids (PFAAs) in China. *Chemosphere,* **129***,* 87-99.

Wolanski, E. (1977) The fate of storm water and stormwater pollution in the Parramatta estuary, Sydney. *Mar. Freshw. Res.,* **28**(1)*,* 67-75.

Xie, G., Mengersen, K., Cleary, A., Udy, J. and Roiko, A. (2015) EnterosisA: A Statistical Decision Support Tool for Categorization of Microbial Quality of Recreational Water. *Water Quality Exposure and Health,* **7**(3), 295-306.

Ying, G.-G., Rawson, C. A., Kookana, R. S., Warne, M. S. J., Peng, P.-A., Li, X.-M., Laginestra, E., Tremblay, L. A., Chapman, J. C. and Lim, R. P. (2009) Distribution of inorganic and organic contaminants in sediments from Sydney Olympic Park and the surrounding Sydney metropolitan area. *J. Environ. Monitoring,* **11**(9), 1687-1696.

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