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Relationships between extreme flows and microbial contamination in inland recreational swimming areas

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ABSTRACT

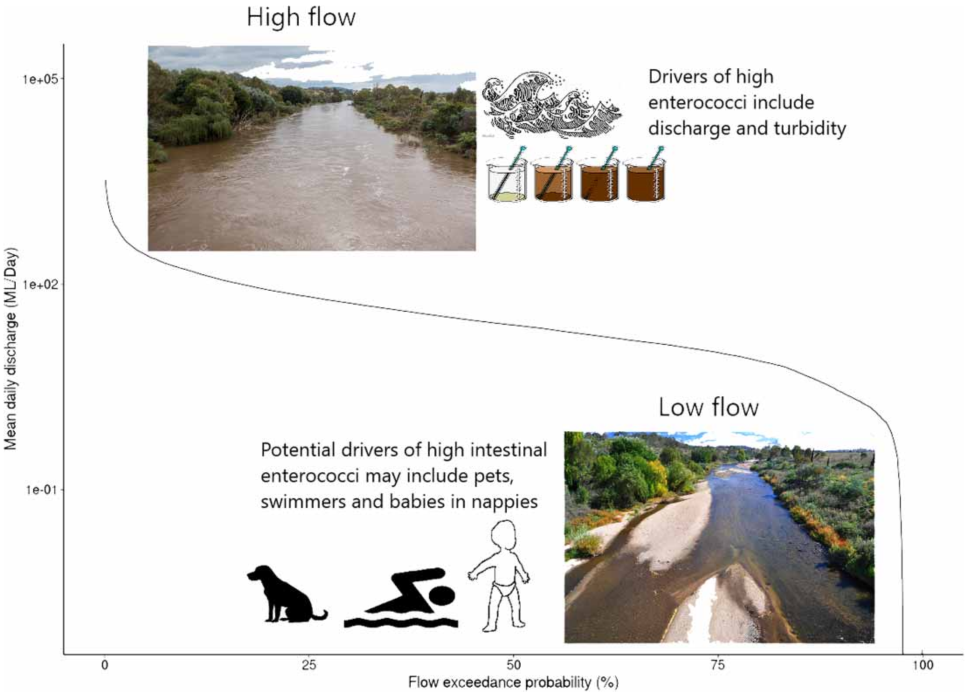
Inland recreational swimming sites provide significant social value globally. This study focused on public recreational swimming sites across the Murrumbidgee River and its tributaries in the Australian Capital Territory (ACT) throughout the swimming season (September–April) from 2009 to 2020 to determine whether high intestinal enterococci concentrations could be predicted with flow exceedance and routinely monitored physical and chemical parameters of water quality. Enterococci concentrations were positively correlated with the turbidity associated with high-flow conditions. The predictive accuracy of high enterococci levels during high-flow conditions was good (mean percentage correctly classified, 60%). The prediction of high enterococci levels at low flows was significantly less reliable (mean percentage correctly classified, 12–15%). As the ACT is expected to experience decreases in rainfall overall but increases in extreme rainfall events due to climate change, understanding the drivers of elevated intestinal enterococci under extreme flow conditions remains important from a public health perspective.

Key words: Australia, extreme flows, inland rivers, primary contact, public health, swimming

HIGHLIGHTS

- Climate change is anticipated to increase the frequency and magnitude of extreme rainfall.
- Extreme riverine flows were associated with high enterococci concentration.
- High flows and turbidity were good predictors of high enterococci concentrations.
- High enterococci during low flows were not well explained by the water quality or flow.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The quality of water in naturally occurring freshwater systems is under increasing pressure from development and population expansion (Buckerfield *et al.* 2019). These impacts will likely be exacerbated by extreme weather events associated with climate change (Alkolibi 2002; Kistemann *et al.* 2002; Signor *et al.* 2005; Sidhu *et al.* 2012). Extreme precipitation can substantially alter the risks to public health, either due to mobilisation of contaminants during flooding or of higher concentrations due to reduced flow volumes during prolonged dry periods (Joosten *et al.* 2017; Buckerfield *et al.* 2019). Heavy rainfall driving the flushing of contaminants into surface and groundwater sources is a well-established precursor to increased gastrointestinal illness (Curriero *et al.* 2001; Tornevi *et al.* 2013). Positive associations between enterococci concentrations and gastrointestinal illness in swimmers (Boehm & Sassoubre 2014) and high-flow conditions have frequently been reported in the literature (Chu *et al.* 2014; Strauch 2017). While there is general consensus on the impact of high-flow events in freshwater systems on public health, the effect of low-flow conditions following prolonged dry periods on the health risks is not well assessed.

Enterococci that are found in human and animal faeces are frequently used as faecal indicator bacteria (FIB) as a proxy for water quality and to assess the public health risks in recreational waters (Boehm & Sassoubre 2014). Four years of data in a Mediterranean coastal river in low-flow conditions showed that bacteria were stored in fine riverbed sediments, creating an in-stream store of bacteria (Chu *et al.* 2014). The presence of submerged aquatic vegetation provides conditions conducive to higher mean densities of enterococci than in sediment or water (Badgley *et al.* 2010), indicating another potential source of enterococci contamination and/or persistence during low-flow conditions. In Florida, USA, beach management activities such as reducing human, dog and bird densities, and reducing homeless populations were associated with lower enterococci concentrations (Kelly *et al.* 2018), suggesting that non-point sources of pollution may be an important source of contamination during low-flow conditions. Collectively, results from previous work identify a clear need to better understand how extreme high- and low-flow conditions can alter the water-related risks to public health.

In Australia, the majority of reported outbreaks of water-related gastrointestinal illness are related to recreational use (Dale *et al.* 2010; Sidhu *et al.* 2012), with concentrations of FIB in urban stormwater runoff frequently exceeding acceptable limits after storm events. Future climate projections for rainfall in Australia include a decrease in overall rainfall in southern Australia, but an increase in intense rainfall events throughout the country (IPCC 2014; BOM & CSIRO 2018). Being able to predict the levels of microbial pollution has locally relevant implications for current management actions, as well as planning for increased risk associated with water-based recreation due to climate change.

The current study focuses on the Australian Capital Territory (ACT). In the ACT, less rain is projected during the winter and spring seasons by 2090, and daily rainfall intensity is expected to increase (Webb & Hennessy 2015). The main aim of this study is to examine and predict how flow and flow variability is associated with intestinal enterococci concentration, while considering additional water quality parameters that are important for management of natural swimming areas. Specific objectives were to (i) quantify flow exceedance at multiple swimming sites over a long time period, (ii) quantify relationships between intestinal enterococci concentrations, flow exceedance, and water quality parameters including turbidity, electrical conductivity, and water temperature, and (iii) predict intestinal enterococci concentrations during extreme flow (high- and low-flow conditions). Additionally, we establish a link between visitation to these areas using traffic count data and periods of high intestinal enterococci concentration.

2. METHODS

2.1. Study area

Within the ACT, the Murrumbidgee River and its riparian corridor are managed primarily for conservation purposes, and as a place of recreation for residents of the ACT and surrounding regions. Currently, there are seven designated recreational swimming sites along the Murrumbidgee River, which flows through the ACT for approximately 66 km. Two additional designated primary recreational swimming sites occur on the Paddys River (which is a tributary of the Cotter River) and the Cotter River, which is a tributary of the Murrumbidgee River (Figure 1). The Murrumbidgee River catchment upstream of the ACT is predominantly rural, with livestock grazing and cropping being the predominant land-uses adjacent to the Murrumbidgee River (ABARES 2021). A considerable proportion of the Paddys River catchment includes agricultural land-uses as well.

2.2. Data sources and calculations and flow exceedance analysis

2.2.1. Intestinal enterococci concentration data

Intestinal enterococci data were obtained from the ACT Data's 'Open Data Portal', which is collected and analysed by the ACT Health Protection Service weekly (Monday or Tuesday, with results reported on Friday) during the open swimming season (September–April). Data were from Austral Spring 2009 to Austral Autumn 2020. The intestinal enterococci counts are obtained through analysis by the ACT Government Analytical Laboratory (ACTGAL), a NATA-accredited facility. These counts are reported as the number of intestinal enterococci organisms or colony-forming units (CFU) per 100 mL of sampled water. According to the ACT Guidelines for Recreational Water Quality 2014, if intestinal enterococci counts are >200 CFU/100 mL another sample is taken. If the repeat sample is >200 CFU/100 mL then the site is advised as closed for primary contact recreation, and the relevant territory bodies are advised to facilitate communication of the risk to the public, with signage displayed (ACT Government Health 2014). To reopen a site, two consecutive samples must produce a count ≤200 CFU/mL. Prior to 2014, a single sample >200 CFU/100 mL was required to advise the closing of a site for primary contact recreation. As such, results are reported as the advisory status for sites, rather than closed, as other water quality and management issues (e.g. blue-green algae) may lead to a site being closed in addition to intestinal enterococci count data.

2.2.2. Flow exceedance calculation and water quality data

River streamflow gauges for the Murrumbidgee River, Gudgenby River, Tuggeranong Creek, Paddys River, and Cotter River were used to explore the role of streamflow on intestinal enterococci concentrations. Daily streamflow data (mL/day) from 1980 to 2020 were used to calculate the long-term streamflow exceedance curves. Summation of streamflow from gauges on tributaries with the Murrumbidgee River gauges was used to compute streamflows for intestinal enterococci sampling sites not associated with a streamflow gauge. This produced five unique streamflow datasets for analysis (Supplementary Material, Figure 1). Missing streamflow data were interpolated from upstream or downstream gauges, or from time series of streamflow data generated by a calibrated catchment model for the ACT (eWater Source model). Flow exceedance was calculated as:

$$P = 100 \times \left[\frac{M}{n+1}\right] \tag{1}$$

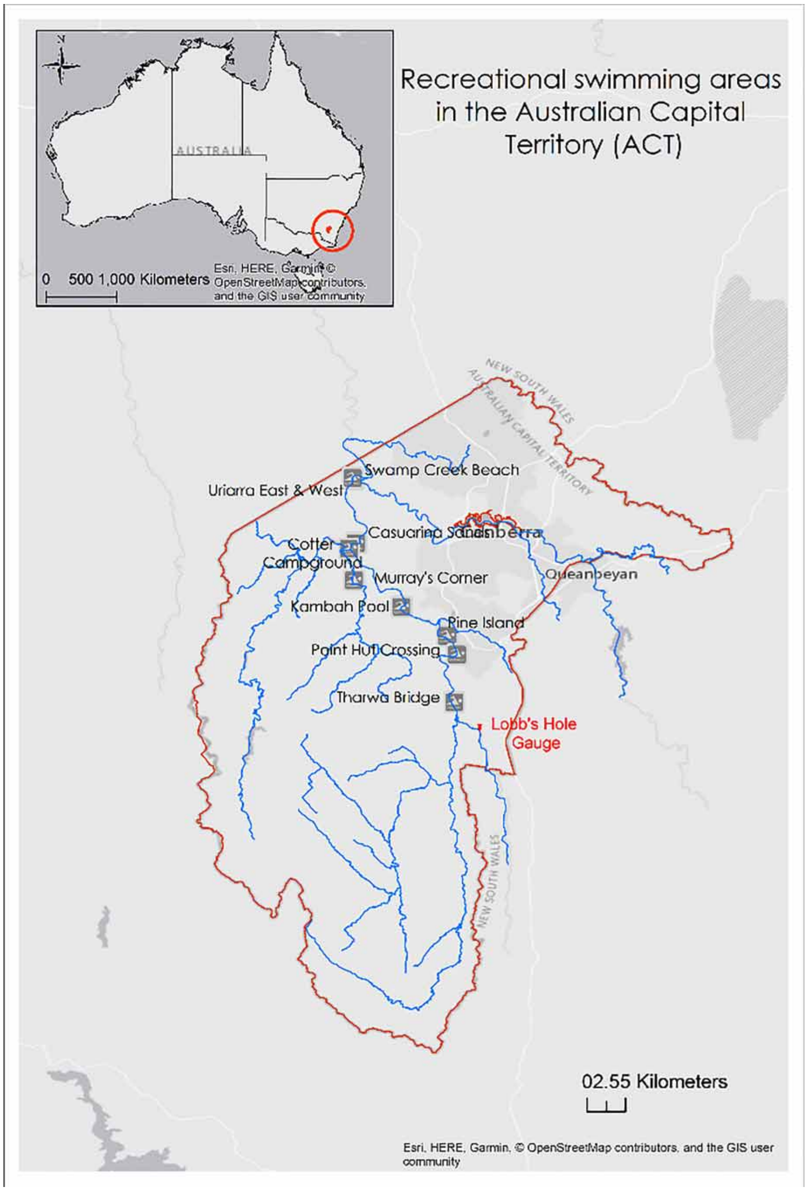


Figure 1 | Location of study sites along the Murrumbidgee River and its tributaries in the ACT, Australia.

where P is the probability that a given discharge value will be equalled or exceeded; M is the ranking of the discharge value; n is the number of values in the dataset.

Analyses were based on the flow exceedance probability (FEP) rather than daily streamflow, to account for the differences in streamflow between sites which make between-site comparisons problematic. Analyses focussed on exploring the relationship between intestinal enterococci count (CFU/100 mL) and FEP at each intestinal enterococci sampling location. Intestinal enterococci counts at Cotter Campground were examined with both the Cotter River flow and Paddys River flow to assist in determining whether tributary inputs from the Paddy's River better explain intestinal enterococci counts at the Cotter River swimming site. To further understand the possible role of antecedent flow conditions (e.g. 1–7 days prior to intestinal enterococci samples being taken), flow exceedance was lagged sequentially each day for up to 7 days. Antecedent flow variability was calculated as the difference between FEP and lagged FEP (daily, up to 7 days), divided by FEP. Antecedent flow variability was $\log_{10}(x+1)$ transformed prior to analysis to minimise the leverage due to outlier values.

$$V = \frac{\mathrm{FEP}_i - \mathrm{FEP}_0}{\mathrm{FEP}_0}$$

where i is between 1 and 7 days preceding, and 0 is the day on which the intestinal enterococci sample was collected. V is the antecedent flow variability; FEP is the flow exceedance probability.

A single *in situ* water quality sonde is located on the Murrumbidgee River at the upstream margin of the ACT (Lobbs Hole, gauge #410761; Figure 1). This sonde records water quality parameters (turbidity, water temperature, dissolved oxygen, pH, and electrical conductivity) at 15-min intervals. Time-weighted mean daily values were calculated for each parameter for analysis. Missing data (e.g. due to equipment malfunction) were not infilled or replaced, as no alternate data source was available. Water quality data were standardised (centred and scaled to mean = 0 and standard deviation = 1) both within year, and within month and year to remove annual and seasonal patterns from the data. Given the extreme variability in mean daily turbidity, turbidity data were also categorised into 'low' and 'high' turbidity, based on the recommended threshold value (25 Nephelometric Turbidity unit (NTU)) presented in the ANZECC guidelines for upland rivers in south-eastern Australia (ANZECC & ARMCANZ 2000).

2.2.3. Traffic count data

Road traffic count data were obtained from ACT Parks and Conservation Service for the Murrumbidgee River corridor. Vehicular traffic into carparks at some of the swimming sites has been monitored periodically since 2011. Data are collected from traffic counters on the first day of each month. Where there were missing data (due to equipment malfunction, theft, or vandalism) no attempt was made to infill or replace the missing data, as no reference data were available.

2.3. Statistical analysis

Relationships between $\log_{10}$ transformed intestinal enterococci concentrations (CFU/100 mL), water quality parameters (both raw and standardised), and streamflow characteristics, including flow exceedance and antecedent flow exceedance variability were examined. Intestinal enterococci concentrations were $\log_{10}(x+1)$ transformed due to non-normally distributed modelled residuals, which were adequate after transforming the response variable. Intestinal enterococci count data for the three sites closest to the Lobbs Hole streamflow gauge (Tharwa Bridge, Point Hut, and Pine Island) were examined for relationships with water quality parameters and the above-mentioned metrics for streamflow. Intestinal enterococci concentration and streamflow metrics were examined for every intestinal enterococci monitoring site. No attempt was made to apply the water quality data to other intestinal enterococci monitoring sites, as additional significant tributary inputs (including urban inflows) may lead to incorrect interpretations. A single model with all explanatory variables was fitted for each site to examine sources of variation in intestinal enterococci concentrations.

Tests for significant relationships ($\alpha = 0.05$) between $\log_{10}$ transformed intestinal enterococci concentration and streamflow and water quality were performed by linear regression. Models were fitted with generalised least squares (GLS) and an AR(1) autoregressive error structure to account for temporal autocorrelation in residuals. Explanatory variables were examined for collinearity prior to fitting. Suitability of model fit was examined for all fitted models, through examination of model residuals and Akaike Information Criteria (AIC) values.

To inform whether the prediction of high intestinal enterococci could be undertaken using streamflow and/or water quality data to inform future management of the public health risks, a repeated k-folds cross-validation analysis was conducted to test the efficacy of a linear model to predict high (>200 CFU/100 mL) intestinal enterococci concentrations at each monitoring location. Intestinal enterococci data were converted to a binary variable, around the management threshold of 200 CFU/100 mL. The dataset was split into five randomly selected blocks, with four used for training and one for validation. Each block was sequentially used as the validation set, with the remaining used for training the model. This was repeated 100 times (with data randomly assigned to blocks after each iteration) to evaluate model performance. Variability in model performance was explored, and residual risk to the community was inferred through relative changes in recreational water quality. Monthly traffic counter (2011–2020) data for sites where data were available were standardised by site and plotted against the proportion of intestinal enterococci samples exceeding 200 CFU/100 mL per month to visually examine any potential correlation between visitation rates and increased risk of exposure to high intestinal enterococci concentrations.

3. RESULTS

3.1. Intestinal enterococci concentrations varied both spatially and temporally

Intestinal enterococci count data (CFU/100 mL) varied spatially across the nine river swimming sites sampled (Figure 2). Temporal variation was seen with both annual and seasonal patterns (Figures 2 and 3). Murrays corner (Paddys River) exhibited the highest (mean ± standard error (SE)) intestinal enterococci counts over the period of study (436 ± 80), with Kambah Pool exhibiting the lowest mean intestinal enterococci counts (118 ± 15). February had the highest mean intestinal enterococci counts (426 ± 83), while September had the lowest counts (42 ± 9). February had the highest percentage (nearly 34%) of occasions where the CFU was >200 CFU/100 mL (Supplementary Material, Table 1).

Advised periods of no primary contact recreation varied through time and between swimming sites (Figure 3). This was further compounded by the change in ACT Guidelines for Recreational Waters, that occurred between the 2013/14 and 2014/2015 swimming seasons. Casuarina Sands exhibited the lowest average number of days advised closed to primary contact recreation (11.36 ± 3.67), while Murrays Corner on the Paddy's River exhibited the highest average number of days advised to be closed (104.91 ± 24.12) (Figure 3).

3.2. Intestinal enterococci varied with flow duration, antecedent flow exceedance variability, and turbidity

At high levels of turbidity, there was an inverse association between FEP and enterococci counts (Figure 4). This relationship held at all sites, except Paddys River, Cotter River, and Casuarina Sands which exhibited no significant relationship between flow exceedance and intestinal enterococci counts (Supplementary Material, Table 2). Inclusion of Paddys River flow to explain variation in intestinal enterococci counts in the Cotter River provided a better model fit than using the Cotter River discharge (AIC: 415.69 vs. 433.52). An examination of public visitation to swimming sites suggests there is a strong seasonal pattern in traffic counts with the largest standardised counts occurring in December, and the lowest in June (Figure 5).

3.3. Model performed well at predicting high-flow intestinal enterococci, but poorly at low flow

The inclusion of water quality parameters further revealed that high turbidity associated with high-flow periods is positively associated with increased intestinal enterococci counts, whereas high flow associated with lower turbidity was not associated

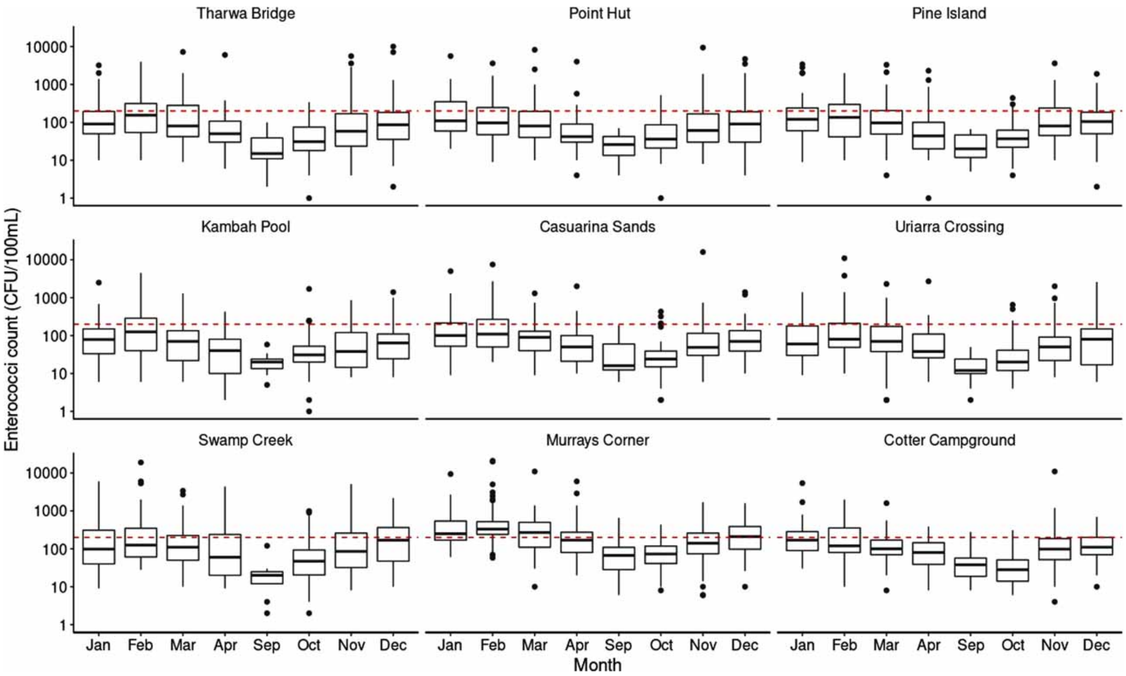


Figure 2 | Box-and-whisker plots of intestinal enterococci count (CFU/100 mL) by month for nine river swimming locations in the ACT 2009–2019, on $\log_{10}$ scale. The red dashed line indicates the management threshold of 200 CFU/100 mL, over which swimming locations are advised as closed to primary contact recreation due to intestinal enterococci counts. See Figure 1 for map of sampling locations. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wh.2022.294.

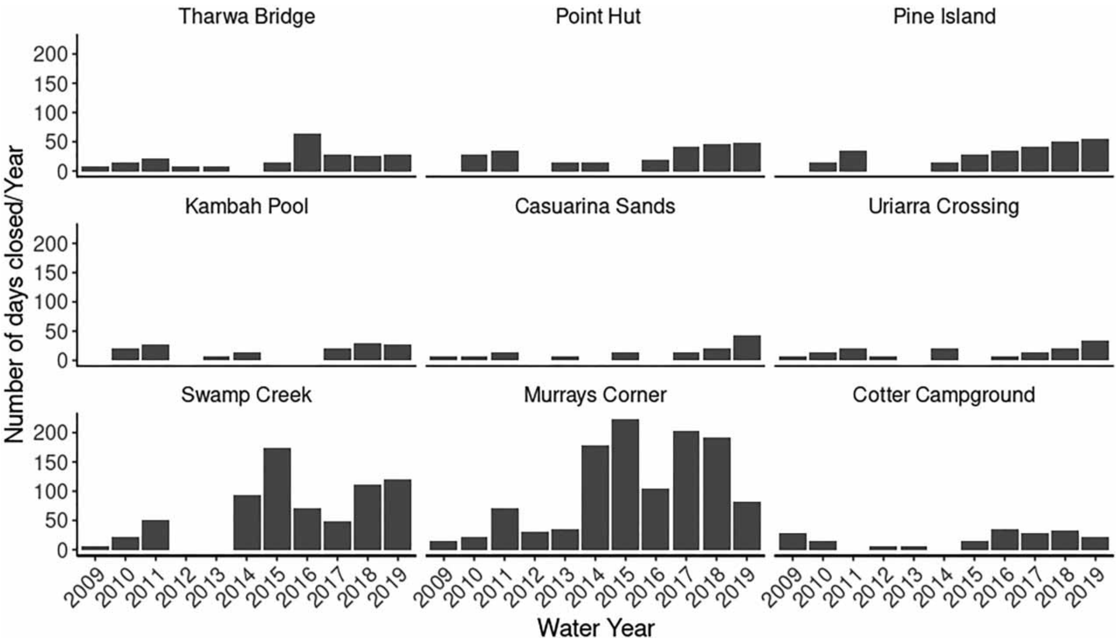


Figure 3 | Putative number of days each site was advised as closed to primary contact recreation due to intestinal enterococci counts per year from Spring 2009 to Autumn 2020. Note that year is the water year (July–June), with the swimming period defined as September–April.

Table 1 | Model summary showing the prediction classification accuracy (proportion of samples correctly classified as >200 CFU/100 mL, mean and range) for all data, proportion correctly classified as >200 CFU/100 mL under high flow (FEP < 50), proportion correctly classified as >200 CFU/100 mL under low flow (FEP > 50), and RMSE for fitted models

Site	All data	High flow	Low flow	RMSE (all data)
Tharwa Bridge	0.82 (0.80–0.83)	0.60 (0.54–0.68)	0.12 (0.06–0.16)	0.52 (0.51–0.54)
Point Hut	0.85 (0.83–0.86)	0.59 (0.53–0.67)	0.13 (0.05–0.2)	0.49 (0.48–0.51)
Pine Island	0.85 (0.83–0.86)	0.59 (0.53–0.64)	0.14 (0.05–0.25)	0.49 (0.48–0.51)
Kambah Pool	0.86 (0.84–0.87)	0.33 (0.29–0.40)	0.07 (0–0.15)	0.47 (0.46–0.49)
Casuarina Sands	0.88 (0.87–0.88)	0.39 (0.36–0.44)	0.16 (0.08–0.17)	0.46 (0.45–0.49)
Uriarra Crossing	0.87 (0.86–0.87)	0.40 (0.35–0.46)	0.18 (0.10–0.20)	0.45 (0.44–0.47)
Swamp Creek	0.77 (0.76–0.79)	0.49 (0.41–0.56)	0.16 (0.13–0.21)	0.52 (0.52–0.53)
Paddys River	0.70 (0.68–0.71)	0.71 (0.67–0.75)	0.60 (0.55–0.62)	0.42 (0.41–0.45)
Cotter River	0.79 (0.78–0.80)	0.29 (0.23–0.32)	0.04 (0.02–0.07)	0.42 (0.41–0.43)
Cotter River/Paddys Flow	0.81 (0.80–0.82)	0.49 (0.45–0.52)	0.004 (0–0.04)	0.40 (0.39–0.42)

Mean and range calculated from 100 iterations of a *k*-folds cross-validation ($k = 5$).

with higher intestinal enterococci counts. Antecedent flow conditions up to 7 days prior were associated with intestinal enterococci counts, with increased variability in antecedent flow exceedance being associated with high intestinal enterococci counts (Supplementary Material, Table 2).

Linear models exploring the relationship between intestinal enterococci counts, flow exceedance, antecedent flow variability, month, turbidity, and site explained 47.9, 40.3, and 40.8% of the variation in intestinal enterococci counts at Tharwa Bridge, Point Hut, and Pine Island, respectively (Supplementary Material, Table 3). Flow exceedance, flow exceedance variability, and month were all significant predictors at all sites.

A *k*-folds validation produced a root mean square error (RMSE) of 0.525 (range 0.515–0.54) for Tharwa Bridge. Overall, minimal variability in RMSE indicates that models are robust (Table 1). Model prediction efficiency for high flow (flow exceedance percentile <50) and high intestinal enterococci counts (>200 CFU/100 mL) was variable, with a range of 29.67%

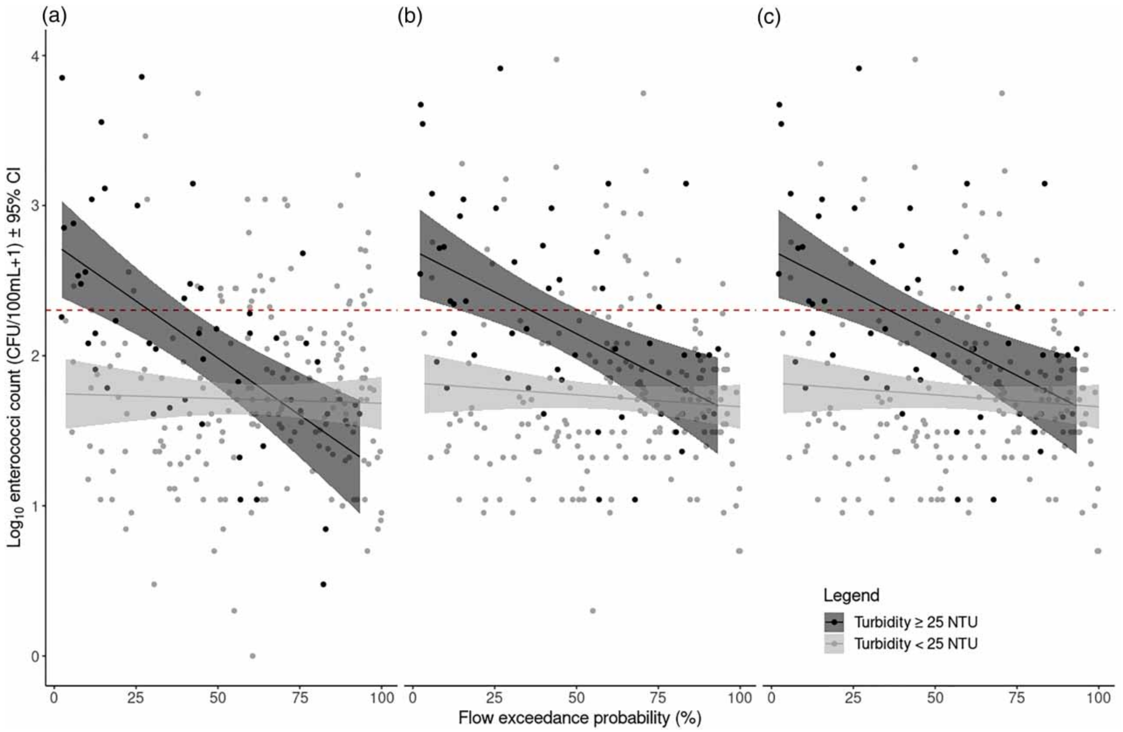


Figure 4 | Relationship between log$_{10}$ intestinal enterococci concentration (CFU/100 mL), streamflow exceedance probability and turbidity at (a) Tharwa Bridge, (b) Point Hut Crossing, and (c) Pine Island on the Murrumbidgee River. Red dashed line denotes the management threshold of 200 CFU/100 mL. Increased intestinal enterococci concentrations at higher stream flows is associated with high turbidity ($\geq$25 NTU). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wh.2022.294.

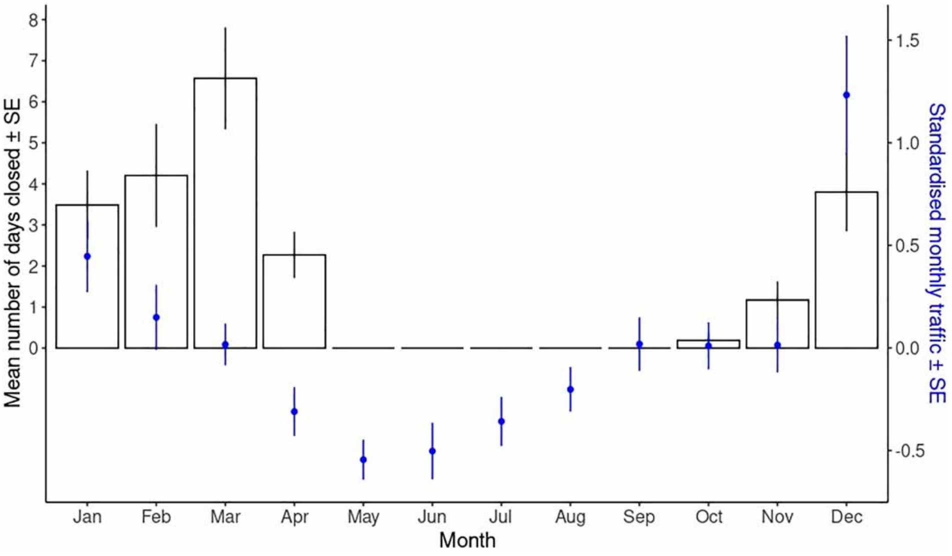


Figure 5 | Mean number of day sites were advised as closed to primary contact recreation due to intestinal enterococci $\pm$ SE (black) (2009–2020) by month, and standardised monthly traffic counts $\pm$ SE (blue) for recreational swimming sites (2010–2019). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wh.2022.294.

correct (the Cotter River with the Cotter River flow) to 71.24% correct (Paddys River). Conversely, the prediction accuracy of high intestinal enterococci under low-flow conditions (flow exceedance percentile >50%) was poor, ranging from 0.47% correct (the Cotter River with the Paddys River flow) to 16.74% correct (Casuarina Sands).

4. DISCUSSION

Overall, the current study found that extreme flows (high and low) were consistently associated with high intestinal enterococci concentration. We found a consistent positive relationship between high (>200 CFU/100 mL) intestinal enterococci concentrations, turbidity equal to or greater than 25 NTU, and high-flow conditions. High flows are commonly associated with the elevated FIB concentrations. Storm runoff, land-use such as agriculture, and stormwater drain inputs have been implicated as a key driver of short-term increases of intestinal enterococci in freshwater systems (Coffey *et al.* 2013; Daly *et al.* 2013; Chu *et al.* 2014). Disturbance of riverbeds – whether through increased streamflow, direct disturbance from users or livestock, or other means – has been found to resuspend sediment and FIB within sediments (Cho *et al.* 2010b; Cho *et al.* 2016) leading to a secondary non-point source of FIB contamination. The consistent association with high turbidity during elevated flow conditions may be partly attributed to the resuspension of sediments within the stream channel during high-flow conditions, which is known to increase the pathogen and FIB levels in the water (Anderson *et al.* 1997; Gao *et al.* 2013; Abia *et al.* 2017). Suter *et al.* (2011) also found enterococci concentrations positively correlated with turbidity. Increased turbidity may also limit the amount of solar radiation penetrating the water column, decreasing its potential to inactivate microbial contaminants (Williamson *et al.* 2017). Previous studies have modelled the effect of solar irradiance on FIB under high- and low-flow conditions (Deely *et al.* 1997; Coffey *et al.* 2013; Herrig *et al.* 2019). Herrig *et al.* (2019) showed that global solar irradiance was inversely associated with the FIB concentrations. Discharge from urban land-use can cause browning of surface waters, with the potential for highly turbid conditions. Our study highlights the implications of such conditions for the public health risks associated with recreational use in such waterways (Meyer *et al.* 2005).

There is limited literature that examines the association between low-flow conditions and high intestinal enterococci levels. Increased microbial loads due to point sources during low-flow periods can occur due to reduced dilution as a result of reduced water volumes (Thilakarathne *et al.* 2018). Using 4 years of data on Mediterranean coastal river in low-flow conditions, Chu *et al.* (2014) found that bacteria were stored in riverbed sediments forming in-stream stores that were the source of elevated bacterial levels during the first flush event. In addition to bacteria persistence during low-flow conditions, the source of these bacteria may also be different. Due to point and non-point sources of FIB present in sediments, the persistence of FIB in sediments may be highly variable. Previous studies in Australia's Murray Darling Basin have shown that when relative discharge is controlled for, water temperature is positively associated with high cyanobacteria abundance (Lal & Hargreaves 2020). Therefore, high water temperature associated with low flows may also partly explain the high enterococci levels.

The inclusion of water quality parameters (namely, turbidity) improved the ability to model and predict high intestinal enterococci concentrations. Numerous studies previously have demonstrated that both external loading from catchments, in addition to internal resuspension of FIB within waterways during high-flow events, can lead to increased FIB concentrations (Jamieson *et al.* 2005; Cho *et al.* 2010a; Walters *et al.* 2014; Ribolzi *et al.* 2016). Across aquatic systems globally, increased turbidity is commonly associated with intensification of land-use and poor riparian zone condition and management (Smith *et al.* 2013; Terry *et al.* 2014; Davis *et al.* 2015). Within the upper Murrumbidgee River catchment, gulley erosion has been historically problematic, however, this is now considered to be less so than previously (Olley & Wasson 2003). Conversely, poor riparian condition evidenced by the loss of riparian zone depth and complexity (O'Reilly *et al.* 2021) and access by livestock to watercourses may be a significant source of both FIB and continued deposition of sediments to waterways. There is potential for riparian zone restoration, fencing of livestock out of riparian zones to contribute to improved riparian zone condition, and reduced inputs of FIB and sediments to the Murrumbidgee River, leading to overall improved waterway conditions and reduced risk to public health.

4.1. Study limitations, management implications, and further work

Results from this study highlight the ability to predict intestinal enterococci concentrations using routinely collected hydrological and water quality parameters. A strength of this study lies in the consistently high accuracy of prediction with high-flow conditions, suggesting that water quality parameters could be used alongside flow data for other sites to predict intestinal enterococci concentration. Equally important is the consistent finding of low prediction accuracy of high intestinal enterococci concentration at low-flow conditions, indicating the potential importance of non-point sources of contamination, including humans. Collectively, study findings provide a clearer distinction of the potential drivers and therefore management options for reducing intestinal enterococci concentration at high- and low-flow conditions across multiple sites using routinely collected data.

Timeliness is a key metric when assessing the effectiveness of a public health response. Our results highlight the potential impact of the time delay between sample collection and the reporting of results. In the current study, results of samples collected on a Monday/Tuesday were only reported later in the week. Due to this, our analyses were conducted at the weekly scale. The strong association between high flow and high enterococci concentrations suggests that a quicker turnaround of samples would assist with more responsive health risk communication. However, it may be argued that if there is very high rainfall across most days of the week, then the current regime of data collection and reporting is adequate. What our analysis and the current operational system cannot capture is high-flow events that are of very short duration (e.g. less than a day). However, people are unlikely to use these sites when flow is very high, i.e. exposure is low, suggesting that a time lag of 48 hours may not result in a large variation in the potential health risk. Evaluation of the timeliness of any environmental and public health surveillance systems depends on the purpose and goals of the surveillance system. Our findings provide a starting point to discuss the development of timely environmental early warning systems to protect public health.

Our limited prediction accuracy of high intestinal enterococci concentrations during low-flow conditions using water quality parameters combined with the high visitation rates to these locations during this time suggest a role of human sources of contamination including pets, children in nappies, and swimming stirring up sediments. Elmir *et al.* (2007) found that bathers transport a significant amount of intestinal enterococci and staphylococcus aureus into the water column. In Florida, management actions that included restricted pet access, bird management policies, and access fees were associated with a lower frequency of intestinal enterococci exceedances (Kelly *et al.* 2018). Intestinal enterococci does not identify the specific pathogens that are capable of causing human illness. The presence of high concentrations of FIB in water is indicative of faecal contamination, but due to their ubiquitous presence, concentrations alone do not provide information on the source(s) of contamination (Codello *et al.* 2021). For example, human faecal pollution typically presents the greatest risk because of the possible presence of human pathogens, while cattle manure may be a close second because of the possible presence of zoonotic pathogens such as *Cryptosporidium* spp. and enteropathogenic *E*scherichia *coli*. Microbial source tracking methods and environmental DNA (eDNA) barcoding can help identify sources of faecal contamination in complex environments (Yan & Sadowsky 2007; Staley *et al.* 2018). When combined with different base flow conditions, such nuanced information can help inform management options to reduce non-point sources of contamination, while protecting public health.

Regression-based models such are useful in operational contexts and for short-term predictions, but cannot be used to understand underlying processes, which is achieved mainly through the use of mechanistic models (de Brauwere *et al.* 2014). Another approach is to use a Bayesian framework to predict bacterial water contamination in New York City Harbour. This approach provides the predictions with uncertainty ranges included in model output, which can help water managers to better assess the risk of contamination to water users. Linking such macro-ecological data with hydrological and health outcome data could provide evidence-based solutions to contemporary public health problems, and in turn help to develop locality-specific guidelines for water quality (Verhougstraete *et al.* 2020) that will enhance aquatic ecosystem health.

Including rainfall and the full range of hydrological characteristics and other drivers of contamination and flow would be important in future investigations. For example, a recent study of flow exceedance in relation to urban land-use has shown that impervious surfaces correlated with increased frequency of high-flow events in Missouri streams (Zeiger & Hubbart 2019). Although including rainfall is a natural extension of the current work, a similar modelling study in Hawaii showed that in addition to rainfall, including the relative change in discharge incorporates a proximate representation of the energy available to transport particulates, improving predictions of near-shore water quality (Strauch 2017). It is important to note that rainfall itself may not be a useful predictor of intestinal enterococci concentrations, due to the complex hydrology of water catchments. French (2012) used multiple regression analyses of rainfall and intestinal enterococci concentrations in coastal waters of southern New South Wales, and found no statistical significance between the two variables, although we acknowledge the difference between coastal waters and inland rivers. So, while including rainfall is important, discharge and flow may be better predictors of the proximate drivers of changing intestinal enterococci concentrations. Despite the limitations in the data and analytical framework used here, our results provide useful insights into high- and low-flow-related drivers of intestinal enterococci concentration across multiple sites over a long time period.

5. CONCLUSIONS

There is a need to monitor flow conditions for public health in natural, recreational swimming areas. Our findings, consistent across multiple sites over a long time period, indicate that management actions that relate to high- and low-flow events leading to increased intestinal enterococci in these inland systems may have to be different, with implications for the health risks associated with natural swimming areas globally. With climate change projections indicating a greater likelihood of reduced rainfall (and thereby streamflow) in southeast Australia, risks associated with low streamflow and increased FIB could grow. Similarly, with the intensity of severe storm events likely to increase under climate change projections, the risks associated with the increased FIB concentrations under higher flows could also increase. As the risk is anticipated to increase, enhancing the ability to predict and model FIB concentrations would enhance the timeliness of risk communication and therefore decrease the public health risks to the community.

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COMPETING INTERESTS

The authors have no competing interests to declare

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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