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A water quality index for recreation in Brazilian freshwaters

F. W. Azevedo Lopes, R. J. Davies-Colley, E. Von Sperling and A. P. Magalhães Jr

ABSTRACT

Use of water for leisure activities has long been prevalent in human societies, especially where the climate is favorable. Water resources with appealing conditions for primary contact recreational activities include rivers, waterfall plunge pools, dams and lakes, as well as sea coasts. Recreational use has specific demands for water quality, particularly as regards risks to human health such as exposure to pathogenic organisms, toxic substances, and submerged hazards. In Brazil, there is insufficient monitoring of bathing water conditions and currently used methodology has some limitations particularly the lack of guidance on interpretation of variables other than faecal bacterial indicators. The objectives of this study were: (1) to establish variables contributing to assessment of freshwater bathing conditions in Brazil; (2) to develop an integrated index of suitability-for-use for bathing in Brazil; and (3) to improve the methodology for assessing bathing water quality in Brazil. Based on a metadata analysis and consultation with Brazilian water professionals, a water quality index was developed incorporating the variables: *Escherichia coli*, cyanobacterial density, turbidity (visual clarity) and pH. This index should advance the management of recreational waters in Brazil, by improving the evaluation of freshwater bathing conditions and protecting the health of frequent users.

Key words | bathing, cyanobacteria, *E. coli*, human health risks, visual clarity, water quality index

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INTRODUCTION

The use of water resources for recreation is very common in Brazil and seems to be increasing, apparently driven by the demand for activities in contact with the natural environment as an 'antidote' to modern urban life. However, despite the prevalence of water-based recreation, there have been few studies and monitoring programs in Brazil to assess conditions for bathing, especially in freshwaters which are frequently contaminated by farmland runoff, domestic and industrial wastewater and stormwater (Lopes *et al.* 2014).

Contact recreation in faecally contaminated waters may expose the users to some diseases, especially the elderly and children, and immune-compromised people. Children are often the highest risk group because they have more frequent contact with water compared to other age groups, and during their activities there is a comparatively high likelihood of incidental water ingestion (Pond 2005). Although microbial pathogens are often the main concern for recreational users, other attributes of water may also constrain suitability-for-use for bathing, including potentially toxic cyanobacteria, restricted water clarity that reduces aesthetic quality and masks submerged hazards, and highly acid or basic conditions outside the range of tolerance of the human eye. Furthermore, trash littering the banks and bed of a water body is both aesthetically repulsive and, in the cases of broken glass or steel fragments, may also present a submerged hazard particularly in areas of restricted water clarity.

One of the main challenges facing environmental managers is the conversion of complex environmental data into information that is understandable and accessible to non-technical audiences. Several disciplines, including air

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quality, water quality and economics have developed indexes that aim to convert data into concise and understandable information (e.g., Smith 1989). The use of water quality indices has grown over recent years in an attempt to convey information about the condition of water bodies to non-specialists and the public. However, many of the published indices have various limitations, notably the loss of information during the aggregation process and the 'swamping' of one (unfavourable) variable by others indicating fair to good suitability-for-use (e.g., Nagels *et al.* 2001).

A water quality index based on the minimum operator, as proposed by Smith (1990), seeks to reduce or eliminate such limitations, and allows the inclusion or omission of variables, with less likelihood of interference in the overall result of the index. A minimum operator index takes the overall water quality index value to be the minimum suitability-for-use among contributing variables or attributes, on the basis that one variable will be most severely limiting of suitability-for-use. The minimum operator is superior to those indexes based on aggregation of data, particularly in that it avoids difficult decisions around the relative importance (and hence 'weighting') of different variables.

This work has the main goal of developing a methodology for assessing the suitability of conditions for bathing in fresh water in Brazil, and improving the methods currently used for assessment (established by the Brazilian National Environmental Council; CONAMA 2000), based only on microbial water quality (Hirai & Porto 2014). Our motivations in this research include the apparently poor quality of some Brazilian freshwaters that are nevertheless heavily used for bathing and the (implied) limitations of current Brazilian legislation and regulation, plus the dearth of recent research globally on bathing water quality. An integrated index of water quality, termed ICB, Index of Conditions for Bathing, is proposed and its practicality considered for informing recreational users of freshwaters in Brazil.

METHOD

We used the Delphi ('dispute resolution') technique with a panel of water quality experts to choose appropriate water quality variables for assessment of suitability of freshwaters for primary contact recreation in Brazil. The Delphi method refers to a research methodology that aims to obtain information by consulting experts in a way that minimizes subjectivity (Linstone & Turoff 1975). We consulted 18 Brazilian experts in the areas of water quality, sanitation and public health, working in universities, environmental agencies and sanitation companies. These professionals were selected through the *Lattes* Platform from the Brazilian National Council for Scientific and Technological Development (CNPQ 2011).

We asked the panellists to evaluate 43 variables, selected by metadata analysis of Brazilian standards for water quality assessment, for their influence on contact recreation in Brazilian freshwaters. The technique was applied in two rounds, using electronic questionnaires. In both rounds the participants could suggest the inclusion of other variables and, in the second questionnaire, participants were asked to select the most relevant variables for the composition of the index. For the selection of the variables that should be included in the index, various factors were considered such as the outcome of the expert panel, relevant literature, notably the epidemiological evidence, and feasibility of implementation – which considered duration and costs of analyses, and general availability of suitable laboratory services.

The suitability-for-use curves used in this work to interpret water quality variables, were guided by epidemiological studies, international guidelines, and specific legislation, when available. We considered that this approach might be more appropriate than use of a Delphi panel to determine suitability curves. In cases where a Brazilian standard applies, the standard was adopted as the reference suitability-for-use value of 50%, corresponding to the lower limit of 'suitable' water quality (where 100% represents 'perfect' suitability-for-use and 0% represents the worst conceivable water quality). A metadata analysis of international guidelines and standards (and underpinning research) in water quality, provided the basis for deciding how suitability-for-use changes as a function of water quality variables consistent with existing Brazilian standards.

However, for some variables, such as turbidity, established guidelines are lacking. In such cases we refer to standards established by the Brazilian National Environmental Council resolution 357 (CONAMA 2005) that classifies Brazilian waters by use and establishes standards supporting those uses.

We also used an existing approximate inverse relationship between turbidity and visual clarity of water to assist with interpretation of turbidity (Davies-Colley & Smith 2001; Davies-Colley et al. 2014). Visual clarity is widely measured in New Zealand, a country with legal standards protecting visual clarity of waters (RMA 1991). For example, visual clarity has been measured routinely for 26 years at 77 sites in New Zealand's National Rivers Water Quality network (NRWQN; Davies-Colley et al. 2011). In most other countries, including Brazil, there is considerable historical turbidity data, which is perhaps best interpreted in terms of approximately equivalent visual clarity. Numerical turbidity is somewhat instrument-specific, so the particular nephelometer used should ideally be identified. Furthermore, turbidity should be calibrated (locally) to visual clarity (Davies-Colley & Smith 2001), although a rough estimate can be made using a conversion algorithm given by Davies-Colley et al. (2014).

For the formulation of the proposed index, the methodology adopted was the minimum operator, as used, for example, by Smith (1989, 1990) and Nagels et al. (2001). No weights, reflecting different relative importance, needed to be assigned to the variables, since we intended that the limiting variable (that with the greatest effect on suitability-for-use) should determine the overall index value. The minimum operator seems particularly appropriate for contact recreational water use which is usually most strongly limited at any given time by one particular variable.

Curves were plotted by the authors relating suitability-for-use to water quality through polynomial equations following PNMA (2005) and Davies-Colley & Ballantine (2010). The suitability-for-use as a function of contributing variables changes gradually and does not go abruptly from suitable to unsuitable (Davies-Colley & Wilcock 2004). Thus, the representation of variation between different classes is a useful management tool to check for trends and to facilitate comparisons between water bodies.

The equations describing the suitability-for-use curves (q) allow the calculation of suitability-for-use for each index variable and subsequent classification into quality classes. We extended the (CONAMA 2000), classification of Brazilian recreational waters, based on *Escherichia coli* and faecal coliforms, into four classes: 'Excellent', 'Very good', 'Suitable' and 'Unsuitable'. We also added a fifth 'Very bad' class, to account for the possibility of high levels of contamination, or other very poor conditions that would justify posting warning signage and demand action by managers in order to return water towards suitability for recreation. These water quality descriptors are presented in Table 1, together with an 'intuitive' colour signalling system (discussed below).

RESULTS

Water quality variables and suitability-for-use curves

From the evaluation by the Delphi panel of potential water quality variables affecting bathing-water quality it was possible to discern which variables were the most applicable to Brazil. The panellists agreed by a majority for the inclusion in the index of the following variables: *E. coli* (indicating faecal pollution), (potentially toxic) cyanobacteria, turbidity (indicating visual clarity – which affects aesthetics as well as safety) and pH (which, at extreme values, can irritate the human eye).

It is noteworthy that the panellists were consulted only about which variables were most relevant and should be integrated into a water quality index for Brazilian recreational freshwaters. The suitability-for-use (q) curves were prepared by the authors, guided by epidemiological studies, international guidelines, and specific Brazilian legislation. The selected variables contributing to the bathing suitability index and their rationale are presented in Table 2, and the variables, and their suitability-for-use curves, are considered separately below and compared with curves developed for the same or comparable variables in a recreational water quality index for New Zealand (Nagels et al. 2001).

Table 1 | Classification of water quality classes in the contact recreation index (ICB)

Class	Range
Excellent	$100 \geq ICB \geq 90$
Very good	$90 > ICB \geq 70$
Suitable	$70 > ICB \geq 50$
Unsuitable	$50 > ICB \geq 25$
Very bad	$25 > ICB \geq 0$

Table 2 | Water quality variables selected for the contact recreation index

Variable	Units	Rationale
E. coli	cfu/100 mL	Faecal bacterial indicator (indicator of potential pathogen presence and disease risk)
Cyanobacterial density	Cells/100 mL	Human health risks and aesthetic quality
Visual clarity	Visibility (m) (or turbidity; NTU)	Swimming safety (submerged hazards) and aesthetic quality
pH	pH scale	Safety and comfort for swimming (eyes and skin)

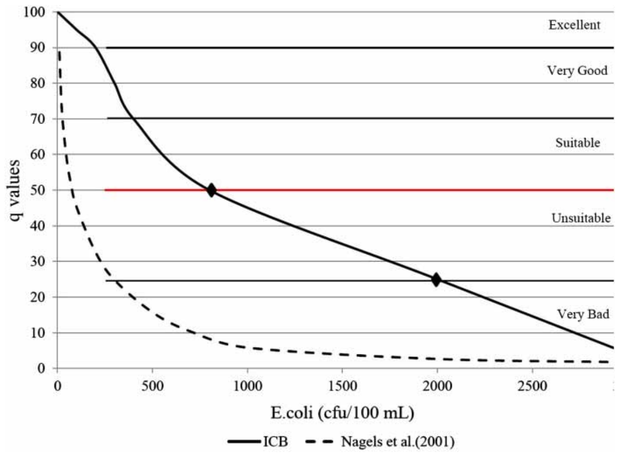

Figure 1 | Suitability-for-use curve for *E. coli.* The ICB curve (solid curve; $q = 9 \times 10^6 x^2 - 0.058x + 97.7$) is anchored by two points as shown that are discussed in the text. The suitability-for-use curve proposed by Nagels *et al.* (2001) is also shown (dashed curve).

Faecal contamination

Microbiological indicators such as *E. coli*, were strongly recommended by the group of experts surveyed (all favoured inclusion). International guidelines and related epidemiological studies point to *E. coli* as the best indicator (currently available) of faecal contamination of fresh water and possible incidence of gastrointestinal pathogens (Dufour 1984; Pruss 1998).

The suitability-for-use curve for *E. coli* (Figure 1; solid curve), was adopted with reference to guidelines already proposed by CONAMA (2000), recognising the absence of specific epidemiological studies for the Brazilian environment. Furthermore, *E. coli* is already regulated in Brazil, consistent with epidemiological studies for freshwaters reported internationally. Also shown for comparison is the suitability-for-use curve as a function of *E. coli* developed by Nagels *et al.* (2001) (Figure 1; dashed curve).

According to CONAMA (2000), freshwaters are considered unsuitable when *E. coli* is greater than 800 cfu/100 mL, in any sample, due to the risk of disease incidence, particularly gastroenteritis. So the Suitable/Unsuitable (q = 50%) boundary was placed at 800 cfu/100 mL. This threshold of suitability may be compared to the (slightly less restrictive) limit of 900 cfu/mL *E. coli* adopted by European Directive 07 (EU 2006).

The incidence of gastrointestinal diseases is significantly higher in swimmers who have contact with contaminated water over 2,300 cfu/100 mL (Stevenson 1953) and 2,700 cfu/100 mL coliforms (Krishnaswami 1971). However, Zmirou *et al.* (2003) found no evidence of a threshold faecal contamination level below which there was no risk of gastrointestinal infection to bathers. In this work, 2,000 cfu/100 mL was adopted as the threshold for the 'Very bad' class, considering that this value is already used by CONAMA (2000), as a standard for unsuitable conditions. So the Unsuitable/Very bad boundary (q = 25%) was placed at 2,000 cfu/100 mL (Figure 1).

The suitability-for-use curve proposed here is appreciably more 'lenient' than that proposed by Nagels *et al.* (2001) (Figure 1). This recognises the reality of widespread faecal contamination of rivers in Brazil due to un-sewered human populations as well as livestock sources, which demands a 'relaxation' of water quality interpretation compared to 'developed' countries such as New Zealand. This amounts to accepting a greater risk of infection to bathers in Brazil.

Cyanobacteria density

The Delphi panel recognised the need to include a variable indicating possible contamination by cyanotoxins, with consequent health risks arising from cyanobacterial blooms in tropical and subtropical freshwater environments. Therefore, cyanobacteria density was the second indicator recommended by the experts surveyed, with 92% voting for inclusion.

Despite the lack of conclusive epidemiological evidence about risks associated with recreational contact in waters with cyanobacteria blooms, the World Health Organization (WHO) and countries such as Australia, Canada and several European nations have recommended guidelines or standards for cyanobacteria density in recreational waters (Stewart *et al.* 2006).

Besides the potential health risks, algal blooms can become aesthetically repulsive to recreational users contacting surface scums, and there is also the possibility of unpleasant odors. Indeed, the taste and odor of the water might potentially provide a warning of the possible occurrence of cyanobacteria. However, it is important to emphasize that the absence of taste and odor does not imply the absence of cyanobacteria and hence (potential) cyanotoxins (Chorus & Bartram 1999).

The cyanobacteria density value proposed for the Excellent/Very good class boundary was adopted from the guidelines in New Zealand, which sets the value of 500 cell/mL as the limit for the best quality class in its classification system (NZMFE 2009) (Figure 2).

The 5,000 cell/mL value, stipulated for the Very good/Suitable class boundary (Figure 2), derives from the epidemiological study of Pilotto *et al.* (1997), who found that swimmers exposed to concentrations exceeding this value had an incidence of symptoms significantly higher than unexposed users.

According to the Brazilian Health Foundation, cyanobacterial counts between 10,000 and 20,000 cell/mL indicate the beginning of a cyanobacteria bloom. Cyanobacteria blooms with densities between 20,000 to 100,000 cell/mL confirm the water quality degradation, while values above 100,000 cells/mL indicate high risk to users, especially by potentially toxic genera (FUNASA 2003).

Guidelines for recreational waters in Australia and Canada recommend a limit of 20,000 cells/mL and 100,000 cells/mL, respectively, for contact recreation. However, Pilotto *et al.* (1997) question the adoption of the (lower) limit of 20,000 cells/mL, considering it insufficient to protect bather health.

In Brazil, CONAMA (2005) establishes the standard of 20,000 cells/mL for density of cyanobacteria in water bodies used for contact recreation, so the Unsuitable/Very bad boundary was set at 20,000 cells/mL (Figure 2). Moreover, COPAM/CERH (2008), which establishes standards for the classification of water quality in the Brazilian state of Minas Gerais, specified the value of 10,000 cells/mL as the threshold for contact recreation, which, as a precaution, was taken as the limit of suitability for the index developed here (i.e. the Suitable/Unsuitable boundary was set at 10,000 cells/mL; Figure 2).

Visual clarity (turbidity)

Among several variables associated with visual aesthetic aspects of water quality (particularly colour and visual clarity measures), turbidity was the most commonly recommended (67%) by the experts consulted in the Delphi panel.

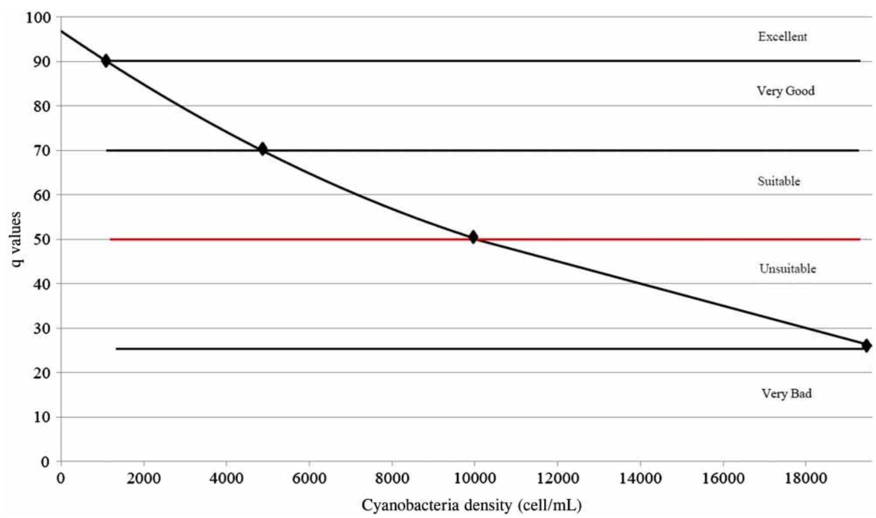

Figure 2 | Suitability-for-use curve for cyanobacteria density ($q = 3 \times 10^{-8}x^2 - 0.0043x + 93.9$). Four 'anchor' points as shown are discussed in the text.

Turbidity is often used by regulatory agencies as an index of the visual clarity of fresh water, even though the correspondence with visual clarity or other attribute versus turbidity is seldom quantified or even understood (Davies-Colley & Smith 2001). As well as being an aesthetic concern, visual clarity influences the safety of recreational activity, particularly the ability of bathers to recognise submerged hazards such as the presence of rocks, snags or dangerous items of trash. Davies-Colley & Smith (2001) and Steel & Neuhausser (2002) recommend (direct) measurement of visual clarity of waters by (horizontal) black disc sighting range ('visibility'). Black disc visibility has the advantage of providing 'real-time', on-site evaluation of visual clarity that is closely related to the fundamental optics of waters (Zanevald & Pegau 2003).

Nagels *et al.* (2001) report use of turbidity as well as visual clarity in their recreational water quality index for New Zealand, with reference to the inverse relationship between these quantities. The overall relationship of visual clarity and turbidity is only approximate because of the diversity of light-scattering particles in different natural waters. But usually a fairly close (inverse) relationship exists in any one particular natural water in which suspended particulate matter is less diverse overall and usually changes systematically with flow-state (Davies-Colley & Smith 2001; Davies-Colley *et al.* 2014). The turbidity corresponds to approximately three times the sighting range (in m) measured (horizontally) by the black disc method (Smith *et al.* 1997) and four times the sighting depth (m) of the *Secchi* disc (Davies-Colley *et al.* 2003). However, the relationship between these variables is not exactly inverse, and a power law probably represents a more general model. For example, Davies-Colley *et al.* (2014) reported data for 77 diverse New Zealand rivers over a three orders of magnitude range as follows: $y_{BD} = 3.09 \times T^{-0.786}$, (R = –0.95) where y_{BD} is the (horizontal) black disc visibility and T is turbidity measured with a Hach 2100AN nephelometer. Turbidity is somewhat instrument-specific, so it is important to state the model of instrument used.

Turbidity can be used as a surrogate for the assessment of visual clarity of waters, especially in places where historical turbidity data records are available but not direct measurements of visual clarity. In Brazil, direct visual clarity measurement has only recently been adopted, which limits its use in the proposed index.

CONAMA (2005) recommends the values of 40 and 100 NTU as borderline for contact recreation and the value of 40 NTU was set as the Unsuitable/Very bad boundary (Figure 3). However, using the power law of Davies-Colley *et al.* (2014), a turbidity of 40 NTU (100 NTU) corresponds to a visual clarity of only (approximately) 17 cm (8 cm), which is obviously insufficient to allow detection of any submerged hazards, including dangerous items of trash, within the water body. These turbidity standards appear to have been promulgated without reference to corresponding visual clarity and without due consideration of the implications for recognising submerged hazards, so their ongoing relevance is questionable.

In the meantime, the reference values for the suitability-for-use curve for turbidity (Figure 3), were prepared by adapting criteria related to visual clarity, proposed by Nagels *et al.* (2001). The standard of 10 NTU (which would correspond to about 51 cm of visual clarity) was adopted as the Suitable/Unsuitable boundary in Figure 3.

The resulting suitability-for-use curve in Figure 3 is appreciably less restrictive than guidelines, adopted in New Zealand and Australia (and the bathing index developed by Nagels *et al.* 2001), but we had to consider Brazilian conditions, particularly the often high turbidity levels due to erosion of deeply-weathered soils rich in highly light-attenuating layer clays, together with soil disturbance by agricultural activities and intense seasonal precipitation in many watersheds. For example, between 1997 and 2012, turbidity values (measured using a Hach 2100 AN nephelometer) averaged 134 NTU (range: 0.3 to

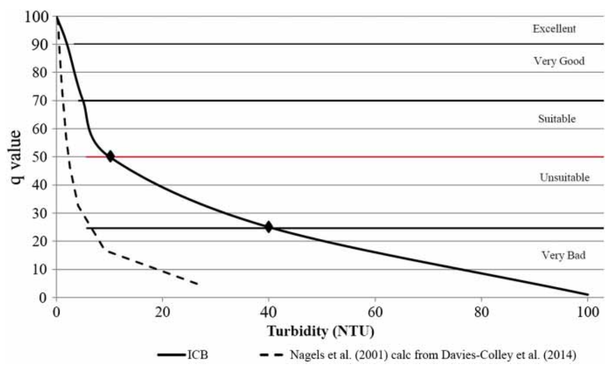

Figure 3 | Suitability-for-use curve for turbidity (solid curve; $q = 0.015x^2 - 2.37x + 88.6$). The curve is 'anchored' by two points (marked) as discussed in the text. The suitability-for-use curve proposed by Nagels *et al.* (2001) for visual clarity (transformed to turbidity) is also shown (dashed curve).

4700 NTU) in the Rio das Velhas, Minas Gerais, Brazil (see 'Use of the index' section).

According to Health Canada (2010), water with a turbidity of 50 NTU is satisfactory for recreation, including swimming activities, despite corresponding to only (about) 14 cm visibility. This emphasises the connection between visual clarity and submerged hazards – which are difficult for bathers to detect and avoid in low clarity water. There is a case for including also, in a Brazilian water quality index for recreation, a rating for the nature and quantity of trash – for both aesthetic and safety reasons.

Although turbid waters are not aesthetically appealing to most people, experience within Brazil is that high air temperatures and high humidity in summer, which coincides with the main academic vacation, can encourage recreational use in waters of poor visibility, due to the scarcity of leisure options, especially for poor people (Von Sperling & Von Sperling 2013). Thus, behaviour of bathers is very subjective (and not easily controlled), despite the increased risk of accidents in water with low visibility.

We propose, therefore, that water with comparatively low visual clarity in Brazil may still be deemed suitable for recreation when microbiological risks are low (CONAMA 2000) and submerged threats are not expected on the bed of the water body (from previous site inspection and signage). This seems a practical approach given the naturally high levels of turbidity during the wet season (summer) in Brazil, although we acknowledge the increased hazard to bathers.

PH

The final attribute contributing to the index is pH, one of the most often-measured water quality variables, and one that is adopted in most indices (Brown *et al.* 1970; Nagels *et al.* 2001), as well as guidelines for bathing (Health Canada 1992; ANZECC/ARMCANZ 2000). The Delphi panel considered this variable important in the Brazilian context: it was the third most frequently (83%) recommended variable.

The limits promulgated by CONAMA (2000) ($6 \leq pH \geq 9$) were adopted to 'anchor' the suitability-for-use curve (i.e., the Suitable/Unsuitable boundaries were set at pH 6 and pH 9 in Figure 4). The optimum value ($q = 100$) for contact

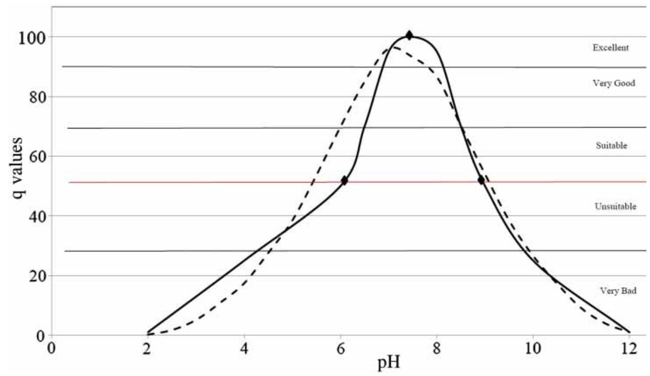

Figure 4 | Suitability-for-use curve (q) for pH (solid curve; $q = -0.122x^3 - 0.747 \times^2 + 31.23x - 64.7$). The curve is 'anchored' by three points discussed in the text. The suitability-for-use curve proposed by Nagels *et al.* (2001) is also shown (dashed curve).

recreation, was taken to be pH 7.4, that according to ANZECC/ARMCANZ (2000) is the pH of lacrimal fluid in the human eye (Figure 4). Note, however, that skin and eye sensitivity (related to pH-buffering) to acid waters can vary appreciably between individuals. The suitability-for-use curve of Nagels *et al.* (2001) overlain in Figure 4 is in broad agreement with that proposed here.

Use of the index – an example

To provide an illustration of its use, the proposed index was applied to a survey of water quality in the Alto Rio das Velhas watershed, from the official monitoring program of Minas Gerais state, between January 2009 and December 2011. Table 3 shows the results of the index for the monitoring site BV013 on the Rio das Velhas, upstream of the Itabirito River, on one occasion.

Rio das Velhas is an important water body for Minas Gerais state, and in response to high levels of contamination, a government program for rehabilitation of water quality has been developed, with the aim of achieving suitability for fishing and contact recreation by 2014. The water sample considered in Table 3 was classified by the ICB as 'Very bad' quality for bathing owing to faecal pollution and low visual clarity (indicated by high turbidity) probably reflecting increased runoff during the rainy season.

The minimum operator formulation allows the calculation of the index even with the absence or loss of data for some variables, owing to problems in sampling or

Table 3 | Example of the Recreational Contact Index in use (Rio das Velhas, Site BV013, March 2014)

	Test results (Site BV013, March 2014)		
Variable	**Results**	**Index value**	**Class**
E. coli (CFU/100 mL)	7,900	1[1]	Very bad
Cyanobacteria (cells/mL)	0	100	Excellent
pH	7	95	Excellent
Visual clarity (turbidity; NTU)	15.2	45	Unsuitable
INDEX value (minimum operator)		1	Very bad
INDEX value (aggregate index with equal variable weighting)		60	Suitable

[1]Minimum sub-index scores = overall index score (very bad conditions for bathing).

analysis for example. However, the possibility should be acknowledged that missing data may be for the variable that would be most limiting, had it been measured. Conventionally formulated indexes (aggregating data) cannot be calculated if any data are missing. Table 3 shows that the poor condition of the Rio das Velhas, as regards both faecal pollution and poor visual clarity, is masked by favourable results for cyanobacteria density and pH in an index based on aggregating variables. For example, application of an aggregate index with equal weightings gave an index value of 60 – 'Suitable' – demonstrating the futility of applying such indices when, as is the case here, some variables are strongly limiting of bathing suitability while others are not limiting.

Another possible use of the ICB is long-term evaluation for classification of bathing sites, as adopted in New Zealand (NZMFE 2003) and Europe (EU 2006).

Figure 5 shows a classification of suitability for contact recreation in the Alto Rio das Velhas watershed based on values from the monitoring data from 2009–2011. The lower course of the Rio das Velhas was classified as 'Very bad' for contact recreation, particularly due to unsewered areas of Itabirito City and some districts of Ouro Preto City. Faecal pollution and low visual clarity (high turbidity) most strongly limit bathing.

The results of application of the index to monitoring on the Rio das Velhas suggests that it will be challenging to achieve acceptable microbial quality (and visual clarity) for bathing. For example, Von Sperling & Von Sperling (2013) showed that even with 95% sewage reticulation and treatment in the watershed (compared to 56% in 2010), the river downstream of Belo Horizonte City may still not achieve the CONAMA (2000) standards for *E. coli*.

GENERAL DISCUSSION

In this paper, we have presented a simple indexing system for contact recreational water quality in Brazilian freshwaters, based on faecal pollution (indicated by *E. coli*), possibility of cyanotoxins (indicated by cyanobacterial cell counts), visual clarity (indicated by turbidity) and pH. The overall suitability-for-use of the water for contact recreation is taken as the minimum suitability-for-use among these four variables, and is classified from 'Excellent' to 'Very bad' (Table 1).

Visual clarity (or its proxy – turbidity) is usually considered an aesthetic concern, but, in developing this index, we have been reminded that visual clarity of waters also relates to safety concerns with turbid (low clarity) waters. There is a case to be made for including also a rating of trash in and near bathing waters. Unsightly trash affects aesthetic quality, but additionally, restricted visual clarity combined with trash may mask some submerged items (e.g., broken glass, steel items, construction garbage) so presenting an increased hazard to bathers.

Braun *et al.* (1995) cite studies with participants speaking different languages, on the perception of risks associated with colours. Red is the colour most associated with high risk and the colours blue, green and white indicate lower risks. Similarly, Griffith & Leonard (1997) found that the colour red is strongly associated with warnings to stop, while black is strongly associated with lethal risk. Here we use red to indicate 'Unsuitable' and black to indicate 'Very bad' conditions for bathing, with a 'traffic light' system (green, amber, red) to cover the range from 'Good' to 'Unsuitable' plus blue for 'Excellent' (Table 1).

The identification and signalling of unsuitable recreational areas in Brazil is the responsibility of the competent environmental authority (municipal, state or federal) (CONAMA 2000). However, the signalling should be employed judiciously by the local environmental

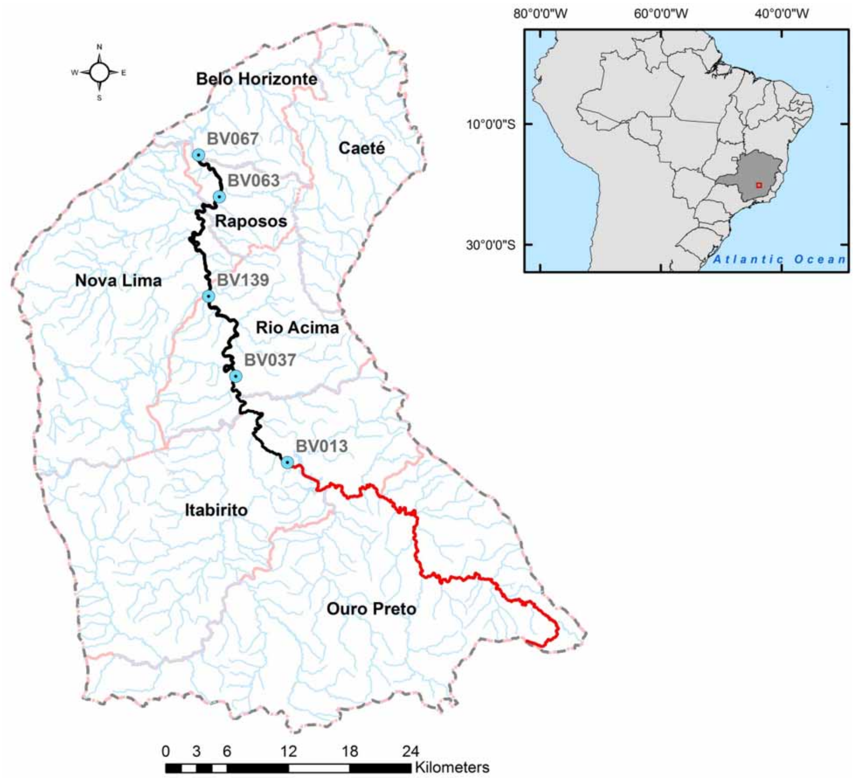

Figure 5 | Contact Recreational Index for Rio das Velhas watershed, between 2009 and 2011. River monitoring sites (labelled) are shown as blue dots. Municipal areas in the vicinity of Belo Horizonte City are shown. Colour coding of the main-stem river indicates the median value of the ICB according to Table 3 (black indicates 'Very bad', red indicates 'Unsuitable'). Please refer to the online version of this paper to see this figure in colour.

authority, given that such signage may have significant economic impacts, especially near resorts that depend on tourism. Long-term monitoring is essential in order to give a fair indication of 'typical' conditions and avoid undue influence of relatively brief episodes of faecal pollution for example.

Some recreational sites may be episodically unsuitable for bathing due to increased runoff following rainfall events or other causes including sewer overflows or algal blooms, which may temporarily impair the water quality. Other waters may have chronically poor recreational quality, which would require a thorough investigation of causes. CONAMA (2000), recommends the investigation of pathogenic organisms at chronically polluted sites.

The proposed indexing system can be regarded as a form of representation of the analytical results of water quality to support decision making by managers and environmental regulators. The water quality index can support the setting of goals for the short, and long term, as well as facilitating comparison between waters and the generation of maps representing suitability-for-use for bathing.

According to CONAMA (2000), the classification of (microbial) water quality for contact recreation should be based on a set of five samples for *E. coli* (or faecal coliforms), collected for 5 weeks or with a minimum interval of 24 hours between samples, in peak use periods. The results of these five samples should be at least 80% compliant with the class standards. However, the commonly used methods for microbiological analysis of water require at least 24 hours incubation (Weisberg 2007), which does not allow near 'real-time' assessment of conditions at the time of contact recreational activity.

In New Zealand a series of at least 100 *E. coli* analyses over 5 years, including any high runoff events intercepted by chance, is used to classify recreational sites (NZME 2003). Such long-term monitoring quantifies the water's long term characteristics at a particular site, as well as providing information on the influence of events that may affect the quality of water, such as rain, sewage overflow or algal blooms. This assessment allows managers to identify 'critical' recreational areas with unsuitable water for bathing, suggesting more frequent monitoring, and specific actions to improve water quality. However, in the case of recreational areas where results demonstrate low risk to users, the standard (low) monitoring frequency would be sufficient.

In this proposed index for bathing waters in Brazil, we recommend maintaining the current monitoring frequency (five weekly samples during the main bathing season) and incorporating long-term evaluation to classify recreational sites so as to optimize the human and financial resources for on-going monitoring and assessment.

The variability in bather numbers among freshwater recreational sites in Brazil needs to be considered. While some waters are popular in specific periods of the year (high season), others are visited every weekend, with weekly monitoring being recommended. At places with well-defined seasons and significant demand for contact recreation, monitoring could be initiated 4 weeks before the start of the high-use season. This would allow the classification of bathing conditions as well as the dissemination of results from the first week, to guide users. The weekly monitoring would ideally be maintained in subsequent weeks throughout the bathing season.

Generally, the water quality monitoring program for contact recreational sites should be planned taking into account the objectives to provide information to users on bathing conditions in certain periods, and allow the acquisition of representative data to support on-going management. The main challenges to be faced in the adoption of systematic monitoring for long-term recreational assessment includes: (1) the selection of priority sites for monitoring; (2) the costs of sampling and laboratory analyses; (3) the logistics of signalling/warnings; and (4) dissemination of results to the public.

One of the main assumptions regarding use of indexes is the practicality of presenting complex information in an understandable manner to non-technical audiences. The adoption of as many as five classes (as recommended in this work – Table 1) may raise doubts in bathers, who probably wish to know, simply, whether or not bathing in the water is recommended. However, the reality is that, for most water quality variables affecting bathing, there is no clear threshold, and suitability-for-use declines gradually and monotonically as indicators such as turbidity or faecal pollution increase (Figures 1–3).

In order to apply the proposed index, adoption of a guidance document incorporating a checklist, including sanitary aspects and threats that could be identified by visual inspection, is recommended. The main goal of this tool would be the identification of risk factors at recreational sites and in the watershed, beyond just the assessment of water quality. This kind of tool is considered essential for management of bathing waters by WHO (2000) and examples have been developed by some environmental agencies elsewhere (NZME 2003; USEPA 2008; Health Canada 2010).

CONCLUSIONS

A recreational water quality index is proposed for Brazilian freshwaters (ICB) that incorporates the four attributes of faecal pollution (*E. coli*), potentially toxic cyanobacteria (cell count), visual clarity (measured directly or indexed by turbidity) and pH. The index integrates the risks to bathers of a biological nature (namely faecal contamination and the incidence of cyanotoxins) as well as aesthetic aspects and physical risks related to the pH and visual clarity of waters. Trash can also affect bathing water quality both in being unsightly and because it represents a hazard particularly where visual clarity is restricted. A possible future development of the index would incorporate trash, ideally character as well as areal density, into assessment of suitability-for-use.

A minimum operator, that is, the suitability-for-use of the most limiting variable, is recommended be taken as the overall index value because of its important advantages over indexes in which variables are aggregated (Smith 1989, 1990). First, the minimum operator identifies the most limiting variable. Second, the minimum operator avoids the 'eclipsing' (or masking) of one (unfavourable) variable by others, which improves the safety and aesthetic assessment of water quality for quality-sensitive uses, such as contact recreation. Third, the minimum operator avoids the need to decide on relative importance (and hence weightings) of different variables, and fourth, the minimum operator can still be calculated even when data for some variables is missing.

Despite the importance of the selected variables for recreation, we recognise the difficulty in establishing standards for the recreational use of waters. The establishment of a suitable methodology for protecting recreational use of freshwaters in Brazil is extremely important in view of the prevalence of bathing which probably reflects the comparative scarcity of leisure facilities, especially for low-income people.

Long-term assessments for contact recreational sites could contribute to the development of action plans by environmental agencies, establishing the conditions for bathing and the main pressures. Long term assessments support management of recreational waters, particularly by meeting the demand for information on the part of potential users.

We believe that the approach to a recreational water quality index presented here has considerable promise for improving the monitoring and management of bathing waters in Brazil, and should stimulate further research and development plus renewed efforts to improve water quality notably the extension of sewage reticulation and treatment. Accordingly, we are currently trialling application of the ICB to several other watersheds in Brazil, and plan to revisit bathing water quality conditions at these locations in a few years' time.

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REFERENCES

ANZEEC & ARMCANZ 2000 *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. National Water Quality Management Strategy. Australia and New Zealand Environment & Conservation Council, Agriculture and Resource Management Council, Canberra.

Braun, C. C., Kline, P. B. & Silver, N. C. 1995 The influence of colour on warning label perceptions. *International Journal of Industrial Ergonomics* **15**, 179–187.

Brown, R. M., McClelland, N. I., Deininger, R. A. & Tozer, R. G. 1970 A water quality index – do we dare? *Water and Sewage Works, Chicago* **117**, 339–343.

Chorus, I. & Bartram, J. 1999 *Toxic Cyanobacteria in Water: a Guide to their Public Health Consequences, Monitoring and Management*. WHO, London.

CNPQ 2011 Painel Lattes: Distribuição geográfica. Conselho Nacional De Pesquisa. http://lattes.cnpq.br/painelLattes/mapa/ (accessed 16 May 2011).

CONAMA 2000 *Resolução 274 de 29 de novembro de 2000*. Conselho Nacional De Meio Ambiente – Estabelece condições de balneabilidade das águas brasileiras, Brasília.

CONAMA 2005 *Resolução 357 de 17 de março de 2005*. Conselho Nacional Do Meio Ambiente – Dispõe sobre a classificação e o enquadramento dos corpos d' água, Brasília.

COPAM/CERH 2008 Deliberação Normativa Conjunta 01 de 05 de maio de 2008. Conselho Estadual De Política Ambiental E Conselho Estadual De Recursos Hídricos – Dispõe sobre a classificação e o enquadramento dos corpos d' água. Diário do Executivo – Minas Gerais.

Davies-Colley, R. J. & Smith, D. G. 2001 Turbidity, suspended sediment and water clarity – a review. *Journal of the American Water Resources Association* **37**, 1085–1101.

Davies-Colley, R. J. & Wilcock, R. J. 2004 Water quality and chemistry in running waters. In: J. S. Harding, P. Mosley, C. Pearson & B. Sorrell (eds). *Freshwaters of New Zealand*. New Zealand Hydrological Society Inc. and New Zealand Limnological Society Inc., New Zealand.

Davies-Colley, R. J. & Ballantine, D. J. 2010 Suitability of New Zealand rivers for contact recreation – a pilot application of a water quality index to the National Rivers Water Quality Network (NRWQN). NIWA Technical Report 133, 19 pp.

Davies-Colley, R. J., Vant, W. N. & Smith, D. G. 2003 *Colour and Clarity of Natural Waters. Science and Management of Optical Water Quality*. Blackburn Press, New Jersey, USA. p. 310.

Davies-Colley, R. J., Smith, D. G., Ward, R., Bryers, G. G., McBride, G. B., Quinn, J. M. & Scarsbrook, M. R. 2011 Twenty years of New Zealand's National Rivers Water Quality Network: benefits of careful design and consistent operation. *Journal of the American Water Resources Association* **47**, 750–771.

Davies-Colley, R. J., Ballantine, D. J., Elliott, S. H., Swales, A., Hughes, A. O. & Gall, M. P. 2014 Light attenuation – a more

effective basis for the management of fine suspended sediment than mass concentration? *Water Science and Technology* **69** (9), 1867–1874.
Dufour, A. P. 1984 *Health Effects Criteria for Fresh Recreational Waters*. EPA 600/1–84–004. US Environmental Protection Agency, Cincinnati, OH.
EU 2006 *Directive 2006/7/EC of 15 February 2006: Concerning the Management of Bathing Water Quality and Repealing Directive 76/160/EEC*. Official Journal of the European Union, Brussels, 2006, p. 15.
FUNASA 2003 *Cianobactérias Tóxicas na Água para consumo Humano na saúde Pública e Processos de Remoção em Água para Consumo Humano*. Fundação Nacional da Saúde, Ministério da Saúde, Brasília.
Griffith, L. J. & Leonard, S. D. 1997 Association of colours with warning signal words. *International Journal of Industrial Ergonomics* **20**, 317–325.
Health Canada 1992 *Guidelines for Canadian Recreational Water Quality*. 2nd edn. Federal-Provincial-Territorial Committee on Health and the Environment, Ottawa, Ontario.
Health Canada 2010 *Guidelines for Canadian Recreational Water Quality*. 3rd edn. Federal-Provincial-Territorial Committee on Health and the Environment, Ottawa, Ontario.
Hirai, F. M. & Porto, M. F. A. 2014 Metodologias de Previsão de Balneabilidade e sua Aplicação na Gestão da Qualidade da Água Destinada à Recreação. *Revista Brasileira de Recursos Hídricos* **19**, 339–345.
Krishnaswami, S. 1971 Health aspects of water quality. *Journal of the American Public Health Association* **61**, 2259–2268.
Linstone, H. A. & Turoff, M. 1975 *The Delphi Method: Techniques and Applications*. Adison-Wesley, Massachusetts.
Lopes, F. W. A., Magalhaes Jr, A. P. & Von Sperling, E. 2014 Metodologia para avaliação de condições de balneabilidade em águas doces no Brasil. *Revista Brasileira de Recursos Hídricos* **19**, 124–136.
Nagels, J. W., Davies-Colley, R. J. & Smith, D. G. 2001 A water quality index for contact recreation in New Zealand. *Water Science and Technology* **43** (5), 285–292.
NZMFE 2003 *Microbiological Water Quality Guidelines for Marine and Freshwater Recreational Areas*. New Zealand Ministry for the Environment, Wellington, New Zealand.
NZMFE 2009 *New Zealand Guidelines for Cyanobacteria in Recreational Fresh Waters – Interim Guidelines*. Prepared for the Ministry for the Environment and the Ministry of Health (S. A. Wood, D. P. Hamilton, W. J. Paul, K. A. Safi & W. M. Williamson, eds). Ministry for the Environment, Wellington.
Pilotto, L. S., Douglas, R. M., Burch, M. D., Cameron, S., Beers, M., Rouch, G. J., Robinson, P., Kirk, M., Cowie, C. T., Hardiman, S., Moore, C. & Attewell, R. G. 1997 Health effects of exposure to cyanobacteria (blue-green algae) during recreational water-related activities. *Australian and New Zealand Journal of Public Health* **21**, 562–566.
PNMA 2005 *Sistema de cálculo da qualidade da água (SCQA)*. Estabelecimento das Equações do índice de Qualidade das Águas. Programa Nacional do Meio Ambiente, SEMAD/PNMAII.
Pond, K. 2005 *Water Recreation and Disease. Plausibility of Associated Infections: Acute Effects, Sequelae and Mortality*. IWA/WHO, London.
Pruss, A. 1998 Review of epidemiological studies on health effects from exposure to recreational water. *Journal of Epidemiology* **27**, 471–478.
RMA 1991 Resource Management Act, New Zealand Parliament, Wellington. http://www.legislation.govt.nz/act/public/1991/0069/latest/DLM230265.html.
Smith, D. G. 1989 A new form for water quality index for rivers and streams. *Water Science and Technology* **21** (2), 123–127.
Smith, D. G. 1990 A better water quality indexing system for rivers and streams. *Water Research* **24**, 1237–1244.
Smith, D. G., Davies-Colley, R. J., Knoeff, J. & Slot, G. W. J. 1997 Optical characteristics of New Zealand rivers in relation to flow. *Journal of the American Water Resources Association* **33**, 301–312.
Steel, E. A. & Neuhausser, S. 2002 Comparison of methods for measuring visual water clarity. *Journal of the North American Benthological Society* **21**, 326–335.
Stevenson, A. H. 1953 Studies of bathing water quality and health. *American Journal of Public Health* **43**, 529–538.
Stewart, I., Weeb, P. M., Schluter, P., Fleming, L. E., Burns Jr, J. W., Gantar, M., Backer, L. C. & Shaw, G. R. 2006 Epidemiology of recreational exposure to freshwater cyanobacteria – an international prospective cohort study. *BMC Public Health* **6** (93), 1–11.
USEPA 2008 *Great Lakes Beach Sanitary Survey User Manual*. EPA-823-B-06-001. US Environmental Protection Agency, Cincinnati, OH.
Von Sperling, M. & Von Sperling, E. 2013 Challenges for bathing in rivers in terms of compliance with coliform standards. Case study in a large urbanized basin (das Velhas River, Brazil). *Water Science and Technology* **67** (11), 2534–2542.
Weisberg, S. B. 2007 A management context for the statistical design of recreational contact water quality monitoring programs. In: L. J. Wymer (ed.). *Statistical Framework for Recreational Water Quality Criteria and Monitoring*. John Wiley & Sons, UK, pp. 13–17.
WHO 2000 *Monitoring Bathing Water: A Practical Guide to the Design and Implementation of Assessments and Monitoring Programs*. E & FN Spon, London, 311 pp.
Zanevald, J. & Pegau, W. 2003 Robust underwater visibility parameter. *Optics Express* **11**, 2997–3009.
Zmirou, D., Pena, L., Ledrans, M. & Letertre, A. 2003 Risks associated with the microbiological quality of bodies of fresh and marine water used for recreational purposes: summary estimates based on published epidemiological studies. *Archives of Environmental Health* **58**, 703–711.

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