Faecal contamination and visual clarity in New Zealand rivers: correlation of key variables affecting swimming suitability

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ABSTRACT

Swimming is a popular activity in Aotearoa-New Zealand (NZ). Two variables that strongly influence swimming suitability of waters are faecal contamination, as indicated by the bacterium *Escherichia coli*, and visual clarity as it affects aesthetics and safety with respect to submerged hazards. We show that *E. coli* and visual clarity are inversely related overall in NZ rivers ($R = -0.54$), and more strongly related in many individual rivers, while similar (but positive) correlations apply also to turbidity. This finding, apparently reflecting co-mobilisation of faecal contamination and fine sediment, suggests that visual clarity, measured or estimated from appearance of submerged features, should be a valuable indicator of faecal contamination status and (more generally) swimming suitability. If swimmers were to avoid river waters <1.6 m black disc visibility (a long-established NZ guideline for swimming) they would also avoid microbial hazards (*E. coli* <550 cfu/100 mL about 99% of the time in NZ rivers). However, urban-affected rivers might sometimes be microbially contaminated when still clear. Water management agencies should measure visual clarity together with *E. coli* in river surveillance. Real-time information on swimming suitability could then be based on continuous monitoring of turbidity locally calibrated to *both* visual clarity and *E. coli*.

Key words | *E. coli*, rivers, swimming, turbidity, visual clarity, water quality

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INTRODUCTION

In Aotearoa-New Zealand, freshwater and coastal beaches provide for a range of recreational activities and connection with the environment. Every year, over one million New Zealanders participate in swimming (Water Safety New Zealand 2015), with swimming recognised in national water policy initiatives (NZ Government 2017) as a value that must be protected. However, there has been national angst over widespread unsuitability of freshwater quality to support swimming in NZ (NZFSS 2017).

Several water attributes affect swimming quality of fresh waters, but the chief concern is usually the faecal microbial status of the water as indicated by *Escherichia coli* (*E. coli*) concentrations. Swimming in water contaminated with human and animal (notably livestock) faecal matter exposes swimmers to a range of pathogens and increases their risk of contracting gastrointestinal illnesses as well as non-enteric infections (e.g. rashes, eye and ear irritation, infected cuts) (Soller *et al.* 2010). As a population, NZ suffers from a high incidence of waterborne enteric diseases (estimated at 18,000–34,000 cases per year for a population of 4.8 M), reflecting a rigorous reporting system (ESR 2015).

To protect the public, regional authorities (the main water management agencies in NZ) monitor the faecal indicator bacterium *E. coli* weekly at popular swimming sites during the summer months (Milne *et al.* 2017). Enumeration of *E. coli* typically requires about 24 hours for bacterial culture, resulting in delays when informing the public of potential health risks. Microbiological guidelines for contact recreation in NZ specify 95th percentile breakpoints for *E. coli* that are based on quantitative microbial risk

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assessment for campylobacteriosis. Guidelines are based on both surveillance (short-term) and grading (long-term average) data (MfE/MoH 2003).

The visual clarity of waters also affects swimming quality, both for aesthetic reasons and for safety reasons – because in turbid waters it is harder to see submerged hazards (Smith & Davies-Colley 1992; West *et al.* 2015). Surveillance of swimming waters in NZ does not currently include measurement of visual clarity, although turbidity is sometimes measured.

Several environmental variables have been shown to correlate with *E. coli* in waters, e.g. rainfall, sunlight, wind, temperature, and turbidity. These 'continuously' measurable variables may provide a near real-time means of assessing microbial risk (Olyphant *et al.* 2003). Of these factors, sediment-related optical properties such as turbidity have shown the most promise for predicting faecal contamination in near real time (e.g. Vinten *et al.* 2004).

The correlation between faecal indicator bacteria and suspended sediment-related metrics in water bodies apparently reflects the similar behaviour, particularly mobilising processes, of these contaminants (Money *et al.* 2009). The strength of correlation might be expected to depend on the source of faecal contamination. Where livestock on grazed pasture are the faecal source, a relatively strong correlation seems probable because livestock also disturb soils resulting in mobilisation of fine (light-attenuating) sediment. Conversely, when wastewater is the faecal source, the correlation might be weak because there is no associated discharge of light-attenuating fines (other than those in the wastewater). However, association of the *ultimate* sources of faecal contamination and fine sediment is not necessary to produce correlations of these variables in river waters. Both faecal bacteria and fines are stored within in-channel reservoirs (e.g. Muirhead *et al.* 2004; Stott *et al.* 2011; Wilkinson *et al.* 2011) notably the hyporheic zone (Drummond *et al.* 2014, 2015), from which they may be released simultaneously by mechanical or hydrological disturbance. So, the commonly observed correlation of *E. coli* and turbidity in rivers probably expresses simultaneous entrainment from in-channel stores irrespective of ultimate sources.

Turbidity has been used in early warning models for water quality in beaches of the Great Lakes (USA) (Francy *et al.* 2013). In a statistical study of 73 sites across the Waikato region of NZ, Collins (2003) found that median turbidity was a relatively strong predictor of median *E. coli*, suggesting that turbidity may be a useful general surrogate for *E. coli*, and perhaps a more precise surrogate (with suitable cross-calibration) in particular waters.

The broad correlation between faecal contamination (*E. coli*) and turbidity in many NZ rivers and streams has been exploited to assist in faecal load calculations using continuous nephelometer records 'calibrated' by auto-sampling over hydrological events (e.g. Davies-Colley *et al.* 2008). Furthermore, faecal contamination and visual clarity (closely inversely related to turbidity – Davies-Colley & Smith 2001) are the variables that probably most commonly degrade swimming quality of rivers, although nuisance periphyton, particularly potentially toxic cyanobacteria (and extreme pH and hazardous trash), also affect suitability for swimming (e.g. Lopes *et al.* 2016). In principle, the correlation of *E. coli* and visual clarity could be the basis of valuable guidance on suitability for swimming based on visual clarity assessment.

This paper reports on the faecal contamination status and visual clarity of a diverse range of NZ rivers and explores the feasibility of would-be swimmers rating suitability of water based on its appearance. We tested the hypothesis that black disc visibility provides a valuable indicator of general swimming suitability. Visual clarity measurements and *E. coli* enumeration are both amenable to collection by volunteers with simple, robust equipment and minimal training (e.g. Storey *et al.* 2016; West & Scott 2016), so improved knowledge of the relationship between these variables has a high potential to empower citizens to make informed decisions about suitability of water for contact recreation.

METHODS

We used data from NZ's National Rivers Water Quality Network (NRWQN) to explore relationships between faecal contamination and visual clarity, turbidity and state-of-flow of rivers. Sites in the NRWQN were sampled monthly (via *in situ* measurements and grab samples) for 13 water quality variables by the National Institute of Water and Atmospheric Research Ltd (NIWA) from 1989 to 2015, and methods in the NRWQN are summarised by Davies-Colley *et al.* (2011). We truncated the dataset at the end of 2015 when NIWA started to scale down its site network. Sampling for *E. coli* only began in 2005, so we analysed the 11 years of monthly data collected between 2005 and 2015 inclusive. Restricting the time period of the analysis also reduces the effects of water quality time trends – for example, visual clarity has been gradually increasing at numerous river sites in NZ (Larned *et al.* 2016).

Up to 2015, the NRWQN included 77 river sites on 35 river systems, which together drain about half the land area of NZ (Davies-Colley *et al.* 2011), and can be considered reasonably representative of the diversity of NZ rivers, excepting small polluted streams including those in urban watersheds.

Thirteen of the NRWQN river sites have highly modified flow regimes due to lake sources or impoundments or major inter-basin water transfers. For these reasons, we confined analysis to those 64 river sites in the NRWQN with minor standing water sources or anthropogenic modification of the flow regime. Eleven years of monthly samplings yielded up to 132 data points from each individual site and a maximum total sample size of 8,448 ($=132 \times 64$) for all 64 sites.

E. coli (*N* = 8,319)

Water samples for *E. coli* assay were collected in 100 mL sterile vials on routine monthly visits to NRWQN sites (from about 200 mm below the water surface so as to avoid any surface microlayers). The vials were promptly transferred to dark, chilled storage containers and freighted overnight to NIWA's Hamilton water quality laboratory. The water samples were analysed on the following day by the Colilert (IDEXX multi-well) most-probable-number (MPN) method – a standard method that agrees fairly well with longer-established membrane filtration methods (e.g. Buckalew *et al.* 2006). We express *E. coli* enumerations here as *culture*-forming units (cfu) – closely analogous to *colony*-forming-units in membrane filtration methods. The full sample volume (100 mL) was analysed directly for *E. coli* unless sample cloudiness or high flow state suggested relatively high concentrations might be present, in which case the sample was diluted (e.g. 10 mL made up to 100 mL in distilled water) to avoid over-ranging (all Colilert wells positive).

E. coli data by the Colilert multi-well method are affected by low numerical precision at relatively low concentrations and relatively high concentrations – causing 'striping' in data plots as discussed in the Results section below. At low *E. coli* concentrations, low precision results from very few positive wells. At high *E. coli* concentrations, enumeration is also approximate because almost all wells are positive. Ideally, samples with high concentrations would have been diluted so as to be more precisely enumerated from roughly equal numbers of positive and negative wells. However, there were some instances, particularly early in the campaign of *E. coli* sampling, when the need for dilutions was not recognised, representing a very small (<1%) proportion of the data.

E. coli measurements reported by the laboratory as 'below detection' (left-censored) were replaced by one half of the detection limit. Right censored values (upper limit) were left as reported. This practice, although imperfect, is preferred to deletion of non-detects which produces an upward bias in subsequent analyses (Helsel 2006). Substitution of one-half the detection limit can be used when censoring percentages are small (and detection limits are constant across the samples) (Helsel 2006), as in this case (3.4% of the data).

Visual clarity (*N* = 8,398)

Visual clarity was measured on-site as the horizontal sighting range of a black disc target (Davies-Colley 1988) (Figure 1) during routine monthly visits to NRWQN sites. Zanevald & Pegau (2003) showed that horizontal black body sighting range is a 'robust' indicator of underwater visibility depending only on one fundamental inherent optical property of water – the beam attenuation coefficient – and is independent, for example, of lighting conditions. Black disc observations were made routinely in the NRWQN (Davies-Colley *et al.* 2011) by wading with a simple underwater periscope fitted with a 45° mirror to enable the user, looking vertically downwards, to view *horizontally* under the water surface (Figure 1(a)). Because target size affects visual detectability, albeit weakly, the apparent size of the disc was kept approximately constant by using three different-sized discs for different sighting ranges: a 200 mm diameter disc for visibilities greater than 1.5 m, a 60 mm

Figure 1 | Measurement of visual water clarity by the black disc method. (a) Visual clarity measurement *in situ* as the horizontal sighting range of a black disc. The observer is using an underwater periscope fitted with a 45° mirror to observe the horizontal extinction distance of the black target (60 mm diameter disc) fixed to a steel stake driven into the streambed. (b) The SHMAK clarity tube for water of relatively low clarity. The black target (20 mm diameter disc) is mounted on an aquarium magnet that is being moved to the extinction distance by the observer's assistant. (*Photo credits*: (a) Graham Timpany, NIWA; (b) Rebecca Stott, NIWA.) Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wh.2018.214.

disc in the visibility range 0.5–1.5 m, and a 20 mm disc for visibilities <0.5 m. Typically, the visual clarity observations were made by a single technician working alone with the black disc visual target fixed to a stake driven into the streambed (Figure 1(a)), or else a telescoping rod system was used to hold the disc rigidly away from the observer. Recently, visibilities <0.5 m have been increasingly measured on a water sample contained in a SHMAK (Stream Health Monitoring and Assessment Kit) clarity tube (Figure 1(b)) which is a microcosm of the *in-situ* black disc method (Kilroy & Biggs 2002). The SHMAK tube method is more precise and convenient for 'dirty' waters, and safer for rivers in high flow state. Visual clarity was enumerated to the nearest 1 cm in the <10 cm (0.1 m) range (<10% numerical precision) – which, as for *E. coli*, results in 'striping' in plots as discussed in the Results section.

Turbidity ($N = 5{,}372$; 2005–2011 inclusive)

Nephelometric turbidity was measured together with most other water quality variables in the NRWQN via collection of 500 mL water samples from about 200 mm below the water surface on monthly visits. Sample bottles were shipped (dark and chilled), together with bacterial vials, by overnight courier to the NIWA Hamilton water quality laboratory, and turbidity measured promptly the following day. Originally, a Hach 2100A nephelometer was used, but this instrument was supplanted by another bench nephelometer, a Hach 2100AN in April 2012 (Graham Bryers, NIWA Laboratory, pers. comm.) after more than a decade of parallel measurements. Despite the very similar model number, the latter instrument reads, on average, about 30% higher than the former for the NRWQN, and the ratio is river-specific (Davies-Colley & Smith 2001). To avoid this artefactual step-change, we truncated the turbidity data from 2012 inclusive: only data from the original Hach 2100 A instrument (seven years of monthly data, 2005–2011) was analysed in this study. Nephelometric turbidity is strongly inversely related to black disc visibility (e.g. Davies-Colley & Smith 2001; West & Scott 2016) – as is confirmed in the present paper.

River discharge ($N = 8{,}310$)

River discharge estimates for times of sampling visits were available for all NRWQN sites, either from hydrometric stations near the water quality monitoring sites or by calculation based on records from more distant hydrometric stations, usually on the same river main stem (Davies-Colley *et al.* 2011). Rivers in the NRWQN vary greatly in size and characteristic flow (medians ranging from 0.35 to 357 m^3/s for the 64 NRWQN sites studied here). In order to index state-of-flow, independent of river size, river discharge values were divided by median discharge.

Statistical analyses

Statistical analyses were conducted in Program R Version 3.3.3 (R Core Team 2017).

The distributions of all four variables (*E. coli*, visual clarity, turbidity, and normalised discharge) were skewed on a linear scale (medians less than means, e.g. 58 cfu/100 mL versus 290 cfu/100 mL for *E. coli*) so the data were log-transformed before statistical analysis. Plots are also displayed on logarithmic scales – both to handle a wide range of data (more than four decades for *E. coli*) and to better display highly skewed distributions. Scatterplots were constructed using the 'alpha blending' facility in R which makes each point slightly transparent – so that higher concentrations of points appear darker.

Pearson's moment correlation was used (mostly) for examining linearity of relationships between (log-transformed) variables. Spearman's rank correlation coefficient, which tests for monotonicity, was usually similar to Pearson's product-moment correlation coefficient, showing that log-transformation successfully eliminated curvilinearity in bivariate relationships.

RESULTS

E. coli concentrations ranged widely (more than four decades) across river sites over the 11-year period (2005–2015 inclusive), from <1 to a maximum of 35,000 cfu/100 mL in stormflows. Likewise, visual clarity also ranged widely, from 1 cm in stormflows to nearly 20 m.

Table 1 gives correlation coefficients for the four variables: *E. coli*, visual clarity, turbidity and (normalised) discharge, and Figure 2 gives mutual X-Y scatterplots of the first three variables, and also *E. coli* as a function of normalised discharge. The Pearson's correlation coefficients (for log-transformed variables) in Table 1 are numerically similar to the equivalent Spearman rank correlation coefficients.

There is an inverse overall relationship between *E. coli* and visual clarity (Figure 2(a)) – that is, clearer waters (and clearer rivers – as discussed below) tend to be less microbially contaminated ($R = -0.54$). Striping of data can be seen in this plot and the other plots in Figure 2, owing to low numerical precision of both *E. coli* and visual clarity at low values, and to low numerical precision of *E. coli* also at a few high values when water samples were not appropriately diluted before analysis.

Table 1 | Correlation coefficients for *E. coli*, black disc visual clarity, turbidity, and (normalised) discharge at NZ river sites. Data are from 64 sites in the NRWQN sampled monthly between 2005 and 2015 inclusive. (The turbidity record was truncated after 2011 so as to avoid a step-change with change in bench nephelometer.) Values below the diagonal are Pearson's product moment correlation coefficients on $\log_{10}$-transformed data, and values above the line are spearman's rank correlation coefficients

	E. coli	Visual clarity	Turbidity	Discharge
E. coli	1	−0.53	0.53	0.24
Visual clarity	−0.54	1	−0.93	−0.57
Turbidity	0.50	−0.94	1	0.57
Discharge (normalised)	0.29	−0.60	0.58	1

Turbidity was strongly inversely related to visual clarity (Figure 2(b); $R = -0.95$), as has been reported elsewhere (e.g. West & Scott 2016). A relatively few outlier points in Figure 2(b) are interpreted as transcription errors arising, for example, from decimal point shift. As could be expected on consideration of Panels A and B of Figure 2, *E. coli* is moderately correlated with turbidity with a very similar correlation strength, but opposite sign ($R = 0.53$), compared to *E. coli* versus visibility (compare Figure 2(c) with 2(a)).

There was a moderately strong relationship between visual clarity and (normalised) discharge ($R = -0.60$; plot not shown); stronger than between *E. coli* and (normalised) discharge (Figure 2(c); $R = 0.31$), with water typically clearer (and with less *E. coli*) at low flow condition. However, the relationship between *E. coli* and discharge was highly variable, with some low *E. coli* values occurring even at very high states of flow in rivers.

The faecal contamination status of individual river sites varied as indicated by median and 95th percentile values for *E. coli* (Figure 3). The most faecally contaminated river site with regard to the median was the Mataura River at Seaward Downs (median *E. coli* = 310 cfu/100 mL and 95th percentile = 2,500 cfu/100 mL). The highest 95th percentile was for a different site – the Manawatu River at Weber Road (95th percentile = 5,600 cfu/100 mL). The lowest faecal contamination was recorded in the (near-pristine) Motueka River at the Gorge (median *E. coli* = 1 cfu/100 mL and 95th percentile = 22 cfu/100 mL). This river site, not coincidentally, is also

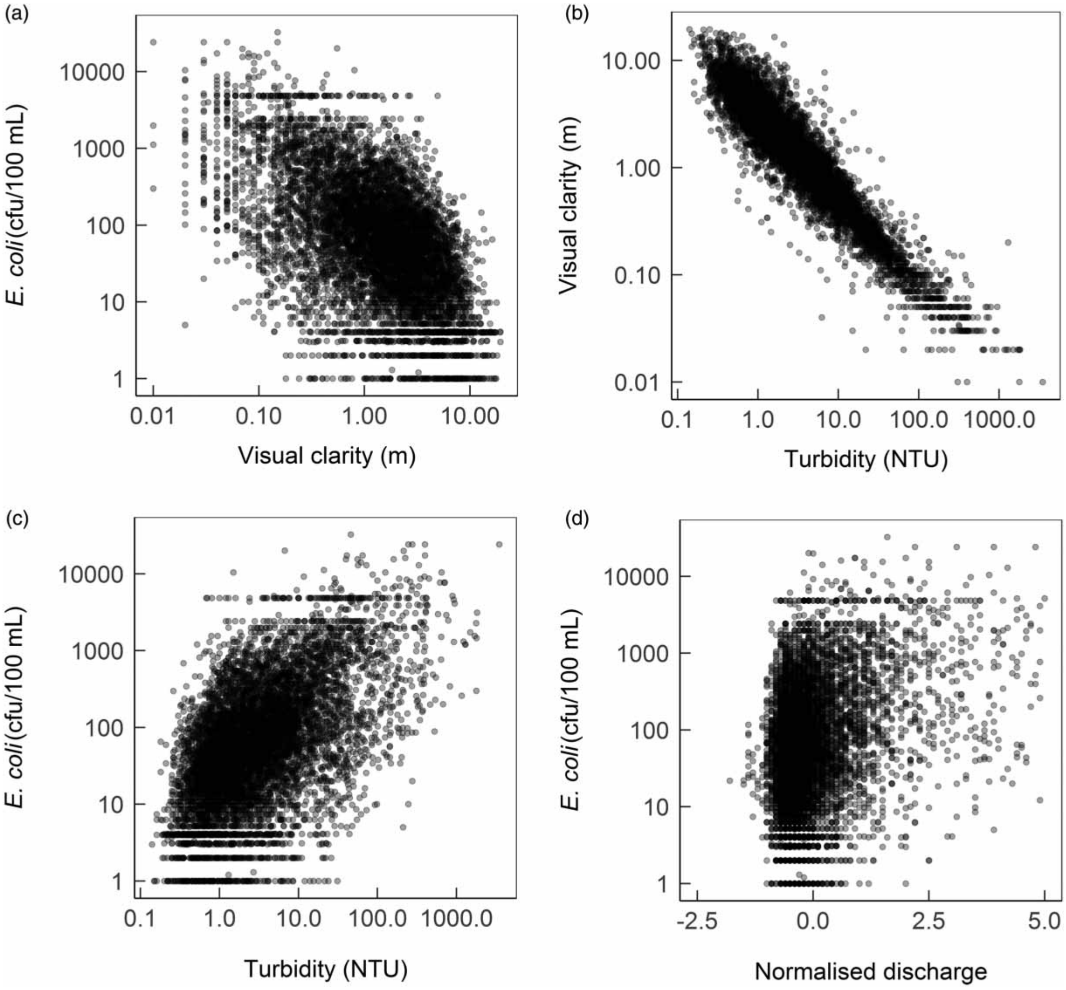

Figure 2 | Mutual relationships of *E. coli*, black disc visual clarity and turbidity across 64 NZ river sites. Also shown is the plot of *E. coli* versus normalised discharge. Sites were sampled monthly between 2005 and 2015 inclusive. (The turbidity record was truncated after 2011 so as to avoid a step-change with change in bench nephelometer.) (a) *E. coli* versus visual clarity, $R = -0.54$; (b) visual clarity versus turbidity, $R = -0.95$; (c) *E. coli* versus turbidity, $R = 0.53$; (d) *E. coli* versus normalised discharge, $R = 0.31$.

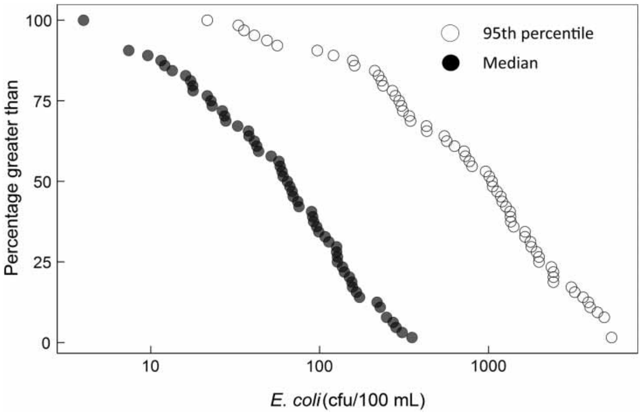

Figure 3 | Distributions of *E. coli* medians and 95th percentiles at 64 NRWQN river sites for the period 2005–2015.

the clearest in the NRWQN with a median visibility during the reporting period of 10.9 m.

As we might expect, the relationship between *E. coli* and visual clarity (and between *E. coli* and turbidity) for individual river sites is sometimes stronger than the overall relationship. By way of example, Figure 4 shows *E. coli* plotted against visual clarity in four different rivers: the Whanganui River at Paetawa (WA4), for which the R value was strongest (at $R = -0.85$); the Shotover at Bowens Peak (AX3) and Makaroro at Burnt Bridge (HV1) ($R = -0.63$ and -0.45, respectively); and the Waimakariri River at the Gorge (CH3) in which there was virtually no relationship between these variables ($R = 0.03$).

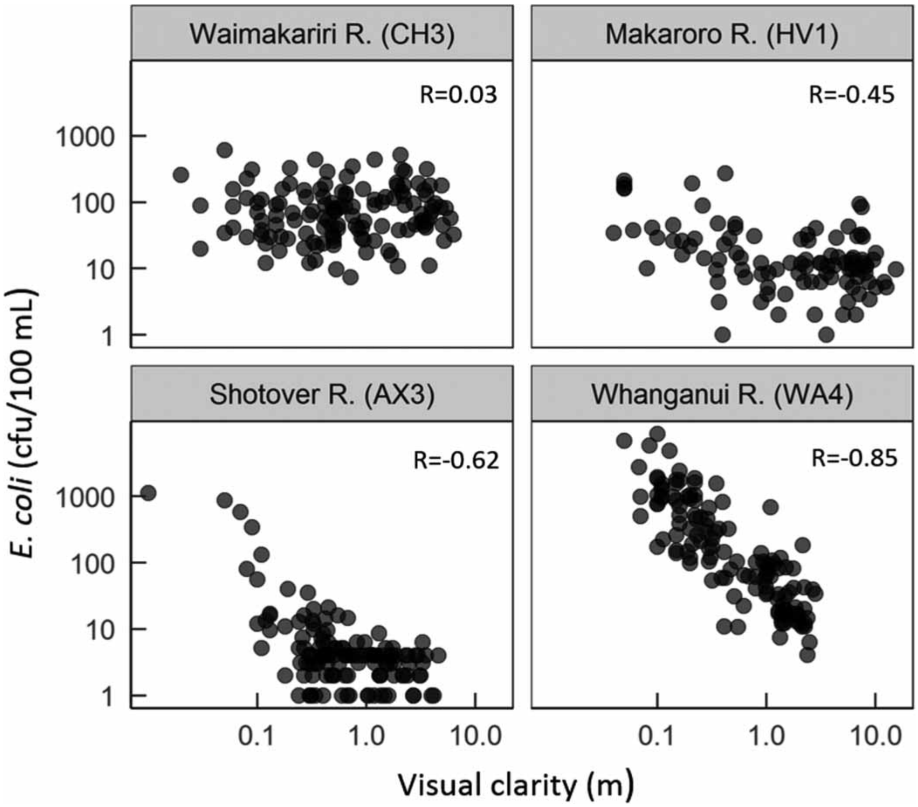

Figure 4 | Example plots of *E. coli* vs visual clarity – for the worst, best, and intermediately correlated (25th and 75th percentile) NRWQN sites. Data are for: the Waimakariri River at the Gorge (CH3), Pearson's $R = 0.03$; the Makaroro at Burnt Bridge (HV1), Pearson's $R = -0.45$; the Shotover at Bowens Peak (AX3), Pearson's $R = -0.62$; and the Wanganui River at Paetawa (WA4), Pearson's $R = -0.85$.

Because hydrological events are expected to result in wash-in of faecal deposits from land and mobilisation of in-stream faecal bacterial stores, we expect a positive relationship of *E. coli* with river discharge. While there is a weak relationship with normalised discharge overall (Figure 2(d)), individual sites sometimes show stronger correlations (Figure 5). The inverse relationship between *E. coli* and visual clarity (and direct relationship between *E. coli* and turbidity) is stronger overall than the relationship of *E. coli* to discharge (compare Figure 2(a) with 2(d)), and in most (all but seven) individual river sites (Figure 5).

DISCUSSION

We have shown that *E. coli* is moderately to strongly (inversely) correlated with visual clarity in most NZ rivers. This correlation is potentially useful for protecting would-be swimmers from microbial hazards, as well as submerged hazards, using visual clarity as a guide. The overall relationship (Figure 2(a)) is only moderate ($R = -0.54$), with too much uncertainty to support estimation of *E. coli* from visual clarity without site-specific 'cross-calibration'. Despite this uncertainty, as we show below, visual clarity is a valuable general guide to the faecal contamination status even in the absence of site-specific information.

A positive correlation of *E. coli* with discharge occurs in most individual NZ rivers because hydrological events mobilise faecal material and faecal bacteria stores. The correlation is weak to moderate because *E. coli* typically displays a strong 'first flush' effect owing to mobilisation of in-channel stores: that is, *E. coli* are often higher on the rising than falling limb (as is sediment and light attenuation, e.g. Stott *et al.* 2011), resulting in hysteretic relationships. Another contribution to a weakening of flow correlation is that different hydrological events flush different amounts of faecal contamination depending on antecedent

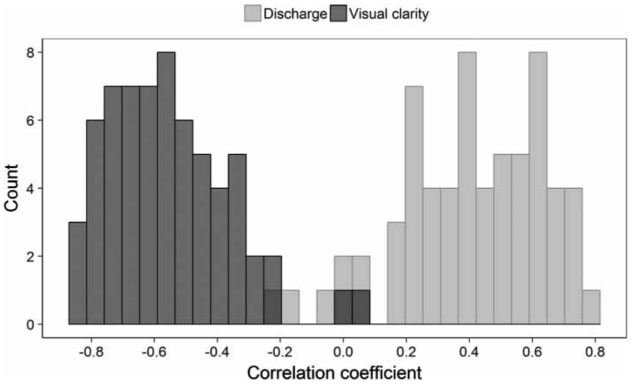

Figure 5 | Histogram of correlation coefficients for *E. coli*-visual clarity relationships and *E. coli*-discharge relationships for 64 NRWQN sites. The range of correlation coefficients for *E. coli* versus visual clarity is $R = -0.84$–0.03 and for *E. coli* versus discharge is $R = -0.24$–0.78.

conditions and rainfall intensity and duration. For example, Muirhead *et al.* (2004) showed that a series of almost identical artificial flood events at 24-hr intervals progressively flushed out in-channel stores of faecal bacteria.

The fairly weak correlation of faecal contamination with river discharge means that discharge, and also salinity which reflects river discharge into downstream estuaries and coastal waters, is typically a weak indicator of faecal contamination. Turbidity, being related to fine suspended matter in water, has often been suggested as a better proxy (e.g. Collins 2003), because the same hydrological processes that mobilise faecal matter or faecal bacterial stores also mobilise fine particles (causing light scattering – turbidity).

Visual clarity is strongly inversely related to turbidity so we expect an inverse relationship between *E. coli* and visual clarity in individual rivers, as reported here. However, visual clarity is a preferred metric to turbidity because it is immediately meaningful (and important) to the general public (e.g. West *et al.* 2015) and, unlike turbidity, is a 'proper' scientific quantity (in SI units) that relates very simply to the fundamental optics of water (Zanevald & Pegau 2003). Furthermore, visual clarity itself affects swimming suitability of waters (Smith & Davies-Colley 1992) for both aesthetic and safety reasons, and the NZ Ministry for the Environment has recommended 1.6 m visibility as a national guideline for swimming (MfE 1994). Apart from faecal microbial status, swimming is unlikely to be aesthetically pleasant or safe in water with less than about 1.0 m visual clarity (e.g. Nagels *et al.* 2001).

An inverse correlation between *E. coli* and visual clarity may occur in many rivers and streams, irrespective of the ultimate sources of faecal contamination and fine sediment and the degree of association of these contaminant sources. Both *E. coli* and light-attenuating fine sediments are stored within the same in-channel reservoirs (notably the hyporheic zone) from which they may be simultaneously mobilised by mechanical disturbance (including by swimmers) or accelerating water currents (Drummond *et al.* 2014, 2015). Therefore, our finding of moderate or better correlation between *E. coli* and visual clarity for New Zealand rivers may be broadly transferable to catchments where livestock grazing is not the dominant source. We encourage further research to test this concept.

Most of the faecal contamination at NRWQN sites in NZ comes from livestock – as shown, for example, by the fairly strong correlation (Spearman's $R_S = 0.8$) of median *E. coli* with the percentage of catchment area in livestock pasture reported by Davies-Colley (2013) (see also Collins 2003). Livestock pasture covers, in aggregate, about 40% of NZ's land area (Davies-Colley 2013). In catchments with a high proportion of livestock pasture, the correlation of *E. coli* and visual clarity is typically strong. For example, $R = -0.77$ for the Manawatu River at Weber Road, with 44% of its catchment in pasture. The correlation between *E. coli* and visual clarity appears to be weaker in partially urban catchments in the NRWQN where, in contrast to street runoff, leaking sewer pipes or cross connections can be sources of faecal contamination that are not accompanied by much light-attenuating suspended matter. Only about 2% of NZ's land area is urban and the NRWQN lacks any fully urban sites.

Because visual clarity can inform decisions on swimming suitability, water management agencies would ideally monitor visual clarity along with *E. coli* as part of routine river surveillance. Swimming quality could then be assessed in real-time based on continuous turbidity records with commonly available nephelometers, locally calibrated to *both* visual clarity and *E. coli*. In a few regions of NZ, correlations between *E. coli* and turbidity are now starting to be investigated for real-time warning of faecal contamination (Milne *et al.* 2017). Even in the absence of instrumental sensors and professional expertise, members of the community can estimate visual clarity from the appearance of submerged features – probably within a factor of two with some practice and eye 'calibration' to black disc measurements. Professional technicians, familiar with particular river waters, can estimate visual clarity to about 50% (standard deviation) before actually measuring visibility with black disc equipment (author's unpublished data). If water management agencies provided the public with guidance for *particular* sites (e.g. by signage or on websites) based on local correlation of *E. coli* with visual clarity, then would-be swimmers could decide whether the water was suitable, unsuitable or indifferent for swimming from the water appearance on a particular occasion.

Figure 6 shows *E. coli* plotted versus visual clarity (Figure 2(a) replotted) with NZ guidelines/thresholds overlain for swimming suitability. The NZ guideline of 1.6 m visual clarity for swimming suitability comes from MfE (1994). The guidelines of 550 cfu/100 mL *E. coli* ('ACTION' level in beach surveillance) and 260 cfu/100 mL ('ALERT' level) are from MfE/MoH (2003). (Microbiological guidelines in NZ have recently been revisited as part of national freshwater policy initiatives, which might, eventually, lead to changes – Milne *et al.* 2017.) These visual clarity and *E. coli* guidelines intersect to divide the dataset into four 'sectors' which can be described as: high faecal contamination-low visual clarity (top-left in Figure 6); low faecal contamination-high visual clarity (bottom-right); low faecal contamination-low visual clarity (bottom-left) and high faecal contamination-high visual clarity (top-right). The lower right sector (high clarity, low *E. coli*), containing the majority (about 60%) of cases, represents conditions suitable for swimming as regards *both* visual clarity and microbiological condition.

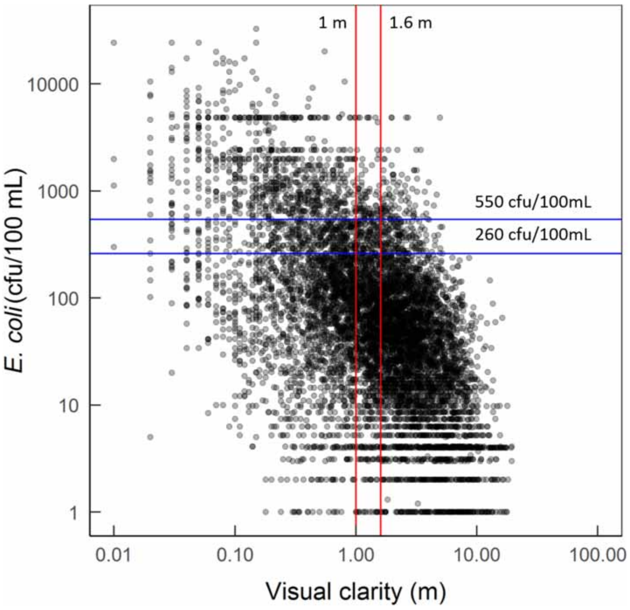

Figure 6 | *E. coli* vs visual clarity at 64 river sites in the NRWQN, 2006–2015, in relation to existing guidelines for swimming water quality in NZ. The horizontal lines represent ALERT (260 cfu/100 mL) and ACTION (550 cfu/100 mL) levels for *E. coli* from MfE/MoH (2003); the vertical lines represent guidelines for visual clarity (1.6 m is from MfE (1994) and 1.0 m an indicative – informal – guideline for visual degradation of water appearance). Only about 1% of points fall into the top-right sector representing relatively high microbial risk (>550 cfu/100 mL) when water is relatively clear (>1.6 m).

Figure 6 suggests that deciding on the basis of visual clarity alone, uninformed by the local relationship to *E. coli*, should protect swimmers from faecally contaminated waters in most rivers in NZ. If would-be swimmers were to avoid waters with visibility <1.6 m, they would also avoid contact with faecally contaminated water with *E. coli* >550 cfu/100 mL in about 99% of cases (top-right sector in Figure 6). If, more conservatively, swimmers were to avoid waters with <1.0 m visibility, for which water is no longer very aesthetically appealing and the riverbed is no longer visible at chest depth (so submerged hazards become difficult to avoid – Smith & Davies-Colley 1992), the *E. coli* concentration would be <260 cfu/100 mL (interpreted as an acceptable level of risk in beach surveillance, MfE/MoH 2003) in about 95% of cases (Figure 6).

However, visual clarity might not reliably indicate absence of microbial hazard in urban-affected rivers where there is often a high and steady background load from sewer leaks. Some urban streams in NZ, in which visual clarity and *E. coli* are routinely measured, appear to be frequently microbially contaminated *while still clear*. For example, in Karori and Kaiwharawhara Streams, Wellington City, medians for these two variables (data from www.lawa.org.nz) would plot in the upper right sector of Figure 6. Routine measurements of both *E. coli* and visual clarity in more urban streams would be valuable.

As pointed out by West & Scott (2016), visual clarity by the black disc technique is very amenable to measurement by volunteer monitors – with the further advantage that the metric is easily understood, in contrast to turbidity. Storey *et al.* (2016) reported good agreement by volunteers with professional measurements of *both* visual clarity and *E. coli* in NZ. This suggests that volunteers could extend professional monitoring, and perform a very valuable public service at recreational sites, by measuring these two key swimming water quality variables.

Faecal contamination status and visual clarity do not together entirely sum up swimming suitability. Another attribute of importance is periphyton, including both nuisance growths and, especially, potentially toxic cyanophytes (NZ Government 2017). Furthermore, trash near swimming sites can severely impact on visual amenity. For example, Lopes *et al.* (2016) suggested that a comprehensive index of swimming suitability should assess the amount and type of trash near the site – particularly because submerged items of some categories (e.g. building rubble, broken bottles) could interact with low visual clarity to increase the hazard to swimmers. Trash and periphyton (including cyanophyte) proliferations would both seem to be amenable to community volunteer assessment with some professional support and guidance (e.g. Lévesque *et al.* 2017).

In ongoing research, we are investigating the potential for NZ's regional water management agencies to provide real-time assessment of swimming water quality. We are also engaging community volunteers to assess swimming suitability, including measurements of the key water quality variables of *E. coli* and visual clarity.

SUMMARY AND CONCLUSIONS

Faecal contamination in NZ rivers, mainly by livestock, correlates moderately (inversely) with visual clarity. Such correlations apparently express co-mobilisation of *E. coli* and fines from in-channel stores. Therefore, measurement (or eye-estimation) of visual clarity can be a valuable guide as regards microbial hazards to swimmers. Such assessment would ideally be informed by a continuous turbidity record (locally calibrated to *both E. coli* and visual clarity) for individual river sites. Even in the absence of such technological and institutional guidance, intending recreational users could visually assess water clarity against an existing national guideline of >1.6 m to decide whether the water is suitable for swimming in terms of both visibility *per se* and faecal microbial status.

Swimming is best avoided when visual clarity is relatively low, certainly when less than about 1.0 m, because, quite aside from microbial status, the water is likely to be aesthetically unappealing and the low clarity may mask submerged hazards. Avoiding swimming in unclear waters will also serve to avoid microbial hazards in NZ rivers generally, although caution is advised near wastewater discharges and in urban-affected rivers which can sometimes be microbially contaminated when still relatively clear.

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