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Water-quality and ecosystem impacts of recreation in streams: Monitoring and management

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ABSTRACT

There is limited published information on the impact of bathing on stream water quality and ecology, except on human pathogens and health. We investigated the relationships between environmental quality of streams and recreational activity at five sites in the Australian Wet Tropics. The streams normally had very low concentrations of nutrients and suspended solids (TSS), but concentrations fluctuated widely during spates, thereby causing difficulties in discriminating impacts. Daily bathing activity disturbed sediments causing an increase in TSS and turbidity, which greatly exceeded national guidelines for maintenance of aesthetic qualities. TSS returned to background levels overnight as bathing areas were flushed clean. Total nitrogen and phosphate concentrations also increased with bather numbers, and phosphate concentrations were directly proportional to bather density. Faecal coliform concentrations were elevated by bathers at one site. Ecological effects of bathers were equivocal and greater on algal than invertebrate assemblages. Water quality degradation, although transient, suggested that some sites were close to their carrying capacity for bathers. Our results show that water quality may vary with local conditions and that cost-effective monitoring and management require development of cause-effect models of water quality processes for each stream site.

1. Introduction

Recreational (including tourism) activity in natural environments can cause impacts associated with travel, accommodation and direct environmental damage, which includes soil erosion and compaction, damage to vegetation, disturbance to wildlife and water pollution (Buckley and Pannell, 1990). Freshwater lakes and streams are significant foci for visitors and positively contribute to human well-being (Venohr et al., 2018), although their value is often poorly acknowledged (Hadwen et al., 2012). Managers of freshwater recreational sites are typically alert to water quality and its potential impairment, with water clarity and water quality important aspects of visitor appeal (Barnett et al., 2018). Understanding of visitor impacts is increasing but requires robust indicators useful for management (Buckley, 2003).

Research on the impacts of human activity on fresh waters has concentrated on the health risks of pathogens introduced through water contact (Anderson et al., 1998; Gerba, 2000; Wade et al., 2008) or human waste from infrastructure, camping or other activities (King et al., 1974; Liddle and Scorgie, 1980; Cooke and Xia, 2020). For example, bathing and wading increased suspended sediment concentrations and coliform densities in an Indian stream (Phillip et al., 2009), while visitor use of two streams in Puerto Rico appeared to have minimal effect on water quality (Santiago and Gonzalez-Caban, 2008). Giardiasis has been linked to bathing in freshwater bodies (Reses et al., 2018), but the links between pathogens (including protists) in fresh waters and infections are generally not clear, unlike associations at beaches (Dorevitch et al., 2015).

There is little published information on the effects of bathing on stream water quality and its relationship with ecology. Visitor impacts on fresh waters may be caused by direct habitat disturbance or water quality changes at the site or downstream. For example, in Brazilian streams, five-day intervals between periods of intense visitation were insufficient for benthic macroinvertebrate assemblages to recover (Escarpinati et al., 2014). However, teaching programs in which students actively sampled macroinvertebrates caused no impacts on the overall assemblages (Bossley and Smiley, 2019). Similarly, there was rapid recovery from trampling in streams in the Australian Blue Mountains (Hardiman and Burgin, 2011) and in Utah (Caires et al., 2010), reflecting the resilience of macroinvertebrates to physical disturbance (Rosser and Pearson, 2018). Sewage from a recreational site increased the concentration of nutrients and chlorophyll-a, and changed benthic algal assemblages in Bohemian streams (Lukavský et al., 2006). However, there is limited information on ecosystem effects of water quality deterioration.

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Tourism in northern Queensland is estimated to contribute $2 billion to the economy (Prideaux and Falco-Mammone, 2007). Although the major attraction is the Great Barrier Reef World Heritage Area, land-based tourism is growing in parallel, especially at sites in the Wet Tropics World Heritage Area (hereafter "Wet Tropics"). Streams are an important focus in this area for their aesthetic value and availability for bathing (WTMA 2013), particularly in the summer months, when bathing in the sea is restricted by box jellyfish. Possible environmental impacts of visitors on fresh waters include soil compaction and water contamination (Turton, 2005), but effects on water quality and ecology are not well known. Although impacts may be recognised by park managers at the individual site level, there appears to be limited realisation of this potential problem generally. For example, despite recognition of the importance of natural waterways, the Wet Tropics Management Authority does not identify recreation or tourism as having potential impact on water quality open (WTMA, 1998; WTMA 2013). In order to sustain the attraction and ecological integrity of these sites, it is necessary to understand impacts and avoid increasing pressure by using appropriate people-management strategies.

We aimed to understand the water quality and ecological impacts of wading and swimming (collectively termed "bathing" here) in Wet Tropics streams. Bathing might affect water quality by introduction of contaminants from the bather's body (e.g., nutrients, pathogens) and from disturbance of stream sediments. Effects are expected to vary with time of day and year, with most intense activity during late morning to mid-afternoon on weekends and holidays. Frequent disturbance to ecological assemblages may cause changes to species composition, productivity and food webs as a result of disturbance of substrata and increased turbidity and nutrient concentrations.

Stream water quality in the pristine forests of the Wet Tropics is generally high. It may be characterised as warm (mostly > 18 °C), slightly acid or neutral (pH 5.5–7.2), with low conductivity (< 100 µS/cm) and low nutrient concentrations (total $N < 200$ µg/L and total $P < 10$ µg/L; nitrate < 30 µg/L N and phosphate < 5 µg/L P) (Pearson et al., 2017; Pearson et al., 2019). The invertebrate fauna of the region is diverse (Pearson and Boyero, 2009; Pearson et al., 2017). Surveys of visitors to Wet Tropics stream sites showed that perceived water quality (mainly water clarity) and the number of people at the site were major factors determining the quality of the visitors' experiences (Butler et al., 1996). Visitors included about 62% from the local area ("recreational users") with the rest ("tourists") being from further afield in Australia (22%) and overseas (16%).

We selected five popular sites that were expected to have different levels of impact because of different visitation rates, different flow regimes, and likely capacity of the environment to absorb impacts. We measured water quality variables and their fluctuations, and biological indicators (Rosenberg and Resh, 1993), in relation to the number of recreational users. Sampling was undertaken during holiday and non-holiday periods. We predicted that recreational use of streams would have measurable effects on water quality and ecosystem health, proportional to the intensity of visitor use. We aimed to develop a conceptual model linking interactions between humans, stream water quality and ecology with a view to developing cost-effective monitoring and management.

2. Methods

2.1. Study area

The Wet Tropics stretches in a coastal band from Cooktown 450 km south to Townsville (Fig. 1). The climate of the area is tropical, with a hot wet season and warm dry season (Table 1). On the coast, annual rainfall varies from about 1100 mm in Townsville to 4500 mm in the Tully area, while over 12,000 mm has been recorded on Mount Bellenden Ker. Stream flow closely follows the pattern of rainfall (Cassells et al., 1985; Clayton and Pearson, 2016), with spates common in the summer. Streams descend rapidly from the mountains to the floodplain. They are typically rocky with many falls and cascades and are of great scenic value. Natural vegetation includes rainforest, open forest and woodland. Most lowland forest has been cleared for agriculture. Many tourism and recreation activities focus on sites with waterfalls and bathing areas, both in the uplands and at lower elevations close to the boundary between forest and agricultural land.

2.2. Study sites

We selected five study sites, which represent the most popular freshwater sites for bathing in their immediate districts and spanning most of the latitudinal extent of the Wet Tropics, from Mossman River in the north to Little Crystal Creek in the south (Fig. 1; Table 1; supplementary Fig. S1). Four sites were situated at < 100 m elevation and one (Little Crystal Creek) was at 360 m. Annual visitation rates vary from tens to hundreds of thousands. At each site we selected a "treatment reach" that was used for bathing and an adjacent "control reach" as close upstream as possible, being similar to the treatment reach but not used for bathing.

The Mossman River site (Mossman Gorge) had the highest visitation rate and the largest catchment of the study sites. It is situated at the southern end of the Daintree National Park, 80 km north of Cairns in a granite gorge, in a rainforest setting. The river has numerous tributaries and perennial strong flow, with no distinct, separate pools. Bathing occurs along about 150 m of the stream. Control reaches were located on the two major tributaries upstream of the treatment reach but conductivity measurements showed that water quality at the treatment reach was not simply related to discharge from the two tributaries, which therefore were not ideal controls.

The Babinda Creek site (the Boulders) is situated on the edge of Wooroonooran National Park in rainforest. The stream has many outcrops of granite and cascading perennial flow. The treatment reach included in a series of pools up to 4 m deep. The control reach was a major tributary that was occasionally turbid because of local rainfall, but an alternative major tributary provided a suitable control.

Five Mile Creek is a short stream located in the Cardwell State Forest. Its catchment includes forested mountains and a short coastal plain. The natural vegetation of the plain is woodland, but much of this has been replaced by pine plantations and banana growing, although riparian vegetation is largely intact. The stream occasionally ceases to flow in the dry season, but larger pools are permanent. Bathing is focused on a 50-m-long pool less than 2 m deep. The control reach was close to and morphologically similar to the bathing reach.

Little Crystal Creek and Crystal Creek are located in the Paluma Range north-west of Townsville. The streams descend rapidly from the escarpment and continue to flow in most years, but occasionally surface flow ceases, leaving permanent pools. Little Crystal Creek is a clear rainforest stream that descends through a series of cascades, falls and pools, and around massive outcrops of granite. Bathing occurs in several pools with depths to about 4 m. The control reach was close to and morphologically similar to the bathing reach.

Crystal Creek is located where the mountains meet the coastal plain, amongst open forest. A series of large pools is connected by flowing sections. Bathing mainly occurs in one large pool, which has a depth of 1 to 5 m. The control reach had to be located 2 km upstream to avoid bathers, making natural water quality differences possible.

2.3. Sampling

We sampled across several days during two holiday and adjacent non-holiday periods: the Australia Day holiday and the subsequent weekend at the end of a prolonged dry season (January 25–31, 1995) at Little Crystal Creek, Crystal Creek, The Boulders and Mossman Gorge; and over the Easter holiday period, at the end of the wet season (April 12–18, 1995) at Five Mile Creek, Little Crystal Creek and Mossman

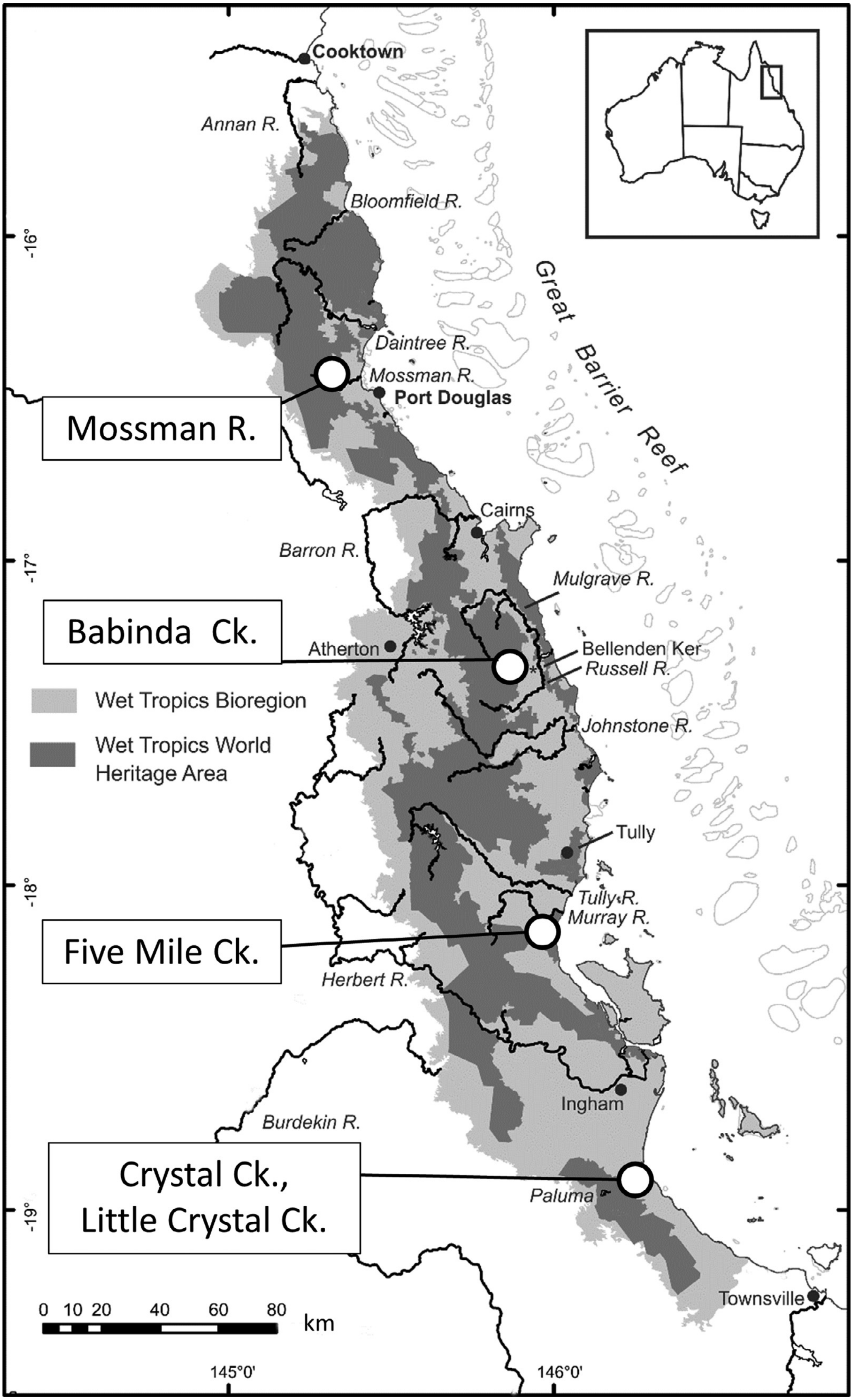

Fig. 1. Locations of study sites in the Australian Wet Tropics bioregion.

Table 1
Characteristics of the study sites.

	Mossman R. Gorge	Babinda Ck. Boulders	Five Mile Ck.	Crystal Ck.	Little Crystal Ck.
Latitude/longitude	−16.472/145.332	−17.343/145.869	−18.3728/146.046	−18.980/146.254	−19.016/146.266
Catchment area (km^2)	88	33	17	42	5
Elevation (m)	90	45	27	48	360
Catchment vegetation	Rainforest	Rainforest	Rainforest, open forest, plantation	Rainforest, open forest	Rainforest
Stream order	4	3/4	3	4	3
Temperature – mean maximum °C (December)†	32.2	30.8	31.8	32.0	32.0
Temperature – mean minimum °C (July)†	17.4	15.4	14.0	13.7	13.7
Rainfall – mean annual (mm)†	2399	4270	2114	2030	2030
Rainfall – monthly CV (%)	88.9	68.6	90.7	92.3	92.3
Flow	strong	strong	often low	often low	usually strong
Bathing area (m^2)	3000	2000	400	1500	800
Annual visitor count*	423,607	85,481	51,000	61,520	63,566#
Disturbance at site**	Significant human impact	Some human impact	N/A	Significant human impact	N/A
Disturbance in catchment	low	low	moderate	moderate	low

*Wet Tropics Management Authority data and **classification of site; †closest weather stations: Mossman, Babinda, Cardwell, Ingham.

Gorge. Data from the January samples indicated that effects of bathing would be most easily monitored at Little Crystal Creek, which was therefore the subject of more frequent sampling in the Easter period.

Head counts of bathers were made at each treatment reach on each sampling day at 20-minute intervals over busy periods, but with reduced frequency when there were few people in the water. Samples of water, algae and invertebrates were collected from control sites upstream of bathing activity, and at the downstream end of pools used for bathing during the same sampling periods (water samples), or in riffles downstream of these pools (algae and invertebrates). On average, we collected 12 water samples from the control reaches and 17 from the treatment reaches at each site.

Water temperature, pH and conductivity were measured in the field using YSI instruments previously calibrated following the manufacturer's instructions. Water samples were collected from 20 to 30 cm below the water surface directly into sample bottles and preserved for subsequent analyses. Bottles were selected in accordance with requirements for preservation specified by Australian Standard 2301.1. Samples for nutrient analyses were filtered, using Sartorius 0.45-µm cellulose acetate filters, then stored in gamma-sterilised plastic tubes and snap frozen upon arrival at the laboratory (a commercial water analysis laboratory in the Australian Centre for Tropical Freshwater Research at James Cook University). Preservation procedures followed (APHA 2017) except that some frozen nutrient samples were stored for up to 2 months. Quality control tests conducted by the laboratory have shown that samples preserved in this manner can be stored for at least 12 months.

Water clarity was measured by three methods: sighting a horizontal black disc in the field and, in the laboratory, nephelometric turbidity measurement (NTU) and gravimetric analysis of total suspended solids (TSS). The horizontal black disc was used as it reflects human perceptions of water quality (Davies-Colley and Smith, 1990), but instream obstructions restricted its use at some sites. Total nitrogen and phosphorus digestions were performed simultaneously using the persulphate digestion procedure of (Hosomi and Sudo, 1986). All other analyses, including the determination of nitrate and phosphate in persulphate digests, were performed using procedures based on (APHA 2017) standard methods. Nutrient analyses were performed using conventional colorimetric techniques on an Alpkem Flow-Solution Auto Analyser. Phytoplankton biomass was estimated by measuring chlorophyll *a* concentrations.

Faecal contamination levels at the study sites were measured using presumptive faecal coliform tests following APHA standard methods by collecting organisms on membrane filters and culturing in M-FC medium at 44.5 ± 0.2 °C, commencing within 24 h of collection. Colonies with typical colour and morphology were counted and presumed to be faecal coliforms. Results were reported as colony forming units (cfu)/100 ml.

2.4. Invertebrate and algal samples

Invertebrates were sampled from individual stones in a control and treatment riffle at each site. Ten stones of similar size (~100 mm diameter, $\varphi = -6$) were selected and individually transferred underwater to a collecting net (mesh size 250 µm). The rocks were gently brushed then scrubbed to remove invertebrates, which were preserved in 80% ethanol. In the laboratory, invertebrates were identified by experienced laboratory staff (Pearson et al., 2017) using available keys (Cairns et al., 2017) and counted.

Algal growth was investigated on stones in riffles at control and treatment reaches. Similar stones to those sampled for invertebrates were collected from a single location and were cleaned and sterilised, then placed at the sample locations for two months. On recovery, they were scrubbed clean in a 63-µm net, the contents of which were held on ice in the dark. In the laboratory, invertebrates were removed from each sample. Epilithon growth was investigated by measuring dry mass of samples oven dried at 60 °C, and chlorophyll *a* and phaeophytin content, by means of acetone extraction.

2.5. Data analysis

We calculated correlation coefficients and regressed water quality data against time of day using linear or curvilinear models in SigmaPlot 12.5 (Systat Software, Inc., San Jose, California). Regressions of bather numbers against time of day showed strong relationships (see below), so time of day was used as the independent variable in order to capture cumulative effects. We compared water quality variables between control and treatment reaches using the non-parametric Wilcoxon rank sum test in Statistix 10 (Analytical Software, Tallahassee, Florida, USA), because of non-normality of data (Fu and Wang, 2012). We also analysed data expressed as percentage change between control and treatment reaches, to allow comparisons between sites with different ambient concentrations. For the two tributaries at Babinda Creek, the control observations were combined, weighted by discharges from the two streams. This approach was not feasible for the Mossman River because of unmeasured inputs.

Multivariate invertebrate data were square-root transformed and analysed using Primer ver. 6.1.2 (PRIMER-E Ltd, Plymouth, UK (Clarke and Gorley, 2006; Anderson et al., 2008)). Relationships amongst samples were illustrated by ordination using non-metric multidimensional scaling (NMDS), and analysed for differences amongst sites and between control and treatment samples using two-factor PERMANOVA, with 999 iterations, such that the minimum value of P was 0.001. Mass of algae on stones was compared between control and treatment reaches using analysis of variance (ANOVA) followed by Tukey

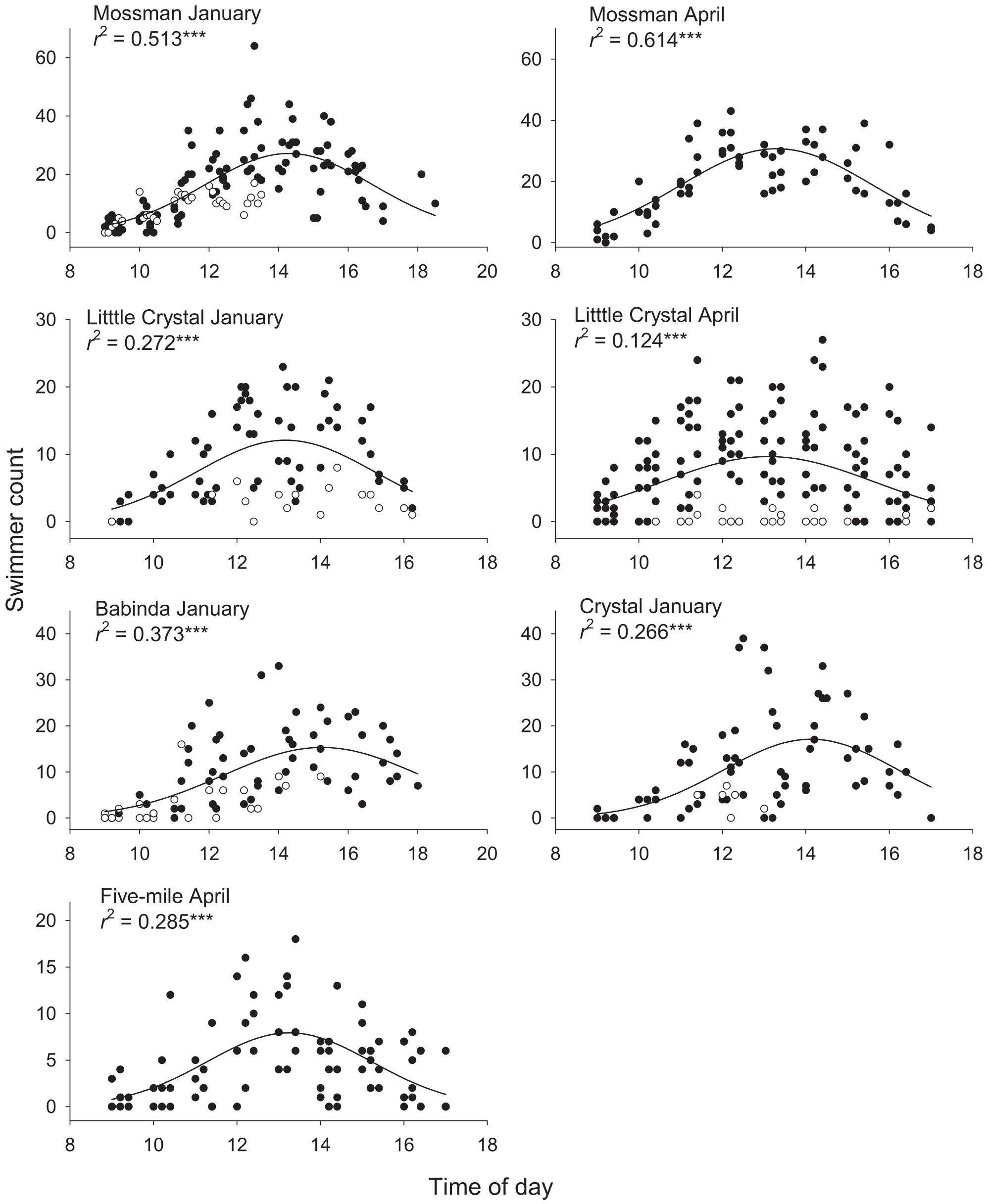

Fig. 2. Bather ("swimmer") counts through the day at study reaches. Black symbols represent holidays, grey symbols represent non-holidays. Regression lines (peak model) relate to holiday periods only. ***All regressions significant at $P < 0.0001$): Mossman, F2, 124 = 65.23, and F2, 63 = 50.03; Little Crystal, F2, 74 = 13.85 and F2, 169 = 11.95; Babinda, F2, 77 = 22.88; Crystal, F2, 70 = 12.70; Five Mile, F2, 84 = 16.73.

tests in Statistix. We also compared the ratios of chlorophyll *a* to total phaeophytin as an indicator of possible differences in species composition or growth phase of algae.

3. Results

3.1. Bather counts

Although bather numbers varied substantially at particular times of day and with time of day, their relationships with time of day were very strong, with peak counts between mid-day and mid-afternoon (Fig. 2).

3.2. Water quality

Background water quality was broadly similar amongst study locations (Table S1), but varied with local rainfall. Dissolved inorganic nitrate and phosphate concentrations were low at all locations. N: P ratios at control reaches were 13.8 and 14.8 (Mossman tributaries), 18.7 (Crystal and Little Crystal creeks), 22.5 and 23.9 (Babinda tributaries) and 33.0 (Five Mile Creek). The control-reach faecal coliform concentrations of 230 – 270 cfu/100 ml at Mossman River 170 – 330 and cfu/100 ml at Babinda Creek would place these streams as category C waters by the (ANZG Australian 2018) guidelines, on a scale of A (low risk) to D (high risk) based on marine waters. Concentrations at other control reaches were within category A.

Correlations amongst 11 water quality variables indicated that phosphate concentration correlated strongly with five other variables (pH, TSS, ammonia, total N, and total P concentrations) and total P concentration largely reflected this (Table S2). The remaining nine variables correlated with two or fewer others. After initial inspection of correlations and plots of water quality against time of day at each site and in January and April samples, we selected for illustration those that appeared to have a linear or curvilinear relationship ($P < 0.10$), or those that had differences between control and treatment samples, according to the Wilcoxon test, with $P < 0.05$ (Tables S3 and S4). We used the correlation cut-off of $P < 0.10$ for selecting relationships to illustrate, but we only discuss relationships where $P < 0.05$ (Fig. 3, Mossman River, Babinda Creek, Five Mile Creek and Crystal Creek; and Fig. 4, Little Crystal Creek).

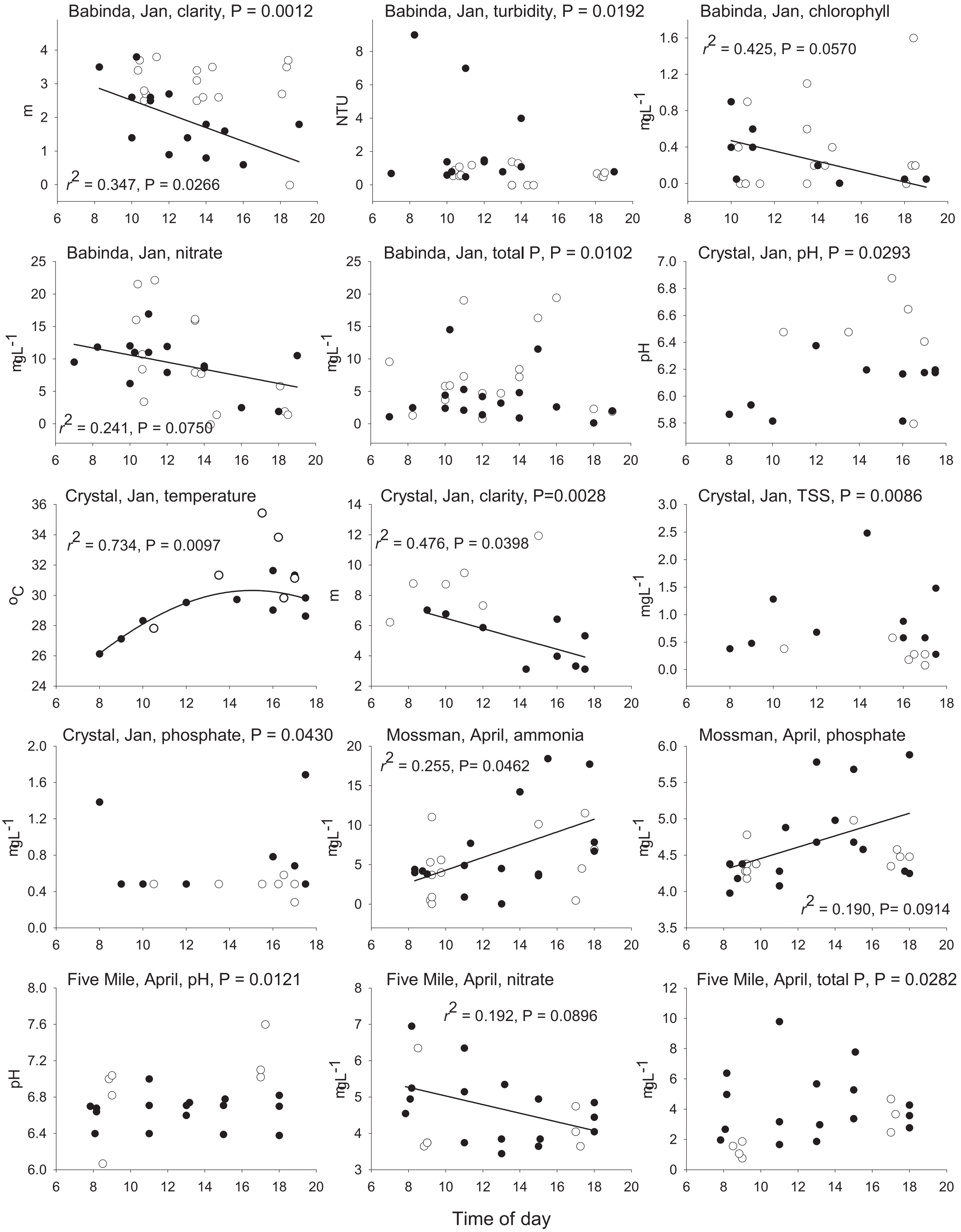

Fig. 3. Summary of significant water quality relationships at four reaches in January and April. Values of P in heading indicate differences between control and treatment samples (Wilcoxon test, see Table S4 for details). r2 and associated P values are derived from the regressions illustrated (linear or peak models; treatment reaches only). Open symbols represent control data; filled symbols represent treatment data.

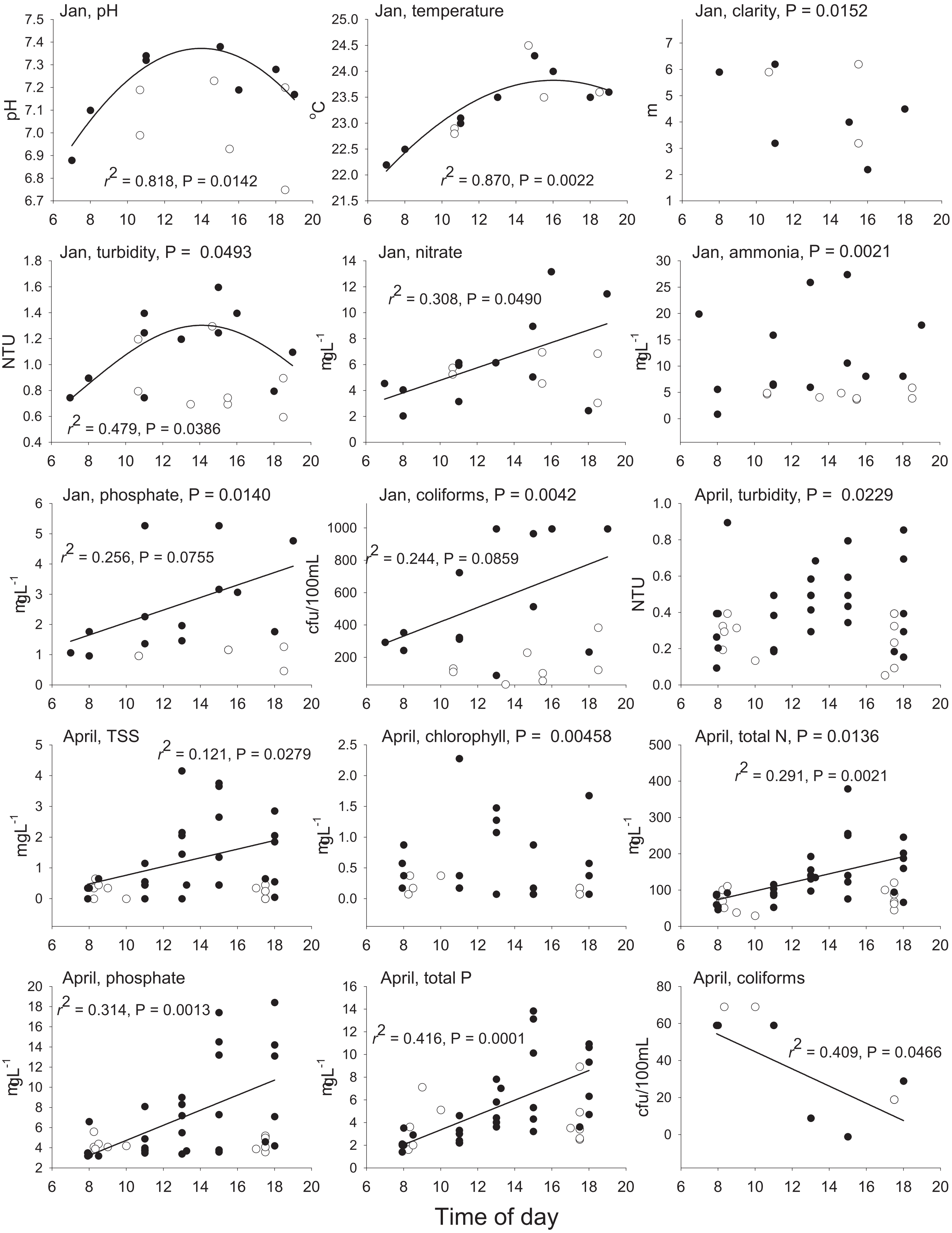

Fig. 4. Summary of significant relationships at Little Crystal Creek in January and April. Values of P in heading indicate differences between control and treatment samples (Wilcoxon test, see Table S4 for details). r2 and associated P values are derived from regressions illustrated (linear or peak models; treatment reaches only). Open symbols represent control data; filled symbols represent treatment data.

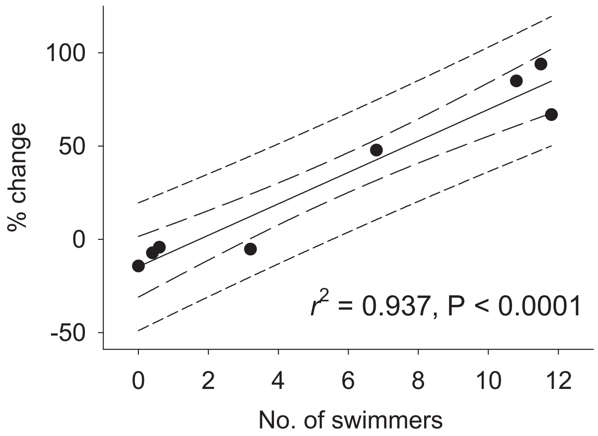

Fig. 5. Relationship between phosphate concentration (change between control and treatment) and bather numbers ("swimmers") at Little Crystal Creek. Regression line (solid), and 95% confidence (long dashes) and prediction (short dashes) bands are shown.

In January, Babinda Creek showed a clear relationship of declining water clarity with time of day (Fig. 3). Maximum turbidity mirrored this change, but the regression was confounded by temporal variability. Total P concentration was lower overall in the treatment reaches. At Crystal Creek, pH was lower in the treatment reaches, while temperature showed a diurnal trend. Clarity declined with time of day, and overall clarity was reduced in the treatment reach, while TSS concentration was elevated. Phosphate concentration was also elevated, but showed no clear trend with time. In April, water quality at Mossman showed increases in ammonia and phosphate concentrations with time. At Five Mile Creek, pH was reduced in the treatment reach. Nitrate concentration in the treatment reach declined with time, but did not differ from controls. Total P concentration was somewhat elevated in the treatment reach, despite substantial overlap.

At Little Crystal Creek in January, pH, temperature and turbidity showed curvilinear relationships with time of day (Fig. 4). Clarity was lower in the treatment reach. Nitrate concentration increased with time, although it did not differ between control and treatment samples. Ammonia concentration differed between reaches but showed no change with time. Both phosphate concentration and coliform count increased during the day and differed between control and treatment samples. In April, turbidity differed between control and treatment samples, while TSS increased with time. Chlorophyll concentration was higher in the treatment reach, as was total N concentration, increasing with time. Phosphate and total P concentrations increased with time, while coliform count decreased. There was a strong linear relationship between daily mean phosphate concentration and bather counts (Fig. 5). Relationships with other parameters were weaker partly because of their cumulative nature through the day.

3.3. Biological samples

The NMDS ordination of invertebrate assemblages suggested some separation by site but not by position of samples (control or treatment) in each stream (Fig. 6). PERMANOVA indicated that site groupings differed (pseudo-$F_{4,\ 29} = 2.11$, $P = 0.001$), and that position, nested within site, also differed (pseudo-$F_{5,\ 29} = 1.90$, $P = 0.001$). However, as post-hoc pairwise tests found no differences in groupings due to site or position, the differences were weak, as the pseudo-F values suggest.

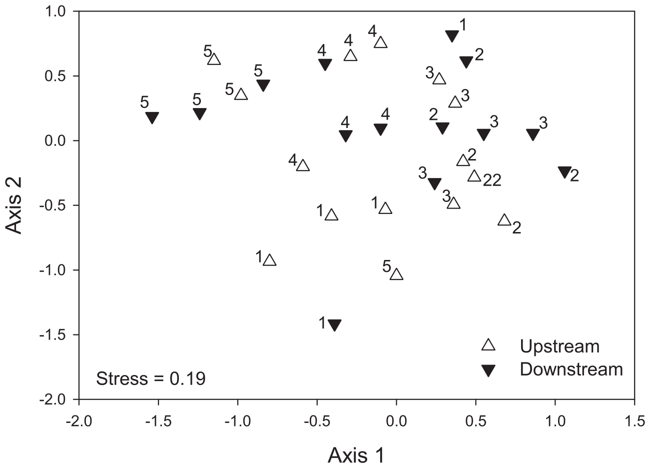

Fig. 6. NMDS ordination of invertebrate assemblages at control and treatment locations at each reach (numbered 1–5). Stream sites: 1, Mossman; 2, Babinda; 3, Five Mile; 4, Crystal; 5, Little Crystal.

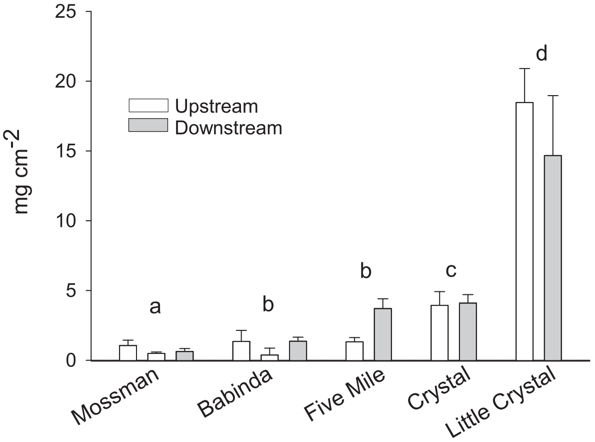

Fig. 7. Dry mass of algae (+ *S*.E.) on rocks at control and treatment reaches at each stream sites. Mass varied amongst sites (ANOVA, F4,71 = 66.87, $P <$ 0.0001), with differences indicated by different letters above each site (Tukey test, $P < 0.05$). Mass did not vary between control (upstream) and treatment (downstream) samples (F1,71 = 0.57, $P = 0.4518$) except at Five Mile Creek (Tukey test, $P < 0.05$).

Algal mass, estimated from chlorophyll *a* concentrations, varied amongst sites, with Little Crystal Creek having much greater mass than the others ($F_{4,71} = 66.87$, $P < 0.001$) (Fig. 7). There was a strong interaction between site and position ($F_{4,71} = 5.78$, $P < 0.001$), but the only difference between control and treatment estimates of mass were at Five Mile Creek, where rocks at the treatment reach had about eight times the algal mass of those at the control reach (Tukey test, $P < 0.05$).

4. Discussion

4.1. Background water quality

Background stream water quality was mostly high, with clear water and low turbidity, TSS and nutrient concentrations, although concentrations increased during rainfall. Total nitrogen and phosphorus concentrations were low, as is generally the case for pristine Wet Tropics streams (Pearson et al., 2017), probably suppressing rates of primary production (mainly periphyton and phytoplankton), decomposition rates and secondary production (ANZG Australian 2018; Connolly and Pearson, 2013). Nitrate to phosphate ratios suggested that phosphorus would be limiting to productivity, as elsewhere in Wet Tropics streams (Connolly and Pearson, 2013), although enhancement of both would boost productivity and decomposition (Pearson and Connolly, 2000).

The high background concentrations of faecal coliforms at some sites were probably due to animal faecal materials being flushed from the catchments. The risk of contacting human pathogens from native wildlife in pristine rainforests is probably not high, but the possibility of faecal contamination from feral pigs, which are widespread in the Wet Tropics (WTMA 2020), is more concerning (McKee et al., 2021). According to ANZG guidelines for recreational bathing (ANZG Australian 2018), existing microbial levels indicate a significant risk. As monitoring of human faecal contaminants in the presence of high background levels would be difficult, site-specific standards may be required. Our bacteriological sampling and analyses were restricted to a single variable. Coliform bacteria were not implicated in downstream environmental impact at our study sites, but could be important from a human health perspective. For this purpose, more extensive sampling and analysis is warranted, including differentiation of coliform bacteria shed by bathers and those emanating from animals (McKee et al., 2021), and investigation of other potential pathogenic organisms (Dorevitch et al., 2015; Reses et al., 2018).

4.2. Effects of bathing at little crystal creek

The January data highlighted some of the problems of this type of monitoring program, including identification of appropriate control reaches. Little Crystal Creek proved to be a good model system, being hydrologically simple, having low variation in natural water quality compared with bathing effects (except during rainfall), having a good control reach, and having a well-used bathing area during holidays but not otherwise, facilitating study of the effects of bathing intensity.

Bathing at Little Crystal Creek caused significant increases in TSS and turbidity during periods of high activity. For a pristine mountain stream with high conservation and ecotourism values, the changes were substantial and greatly exceeded Queensland water quality guidelines (Queensland Government Water Quality Guidelines 2021). The suspended solids released into the water column during bathing were principally due to disturbance of benthic sediments. Sediments would be less disturbed by a bather entering the water directly rather than wading, except for sloughing of epilithic algae. This point may have management implications at some locations (e.g., provision of access to deeper water).

Dissolved nutrients resulting from decomposition of benthic organic matter may remain in interstitial water until the sediment is disturbed. Standard analyses do not discriminate these nutrients from those emanating from bathers, such as from urine, so we can draw no conclusions about origin. Total nitrogen concentrations did not fall greatly in the late afternoon after bathers left, in contrast to TSS, suggesting that the increase is due to dissolved organic nitrogen, which cannot settle to the bottom. This constitutes a source of potential impact further downstream.

A very strong correlation between total phosphorus concentration and numbers of bathers at Little Crystal Creek was evident. Phosphate concentrations, unlike those of nitrate, showed little response to rainfall, so phosphate was an excellent model parameter for examining the effects of bathing. In the absence of bathers, concentrations were usually lower in the treatment reach of the bathing area than in the control reach, indicating that phosphorus is lost to the bottom sediments or bioassimilated by organisms. Because of the high N:P ratios algal growth is likely to be enhanced by the supplemented phosphate concentrations during days of high bathing activity. However, higher concentrations on only a few days per year are unlikely to induce major long-term effects, but at higher frequencies could cause persistent ecosystem changes (Pearson and Connolly, 2000).

As water quality at Little Crystal Creek returned to normal overnight, the water detention time at the bathing area was less than 12 h, leading to low phytoplankton density and chlorophyll concentration. Any increases in chlorophyll concentration were probably due to fragmentation of algae resulting from bathers disturbing the substratum.

4.3. Comparisons between locations

Correcting for natural background fluctuations was less straightforward at the other sites than at Little Crystal Creek, being hampered by lower sampling frequency, rainfall, hydrological complexity and sub-optimal control reaches. These issues may be addressable by more targeted work at each site.

At Five Mile Creek, Big Crystal Creek and Little Crystal Creek, turbidity was a less sensitive indicator of water clarity changes than TSS. TSS was reflected by visual clarity measurements at all sites, indicating that clarity is a robust cost-effective technique. Faecal coliform concentrations at the bathing areas at Little Crystal Creek, the Boulders, Mossman Gorge and Five Mile Creek exceeded the ANZG guidelines (ANZG Australian 2018), although background concentrations were high at Babinda Creek and the Mossman River during rainfall. It is likely that concentrations would increase with declining rainfall and flow in the dry season, at which time any effects of bathers would be most evident. In the drier southern Wet Tropics, during periods of very low flow, sites are frequently closed to bathing because of risk to bathers. Our results indicate that problems may be more frequent than expected and may not be confined to the drier areas. In particular, in the warming months at the end of the dry season, risks are highest because of increasing numbers of bathers while flows remain low.

4.4. Biological monitors of disturbance

It is possible that the biota will provide a clearer idea of impacts than water quality samples, by integrating effects over time (e.g., agricultural effects on invertebrates in the Wet Tropics (Pearson et al., 2017)). We expected invertebrate density to be boosted by nutrient supplements (Pearson and Connolly, 2000; Connolly and Pearson, 2007; Connolly and Pearson, 2013), and composition or density to change with increased algal growth (Connolly et al., 2016). However, our limited invertebrate sampling provided only very weak evidence of bathing impacts.

In the generally clear waters of Wet Tropics streams it is expected that nutrient mobilisation by the activities of bathers will have a measurable effect on algal growth. The absence of contrast in algal biomass between control and treatment reaches in most streams was unexpected. The clear change at Five Mile Creek suggests that our results were due to location-specific factors, which warrant further investigation.

4.5. Towards a general model

Managing the recreational use of inland waterbodies will become increasingly important as demand intensifies and climate change impacts become more severe (Hadwen et al., 2012). Interactions between people and stream ecosystems have rarely been properly quantified and there is need to integrate ecological and visitor management (Venohr et al., 2018). It is clear from this study that, even in favourable situations, the detection of changes in water quality that could signal problems would be difficult and expensive. The most effective management tool would be a predictive numerical model, with calibration for each system.

Here, we outline a preliminary model for prediction of water quality problems on the basis of a few simple measurements. Storm-induced fluctuations in water quality are probably of minor consequence to the ecosystem, because they have short duration and are outweighed by disturbances due to high current speeds (Rosser and Pearson, 2018). Conversely, in the dry season, water quality will exert an increasingly important influence on the biota. The contaminants monitored in this study all occur naturally, so impacts must be assessed on the basis of changes to background levels. A predictive model could be developed for each site based on preliminary trials and straightforward measurements (Fig. 8). The model would be based on the linear relationship between water quality and bather numbers, as we report for phosphate concentrations. Other factors include the amount of bottom sediment

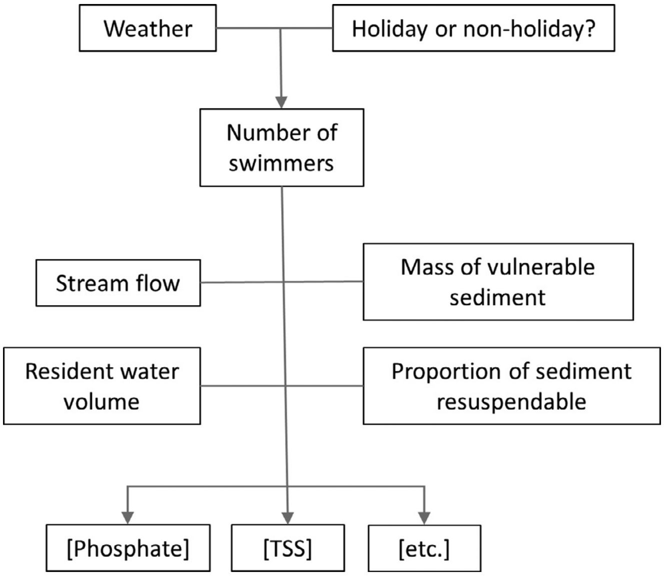

Fig. 8. Conceptual model of main factors affecting bather impacts on water quality at stream sites. Empirical research can define variables at each site to develop a relationship allowing prediction of water quality from bather numbers ("swimmers") or even the variables influencing them. [Phosphate], [TSS] and [etc.] represent changes in water quality variables between control and impacted reaches.

suspended by bather activity and dilution. The degree of sediment resuspension will need to be determined empirically at each site, as will the area of sediment vulnerable to wading or bathing. Following determination of the constants, the model can be implemented by measuring flow and counting bather numbers in the middle of the day, and validated by comparing control and treatment samples.

4.6. Impacts on the aquatic ecosystem

It is possible that the regular physical disturbance to benthic habitats by bathers is more important than the effects of water quality – for example, increased productivity of algae resulting from nutrient enrichment may be offset by the abrasive effects bathers have on algae. Furthermore, since bathing occurs at only a small proportion of stream sites, overall impact on the aquatic ecosystem is inconsequential, and given that the study streams are subject to agricultural and other impacts downstream (Pearson et al., 2019), the effects of bathing may appear unimportant. However, visitors' perceptions and the substantial water quality degradation observed during peak activity periods (Butler et al., 1996) suggest that some bathing areas approach their sustainable carrying capacity. As the sites are located in a World Heritage Area, conservation values are high and ecosystem protection is a major issue. Increased growth of tourism and recreation in the region, and possible competition between the two components, may necessitate opening up new sites to the public, making protection even more crucial.

4.7. Conclusion

This is one of few studies to discuss the effects of bathing on water quality and ecology in streams. Bathing caused measurable effects on water quality, although the ecological effects were marginal. However, limitations imposed by imperfect control reaches indicate that further investigations are needed, including explicit identification of nutrient and bacterial sources and more extensive ecological studies. Nevertheless, changes to water quality and visitors' perceptions of it (Butler et al., 1996) suggest that controls on visitor numbers are warranted, especially in areas of high conservation status. While ultimately it may be possible to set carrying capacities for streams based on visitor experience (Stankey and McCool, 1984), numerical standards are difficult to establish. Valentine & Cassells (Valentine and Cassells, 1991) urge managers to move away from "the simplistic approach of counting heads" towards an understanding of the qualitative elements of visitor experiences. However, we suggest that streams may be more amenable to the use of carrying capacity as a management tool than other environments. For precautionary site management, several approaches may be required. This includes monitoring of visitor numbers and activities; gauging visitor perceptions to inform management approaches (Butler et al., 1996; Hadwen et al., 2012); developing strategies for limiting visitor or bather numbers; assessment of possible impacts at sites that may be opened for recreation in the future (WTMA 2020); developing local or regional guidelines for monitoring and management to minimise impacts; site hardening, such as installation of board walks; controlling water entry points to minimise bank erosion and sediment disturbance; and providing interpretive material to encourage visitors to appreciate the environmental values of streams and their management, and behave accordingly (Butler et al., 1996).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Barry Butler: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Richard G. Pearson:** Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Funding acquisition. **R. Alastair Birtles:** Conceptualization, Methodology, Investigation, Writing – review & editing.

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Supplementary materials

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