Science of the Total Environment 485–486 (2014) 643–652

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Water quality laboratories in Colombia: A GIS-based study of urban and rural accessibility

Jim Wright [a,*], Jing Liu [a], Robert Bain [b], Andrea Perez [c], Jonny Crocker [b], Jamie Bartram [b], Stephen Gundry [d]

[a] Geography and Environment, University of Southampton, Highfield, Southampton SO17 1BJ, UK
[b] The Water Institute at UNC, Gillings School of Global Public Health, University of North Carolina at Chapel Hill, 170 Rosenau Hall CB #7400, 135 Dauer Drive, Chapel Hill, NC 27599-7400, USA
[c] Facultad de Ciencias e Ingeniería, Universidad de Boyacá, Campus Universitario Cra 2a este #64-169 Tunja, Boyacá, Colombia
[d] Water & Health Research Centre, Department of Civil Engineering, Queens Building, University Walk, Bristol BS8 1TR, UK

HIGHLIGHTS

- We calculated drive-times to laboratories and sample holding times in Colombia.
- 11% of required rural samples are more than 6 hours' drive from the nearest laboratory.
- 30% of required rural samples may be stored in transit for more than 6 h.

ARTICLE INFO

Article history:
Received 29 January 2014
Received in revised form 26 March 2014
Accepted 26 March 2014
Available online xxxx

Editor: Damia Barcelo

Keywords:
Monitoring
Spatial analysis
Drinking water
Faecal indicator bacteria
Water supply
GIS

ABSTRACT

The objective of this study was to quantify sample transportation times associated with mandated microbiological monitoring of drinking-water in Colombia. World Health Organization Guidelines for Drinking-Water Quality recommend that samples spend no more than 6 h between collection and analysis in a laboratory. Census data were used to estimate the minimum number of operational and surveillance samples required from piped water supplies under national regulations. Drive-times were then computed from each supply system to the nearest accredited laboratory and translated into sample holding times based on likely daily monitoring patterns. Of 62,502 surveillance samples required annually, 5694 (9.1%) were found to be more than 6 h from the nearest of 278 accredited laboratories. 612 samples (1.0%) were more than 24 hours' drive from the nearest accredited laboratory, the maximum sample holding time recommended by the World Health Organization. An estimated 30% of required rural samples would have to be stored for more than 6 h before reaching a laboratory. The analysis demonstrates the difficulty of undertaking microbiological monitoring in rural areas and small towns from a fixed laboratory network. Our GIS-based approach could be adapted to optimise monitoring strategies and support planning of testing and transportation infra-structure development. It could also be used to estimate sample transport and holding times in other countries.

1. Introduction

The World Health Organization (WHO) Guidelines for Drinking-water Quality cover both water supply surveillance by public health authorities and operational monitoring by service providers (WHO, 2011). Water quality testing, as part of both surveillance and operational monitoring, is an integral part of assuring the safety of water supplies. Furthermore, microbial and chemical water safety are increasingly recognized as important dimensions of international monitoring of safe drinking-water access for the Millennium Development Goals' target (Bain et al., 2012b; Onda et al., 2012; WHO and UNICEF, 2011) and future Sustainable Development Goals. Despite the importance of water quality monitoring, laboratory infrastructure, trained staff, and transport resources for drinking-water sampling and testing are insufficient in many low- and middle-income countries (Chuang et al., 2011). Monitoring of the small community supplies that often predominate in rural areas is particularly challenging with limited resources, as is the monitoring of supply systems in more remote small towns. This is because such remote areas typically lack personnel who are trained in monitoring techniques and are not able to benefit from the economies of scale that arise from the processing of a large number of samples.

Transportation of samples for microbiological analysis is particularly problematic for small rural supplies, because they are often located far from a laboratory creating problems of sample deterioration especially

* Corresponding author. Tel.: +44 2380 594619.
E-mail addresses: j.a.wright@soton.ac.uk (J. Wright), jenny19880813@gmail.com (J. Liu), rbain@email.unc.edu (R. Bain), aperezv@uniboyaca.edu.co (A. Perez), crockerj@live.unc.edu (J. Crocker), jbartram@email.unc.edu (J. Bartram), stephen.gundry@bristol.ac.uk (S. Gundry).

http://dx.doi.org/10.1016/j.scitotenv.2014.03.127
0048-9697/

for microbiological testing. The WHO (1997: p. 53) recommends "the time between sample collection and analysis should, in general, not exceed 6 h, and 24 h is considered the absolute maximum." It goes on to recommend that samples are transported in an insulated container and under ice, so as to inhibit regrowth of indicator bacteria. Where ice is unavailable, the WHO recommends that sample transportation time should not exceed 2 h. National advice on sample holding times is similar. In Colombia, the *Instituto Nacional de Salud* (INS; National Institute of Health) recommends that sample transport time should not exceed 6 h (Instituto Nacional de Salud, 2011), whilst the US Environmental Protection Agency recommends that the time between sample collection and start of incubation does not exceed 30 h (US EPA, 2005). In response to the logistical difficulties of transporting samples to distant laboratories, a number of microbiological testing technologies have emerged that are based around portable and on-site 'field kits'. A recent review identified 44 such testing technologies (Bain et al., 2012a), though these field tests are not used for compliance monitoring in most settings.

The scale of the logistical challenge in monitoring remote water supplies has to date remained largely unquantified. This paper therefore aims to estimate drinking-water sample transportation and holding times based on the Colombian network of fixed laboratories. In so doing, we aim to develop a GIS-based method that could be used to estimate sample holding times in other countries. To quantify sample transport logistics, we use three steps. First, we map laboratory facilities and the distribution of water supplies in Colombia. Second, we estimate the number of microbiological samples required from these supplies under national regulations and standards. Third, we estimate the travel times from water supplies to laboratory facilities so as to quantify the scale of the logistical challenge associated with water quality monitoring. Through this analysis we identify areas that are too remote for monitoring via the existing laboratory network.

2. Methods

2.1. Study setting

According to the latest WHO/UNICEF Joint Monitoring Programme (JMP) estimates for 2011, 93% of Colombians make use of an improved water source, with 88% having water piped into the household. However, in keeping with many other countries, access to piped water within the home is lower in rural areas at 61%, compared with 97% in urban areas (WHO and UNICEF, 2013). The analysis presented here focuses only on piped supplies.

Water quality monitoring in Colombia can be divided into operational monitoring, intended to inform operational planning and management of water quality, and surveillance monitoring, which provides oversight of drinking-water safety. Overall regulation of drinking-water suppliers in Colombia is the responsibility of the *Superintendencia de Servicios Públicos Domiciliarios* (SSPD; Superintendency of Public Utilities), which prescribes the number of operational monitoring samples required from water suppliers each year. Operational monitoring is the responsibility of water service providers, who must report data to government via the *Sistema Único de Información* (SUI; Single Information System). Results are used for operational purposes, and are additionally sent to the SSPD for compliance assessment, and to the Ministries of Social Protection and of the Environment upon request. Larger, formal providers with structured distribution systems are found mainly in urban areas, whilst small, often informal providers are dispersed in rural and peri-urban areas and small towns (Instituto Nacional de Salud, 2012). The frequency of monitoring and related reporting often meets or exceeds recommended levels among the larger, urban providers (SSPD, 2011), whereas monitoring by small, informal providers is more sporadic and sometimes non-existent.

Surveillance monitoring in Colombia is performed by the *Secretaría de Salud Municipal* (Secretary of Municipal Health) and/or *Secretaría de Salud Departamental* (Secretary of Departmental Health), that report results to the INS via the *Sistema de Información de la Vigilancia de la Calidad del Agua para Consumo Humano* (SIVICAP; Information System for Drinking Water Quality Surveillance) (Instituto Nacional de Salud, 2012). The INS makes use of a network of both public and private laboratories across the country for surveillance monitoring, with at least one INS laboratory per state. Surveillance monitoring results are then sent to the INS *Grupo de Salud Ambiental* (Environmental Health Group) in the capital, Bogota. The frequency of sampling for operational monitoring is higher than that for surveillance monitoring and the total number of samples collected nationally has increased markedly since 2007 as a result of regulatory changes introduced in that year.

2.2. Data sources

To identify laboratories approved for microbiological testing of samples for surveillance monitoring, we extracted the names and addresses of laboratories listed under Articles 1 and 3 of Resolution 431 of the Ministry of Health and Social Protection (Ministerio de Salud y Protección Social, 2012). Article 1 indicates laboratories that are approved for microbiological and chemical testing, whilst Article 3 lists laboratories that are approved only for microbiological testing.

To map the spatial distribution of required water tests, we chose to use census data in preference to data on water service providers (obtainable from the SSPD web site) because census data provide information on the location of small community supply users, unlike the service provider data which only cover large piped supplies. The latest national census, conducted on 3rd October 2005, included a question on the type of household water source: "Where does the household primarily collect water for drinking and preparing food?" Data on household water source type were obtained for 1119 municipalities from an online portal (Departamento Administrativo Nacional de Estadistica, 2013). Statistics for each municipality were further broken down into urban and rural areas, with the urban population defined as that of the *cabecera* or principal municipal town (average population: 28,500) and the rural population comprising the remainder of the municipality (average population: 9800). To further disaggregate these figures, we also drew on gridded estimates of total ambient population from the LandScan database (Dobson et al., 2000). These estimates are derived by assigning population within each municipality to constituent grid cells that have suitable characteristics for human habitation (e.g. proximity to roads and suitable topography).

As a basis for estimating the travel times between water supplies and laboratories, we downloaded map layers depicting the locations of human settlements and the road and river networks from an online portal (UN-OCHA, 2013).

2.3. Spatial distribution of laboratories and required samples

The addresses of Colombian laboratories were translated into a latitude and longitude via the geocoding facility in the Google Maps Application Programming Interface (API). The API provided one or more candidate locations for each address, either at address block, street, town, or department level. All output addresses were then manually reviewed. Where multiple candidate locations were provided or the match address was incorrect, interactive Google Maps searches were used to identify the laboratory's most likely location.

We used 2005 census figures for the number of urban and rural households with piped water to estimate the number of surveillance and operational samples required. For urban piped supplies, we assumed that households with piped water in each of 1093 *cabeceras* were served by a single, integrated supply system. To represent the spatial distribution of rural piped supply systems, we assumed that piped systems would be located in areas of higher population density. LandScan gridded estimates of ambient population were used to identify rural pixels with population counts of more than 200 people (a pixel being approximately 1 km^2). Contiguous groups of such high population density pixels were then grouped together and their total populations and centroids were calculated. Following a dasymetric mapping approach (Mennis, 2003), municipality-level counts of rural households with piped water were then divided up between these patches of higher population density, pro rata to each patch's estimated population according to LandScan. The threshold value of 200 people per pixel for population density was chosen so as to generate a plausible number of discrete piped supply systems, whilst also empirically matching municipality-level counts of households with piped water. Thus, this procedure incorporated all the piped supply users reported in the census and distributed them into areas of higher population density. Almost all rural piped users were accounted for by the procedure, except for 26,650 (0.6% of rural piped users) who lived in municipalities containing no densely populated patches. This threshold generated 5729 discrete rural supply systems, alongside the estimated 1093 urban supply systems described above. This figure exceeded the 4327 providers registered with government (SSPD, 2011), thereby plausibly reflecting incomplete registration among water service providers nationally. Additionally, a count of rural households living in such high density areas better predicted the number of rural households with piped water in each municipality ($n = 1090$; $R^2 = 0.65$), compared to a regression model based on all rural households per municipality ($R^2 = 0.53$).

So as to generate the number of samples required for monitoring, we then applied the regulatory guidance in Resolution 2115 (Ministerio de Protección Social and Ministerio de Ambiente Vivienda y Desarrollo Territorial, 2007) to the *cabecera* and rural populations using piped water (Tables 1 and 2). In translating the number of households using a particular water supply type into a head count, we assumed that household size was constant within the rural versus urban parts of each municipality.

2.4. Calculation of sample travel times to laboratory

To calculate travel times to the nearest laboratory, we generated a gridded cost or impedance surface (Martin et al., 2002). Each grid cell in a cost surface contains an estimate of the time required to cross the cell. These impedance values can then be aggregated to identify the least cost route from a given origin to a given destination. In compiling our impedance surface, we used the national speed limit of 80 km/h on principal roads, 60 km/h on secondary roads, and 30 km/h in urban areas and on unpaved roads, and, following Blyde (2012), 11 km/h on tracks. For 7 departments in southeastern Colombia, where some remoter settlements in the Amazon rainforest are accessible by riverboat only and there is no road network (Armenteras et al., 2006), we assumed a speed of 22 km/h along navigable rivers. We then calculated journey times to the nearest laboratory, and catchment areas of each laboratory, based on this impedance surface.

We used the cost surface technique in preference to travel times automatically derived from the Google Maps API, since the terms of use for the API only allow for web site development, not research (Google, 2013). We also used the cost surface approach because we found via manual searches that Google Maps could not resolve drive-times for approximately 10% of trips from settlements to laboratories, these typically being the longer trips. However, to evaluate our cost surface, we randomly selected 50 cabecera-to-laboratory origin-destination pairs and manually obtained drive time estimates for these journeys from Google Maps. For this random sample of 50 journeys, we then calculated Pearson correlation coefficients between the Google Maps drive-times, those from our cost surface, and simple straight-line distance from *cabecera* to laboratory.

Table 1
Required minimum frequency of testing for operational monitoring for total coliforms/ *E. coli* by piped water service providers in Colombia.
Ministerio de Protección Social and Ministerio de Ambiente Vivienda y Desarrollo Territorial (2007).

Population served by piped supply system	Frequency	Minimum no of samples to be analysed per period
≤2500	Monthly	1
2501–10,000		3
10,001–20,000	Fortnightly	4
20,001–100,000	Weekly	8
100,001–250,000	Daily	3
251,000–500,000		5
500,001–1,000,000		6
1,000,001–1,250,000		7
1,250,001–2,000,000		10
2,000,001–4,000,000		12
>4,000,000		12 plus 1 per each additional 200,000 population served

2.5. Estimation of sample holding times

Finally, we translated the estimated journey times between sample locations and laboratories into sample holding times, as an approximate estimate of the time each sample spent after collection before arriving at the laboratory, reflecting the way monitoring teams operate in practice. Data on daily monitoring patterns are limited, but a study by Crocker and Bartram (2014) found that the number of samples collected per day ranged from 5 in rural India (West Bengal) to 24 in urban Jordan. Based on these figures and the authors' personal experience, we made some simple assumptions in order to estimate sample holding times. In rural areas, we assumed that monitoring teams would spend 2 h travelling to the field and that 45 min would elapse between the collection of successive samples. This latter figure included time for travel between monitoring locations, as well as the task of collecting the sample. In urban areas, we assumed that monitoring teams would spend an hour travelling to the field and 30 min would elapse between the collection of successive samples. These assumptions suggested that 10 samples would be collected per day in urban areas and 4 in rural areas. On the basis of these assumptions, we added a delay to account for the collection of multiple samples on the same day and travel back from the field to the journey times to the nearest laboratory. We first doubled and then halved these estimates to assess the sensitivity of our findings to these assumptions.

3. Results

3.1. Spatial distribution of laboratories and required samples

In total, there were 257 laboratories accredited for both microbiological and chemical testing, and a further 21 laboratories accredited for microbiological testing only. Of these, the locations of 195 were automatically geocoded via the Google Maps API, with the remaining 83 being located through interactive online searches of Google Maps. In terms of precision, 64 laboratories were geocoded to a matching nearby town name, 29 to a matching street name within a town, and 185 to a matching address block. The distribution of these laboratories is shown in Fig. 1.

Fig. 2 shows the estimated number of microbiological surveillance samples required annually from piped supply systems under national regulations. In total 62,502 samples were required for the whole country, with the majority (36,720) being required for rural areas. The estimated number of operational samples was larger (219,434) and dominated by urban areas (140,098 samples).

3.2. Travel times to nearest laboratory for water samples

Fig. 3 shows the relationship between journey times derived from a cost surface and those calculated via Google Maps for a random sample of 50 journeys from *cabeceras* to the nearest laboratory. Overall, the cost

Table 2
Stipulated minimum frequency of testing for health surveillance in Colombia. Ministerio de Protección Social and Ministerio de Ambiente Vivienda y Desarrollo Territorial (2007).

Population served by piped supply system	Minimum no of samples to be analysed per month
≤2500	0.5
2501–10,000	1
10,001–20,000	2
20,001–100,000	5
100,001–250,000	10
251,000–500,000	15
500,001–1,000,000	30
1,000,001–2,000,000	60
2,000,001–4,000,000	96
>4,000,000	96 plus 1 for each additional 50,000 population served

surface generated slightly longer journey times relative to Google Maps, but there was a close correspondence between the two sets of journey time estimates ($r = 0.79$; $p < 0.001$). Relative to these cost surface-derived estimates of journey times, there was a somewhat weaker relationship between straight-line distances and journey times estimated via Google Maps ($r = 0.71$; $p < 0.001$ — data not shown).

Fig. 4 shows the estimated travel time to the nearest laboratory accredited for microbiological testing, based on the cost surface. Travel times to the nearest laboratory in much of the more sparsely populated areas, particularly in the south and east, exceed the 6 hours' sample holding time recommended by WHO.

Fig. 5 shows the distribution of samples required for microbiological surveillance and operational monitoring of piped supplies, versus journey time to the nearest accredited laboratory. 4.5% (1158) of urban surveillance samples and 10.7% (3924) of rural surveillance samples were between 6 and 24 hours' travel from the nearest laboratory, with a

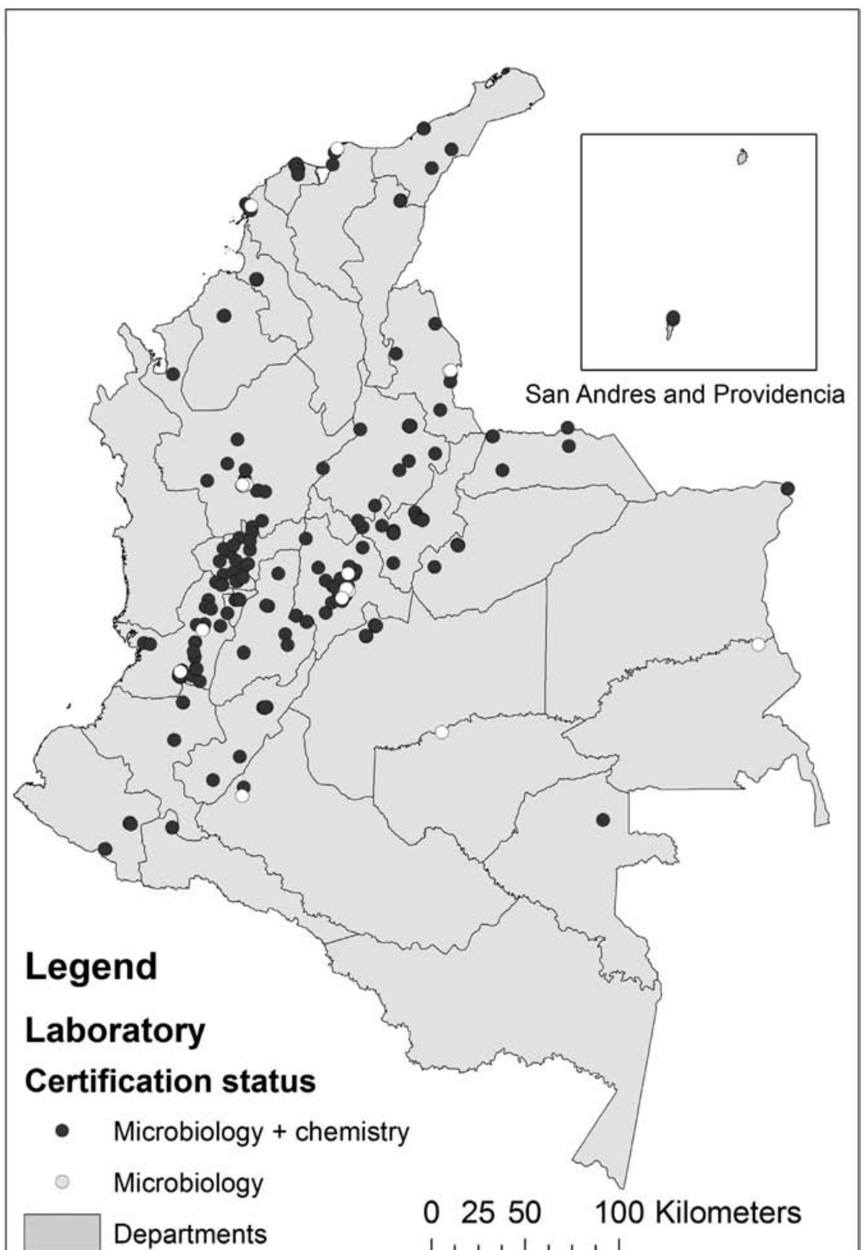

Fig. 1. Map of Colombian laboratories accredited for microbiological testing under Resolution 431 (inset: the archipelago of San Andres and Providencia).

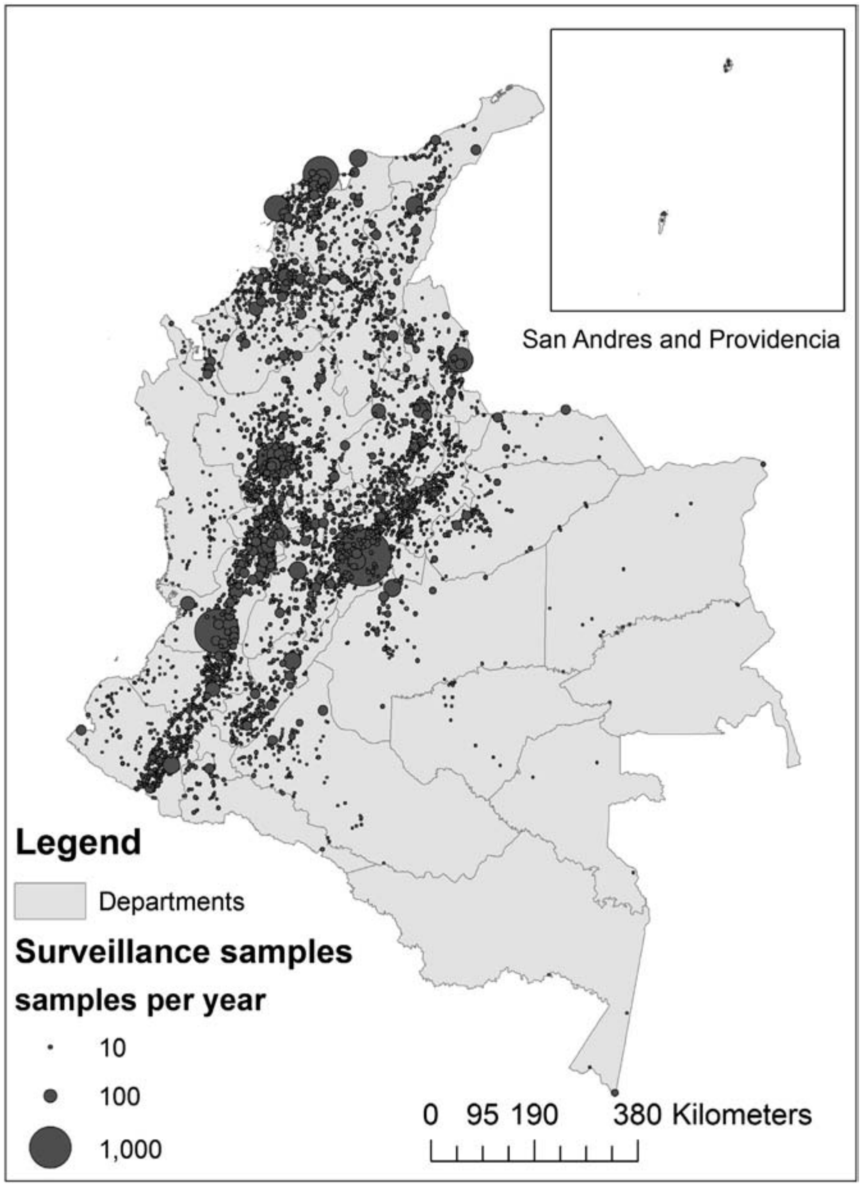

Fig. 2. Map of number of microbiological surveillance samples required per year for piped water supplies (inset: the archipelago of San Andrés and Providencia).

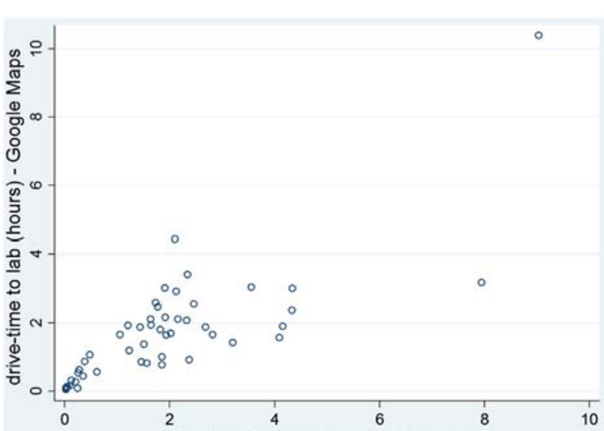

Fig. 3. Google Maps versus cost surface drive times for a random sample of 50 journeys from cabecera to the nearest laboratory.

further 0.8% (216) of urban samples and 1.1% (396) more tha 24 hours' travel from the nearest laboratory. 3.2% (4472) of urban operational samples were 6 to 24 hours' travel from the nearest laboratory, as were 10.1% (8028) of rural operational samples. 0.4% (560) of urban samples and 1.0% (792) of rural samples were more than 24 hours' travel away. An estimated rural population of 275,000 was served by piped systems that were more than 6 hours' travel from the nearest laboratory.

3.3. Estimated sample holding times

Fig. 6 shows the estimated sample holding times for rural and urban areas. For the base case of 4 samples per day in rural areas, 29.4% (25.8–32.4%) of operational samples and 31.0% (27.2–34.1%) of surveillance samples were estimated to arrive in the laboratory after the recommended 6 h for holding samples. For the base case of 10 samples per day in urban areas, these proportions were 11.9% (9.5–13.5%) for operational samples and 16.9% (13.5–20.3%) for surveillance samples. The results from the sensitivity analysis, derived by doubling and halving the number of samples collected per day, are shown in brackets.

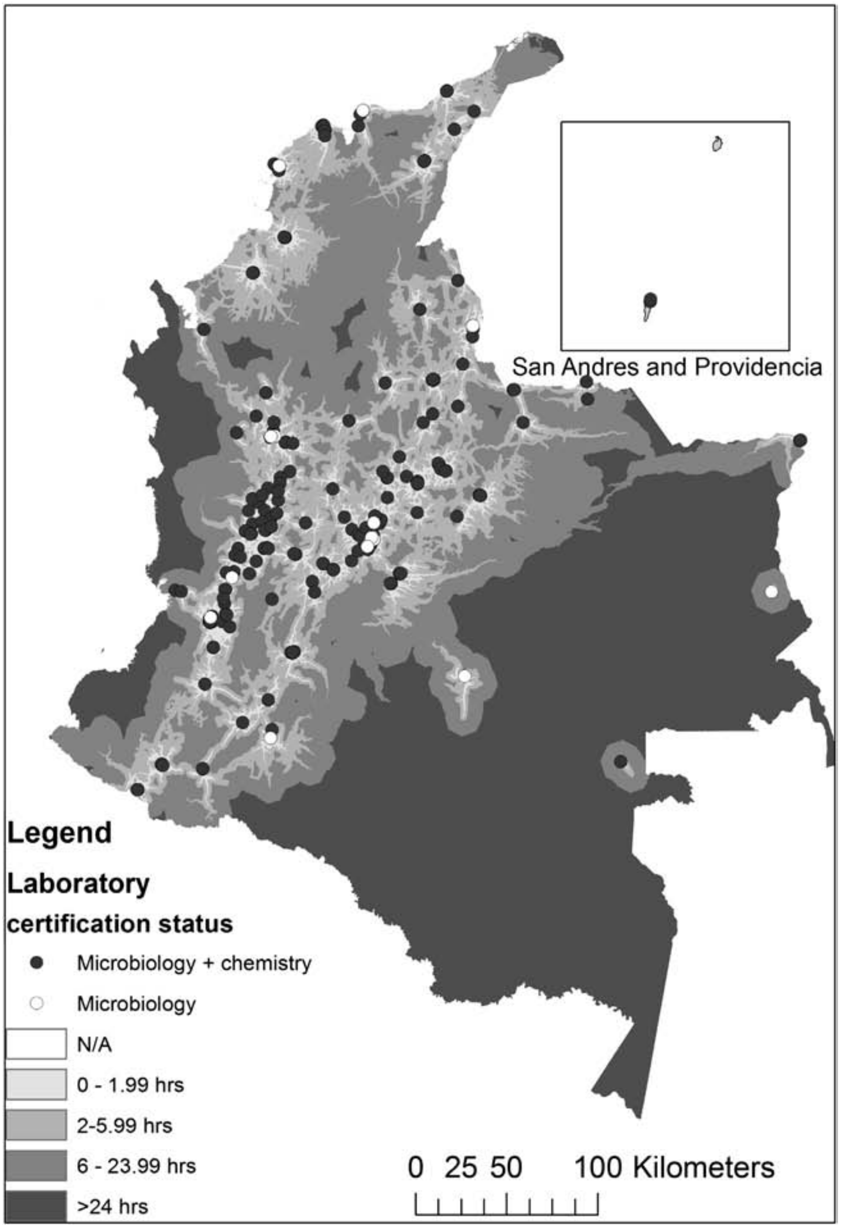

Fig. 4. Travel times (in hours) to the nearest accredited microbiological laboratory.

4. Discussion

4.1. Implications for drinking-water quality monitoring

There is a growing emphasis on ensuring equity in safe water access (Luh et al., 2013; Yang et al., 2013), but despite this, rural areas continue to lag behind urban areas (de Barros et al., 2009). Systematic review evidence drawn from low and middle income countries (Bain et al., accepted) suggests that the microbial quality of rural water supplies is lower than in urban areas and there is evidence from Peru to suggest that this applies even for the same type of water supply (Miranda et al., 2010). A study from seven developing countries found that monitoring of small water supplies has much lower compliance for water safety parameters than large water supplies (Crocker and Bartram, 2014). Specifically, it found that the compliance for large supplies is 100%, whilst smaller supplies have a compliance of approximately 60%. In Colombia, a Water Quality Risk Index (Indice del Riesgo de la Calidad del Agua — IRCA) is used to assess drinking-water quality, calculated as a weighted linear combination of various parameters including total coliforms and *Escherichia coli*. Nationally, total coliforms, residual chlorine and *E. coli* are the parameters that most frequently do not comply with guideline values. The IRCA Water Quality Index values for piped water from 2010 were generally poorer in rural municipalities than in urban ones (SSPD, 2011), suggesting greater rural drinking-water contamination for Colombia. One difficulty in addressing this challenge is the problem of monitoring drinking-water in rural areas and small towns, given that laboratory facilities are typically in urban centres (Fig. 1). Although the number of tests undertaken by larger suppliers exceeded minimum requirements in many cases, the SSPD (2011: p. 188) note: "*In 2010, there was no information about the quality of water consumed by 30.3% of the population, because they are found in zones that are difficult to access for surveillance by the sanitary authorities (usually in rural areas)*". The results presented here quantify the implications for sample holding times of undertaking water quality monitoring via fixed laboratory infrastructure. This difficulty in accessing fixed laboratories potentially exacerbates a rural–urban disparity in access to safe drinking-water that has been documented for much of Latin America (de Barros et al., 2009). It may also impact on more remote

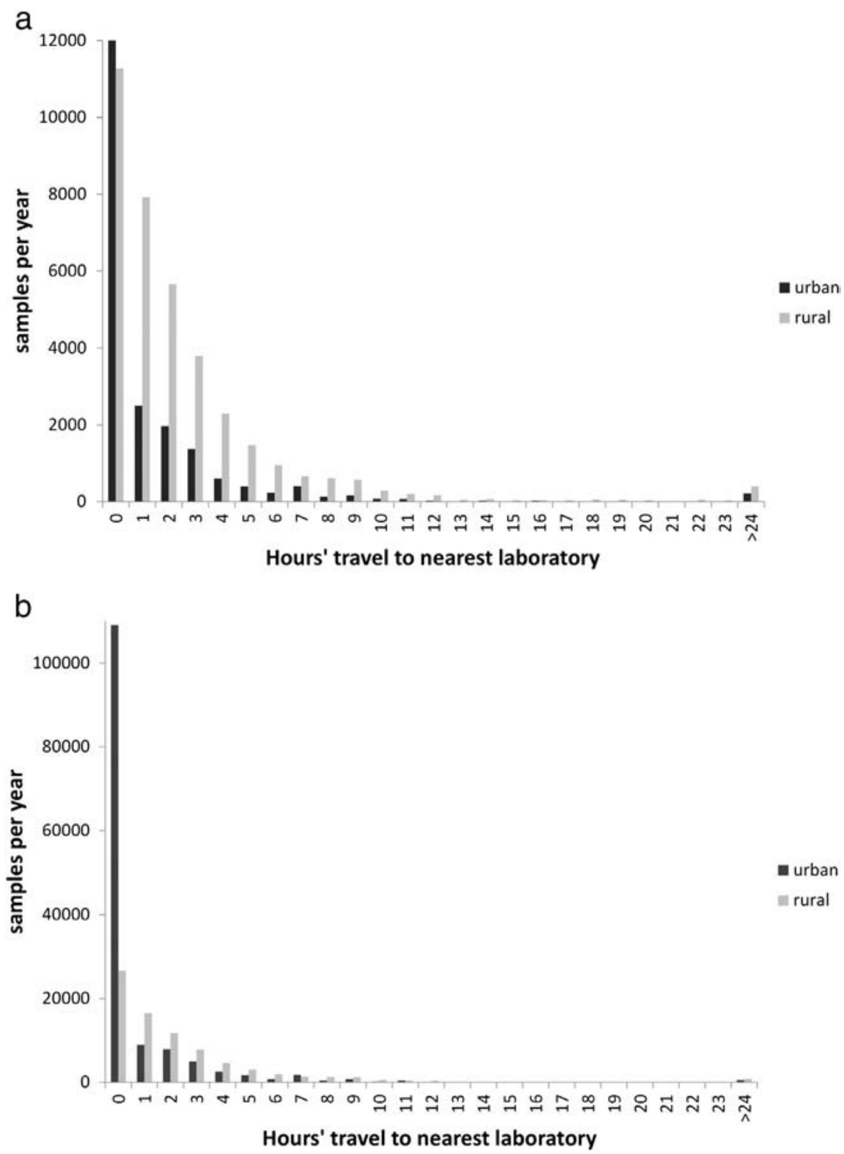

Fig. 5. Distribution of microbiological samples required from piped water for (a) surveillance and (b) operational monitoring, versus journey time to the nearest laboratory.

small towns, which are classed as urban in Colombia where they act as *cabecera*.

There are several ways in which the analysis of sample transportation times presented here could be used to plan water quality monitoring in rural areas. First, the travel time estimates could be used to target use of field-based test kits to distant water supplies, for example those beyond the 6-hour travel time contour in Fig. 5. Some microbiological testing procedures such as the DelAgua field incubator and test kit for thermotolerant coliforms and the H_2S test (Wright et al., 2012) are intended for field use and do not require a laboratory. Where appropriate and where cell phone coverage exists, test results from such field kits can be transmitted via cell phone as a means of reporting back to the communities consuming water, a regulator or a service provider (Rivett et al., 2013). Testing potentially could also be undertaken via mobile laboratories that visit more remote supply systems according to a rota. Second, the spatial distribution of demand for water quality testing based on surveillance and operational monitoring regulations could be used to optimise the location of any new accredited laboratories, so as to maximise the laboratory network's coverage. By exploring the population coverage resulting from the related investments in transport, infra-structure and staff time, such an analysis could also be used to optimise the cost-effectiveness of different combinations of monitoring via fixed laboratories, mobile facilities, and field test kits, as well as assess their equity implications. For example, collecting multiple samples per trip lowers the transportation cost per sample, though it lengthens sample holding times. Finally, by developing understanding of the logistical implications of any regulatory changes for sample transport, the analysis presented here could be used to inform cost–benefit analyses of any future regulatory changes to the surveillance and operational monitoring regimes.

4.2. Uncertainties affecting sample holding times

As a preliminary analysis, our findings are likely to be influenced by a number of assumptions and limitations in the underlying data. The census data are from 2005 and we have not attempted to project population estimates forward to 2012. Our analysis will also be affected by the uncertainty underlying our geocoding and travel time estimation techniques. In terms of geocoding, a study in urban Brazil (Davis and de Alencar, 2011) found a similar pattern of Google Maps API geocoding precision to that found here, with most addresses coded to address block level, some to town level, and the fewest to street level. They

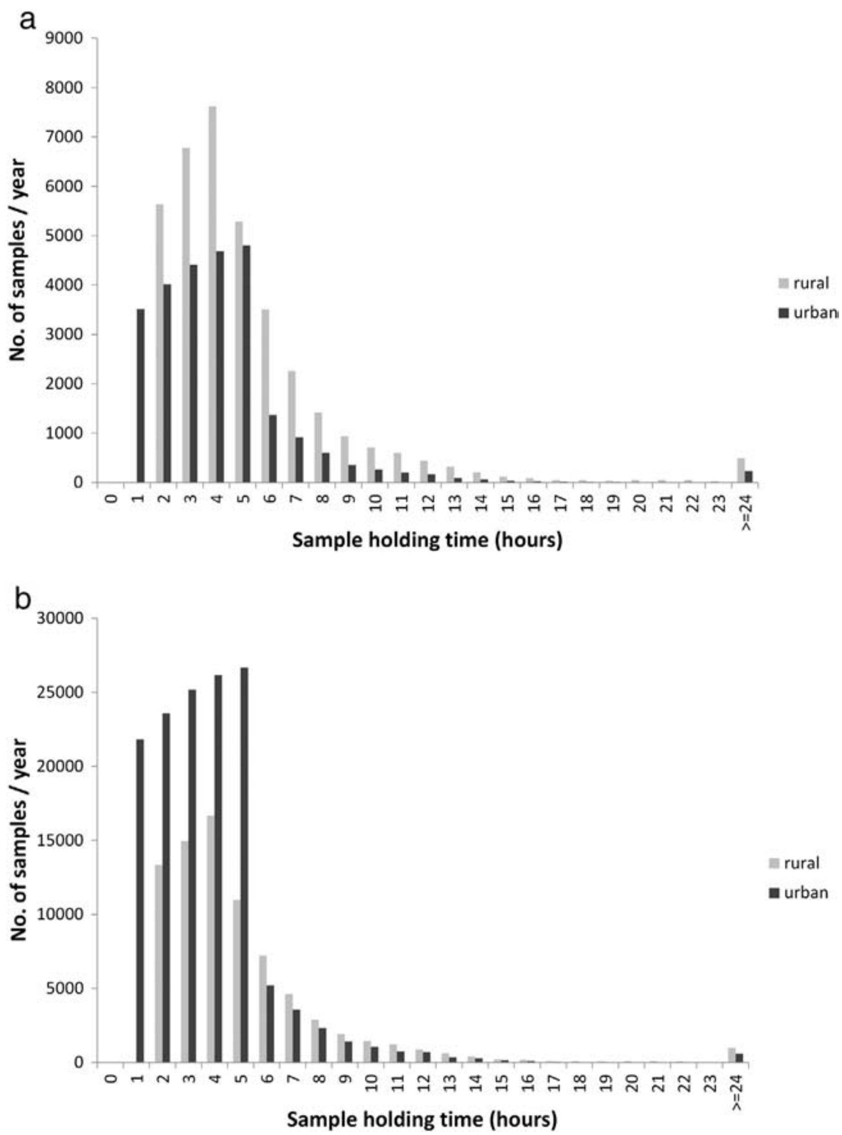

Fig. 6. Distribution of number of microbiological samples required from piped water for (a) surveillance and (b) operational monitoring, versus estimated sample holding time.

found that address block level geocoding was usually accurate to within 150 m, though accuracy was lower in low income neighbourhoods. Elsewhere, a US-based study (Roongpiboonsopit and Karimi, 2010) that evaluated geocoding via the Google maps API suggested that its performance was weaker in rural and industrial areas. On this basis, it is likely that the accuracy of the laboratory address geocoding was lower in rural areas and therefore rural water transportation times will be more uncertain.

Our cost surface calculations ignore the effect of road quality, traffic congestion, and driving over the speed limit. The cost surface output matched travel time estimates from Google Maps more closely than straight-line distances, and enabled us to estimate the travel time contours in Fig. 1 and catchment areas for laboratories. However, the cost surface output remained an approximation of the travel times estimated by Google Maps. The assumption about speeds for river travel also affects estimated journey times for samples from piped systems in the more remote southeastern departments of Colombia. More generally, there remains very little independent literature internationally evaluating the accuracy of the travel times generated by Google Maps, which we used alongside the cost surface methodology. Our findings are also sensitive to assumptions about the number of samples that field staff collect on a single day, since this affects the delay in their transportation to the laboratory. These assumptions were based on data from other countries.

A number of assumptions also underpin our findings. We assumed that samples were processed in-country at the nearest laboratory and that there were no capacity constraints on sample processing by laboratories. We also ignored the regulatory requirement to undertake repeat sampling in response to detection of substantial contamination, which would particularly affect rural areas, given the IRCA values described above (SSPD, 2011). We assumed that samples were collected from the centroid of each urban area and transported by road or boat. In modelling the spatial distribution of operational and surveillance tests required, we used census data rather than data from water utilities and assumed that the rural population using piped supplies was concentrated in more densely populated areas. We assumed that each settlement had a single integrated water distribution system and did not attempt to project the 2005 census population forward to 2012, the year when our data on laboratories was collated. WHO's guidance is that the delay between sample collection and analysis should not exceed 6 h and we have only considered the time from collection to analysis in a laboratory. We have not considered any subsequent delay prior to sample analysis in the laboratory. Collectively, these assumptions are likely to lead to an under-estimate in the sample transportation times presented in Fig. 4. We did not account for 0.6% of geographically dispersed piped water users and we focus here on piped water, ignoring the 12% of mainly rural Colombians who use other water sources. Urban–rural disparities in sample holding times may therefore be even greater than our results suggest.

The evidence underpinning current guidelines suggests a variable and uncertain impact of sample holding times on subsequent indicator bacteria enumeration, depending on microorganisms, water treatment prior to sampling, and physico-chemical sample characteristics (Edberg et al., 2000). For example, McDaniels et al. (1985) found a significant but gradual decline of less than half a log in the coliform counts for piped water samples stored for up to 50 h at 5 °C. Pope et al. (2003) noted a significant decline in *E. coli* counts from some surface water samples stored at 4 °C for 24 h, whilst a more recent study of surface waters (Aulenbach, 2010) identified a decline in total coliform counts in surface water stored at 4 °C for more than 27 h. However, the evidence suggests that holding times have a greater impact on subsequent indicator bacteria enumeration when samples are stored at higher temperatures and the impact is typically to reduce the bacterial count. Thus, the impact of long (>24 h) and even relatively short (<6 h) sample holding times on the enumeration of indicator bacteria remains uncertain, especially if sample temperatures are not carefully controlled.

4.3. Future research

The approach presented here could be developed further in a variety of respects. Given that sample transportation poses challenges in many other countries, and that the spatial distribution of laboratories and water source types vary between countries (Rahman et al., 2011), the study could be replicated usefully elsewhere. Here, we have used census data to model demand for water quality monitoring. However, where these exist, other data sources could be used instead, most notably the databases developed via water point mapping in sub-Saharan Africa by WaterAid (Jimenez and Perez-Foguet, 2008) or georeferenced databases of piped suppliers. Given the need for electricity to make ice for sample transport and to power some models of incubators and some field test kits, the approach could be further refined through the inclusion of a map layer depicting electricity coverage and perhaps also cell phone coverage to facilitate the communication of test results. To validate the broad pattern of travel times to laboratory identified here, our findings could be corroborated via examination of actual (as opposed to prescribed) spatial patterns of testing and interviews with laboratory and environmental health field staff. Examining spatial patterns of actual testing in relation to the distribution of water supplies could also help identify gaps in the monitoring network. Much the same difficulties of sample transportation affect the regulation and monitoring of environmental waters. The analysis could be replicated for environmental and recreational/bathing waters, which in Colombia would entail drawing on the list of laboratories accredited by the *Instituto de Hidrologica, Meteorologia y Estudios Ambientales* (IDEAM; Institute of Hydrology, Metrology and Environmental Studies) (Instituto de Hidrologica Meteorologia y Estudios Ambientales, 2012).

The approach could also be developed further to investigate the sample transportation component of different regulatory and laboratory provision scenarios for water quality monitoring. For example, Blyde (2012) translated Colombian freight travel times from a GIS-based analysis into economic costs by examining driver wage costs, fuel and vehicle maintenance, suggesting that this is feasible. Previous research suggests that the transportation costs of water quality monitoring are significant. Castillo (1994) compared the costs of field versus laboratory-based testing in Chile, and estimated that transportation-related costs contributed 35% of the total costs of laboratory testing. Crocker and Bartram (2014) estimated that transportation contributed between 28% and 43% of monitoring costs depending on the setting, based on data from seven countries.

In using GIS for public health planning, there is a very large and well established literature on the location of healthcare facilities and patient access to clinics and hospitals (Cromley and McLafferty, 2012). However, rather than focussing on population travel to healthcare facilities, here we have examined the logistics and distribution of samples to laboratory facilities and therefore focussed on the movement of goods. The approach could be used to examine medical commodities where the cold chain and associated transportation issues are important, such as vaccines and the transport of anti-venoms as suggested by Gutierrez et al. (2009). In so doing, the approach could be used to support other public health initiatives in remote rural communities.

4.4. Conclusion

The approach presented here provides a new means of using GIS to support water quality monitoring, particularly in remote areas. Our findings demonstrate the difficulty of undertaking microbiological monitoring in rural areas and small towns from a fixed laboratory network in Colombia. Our GIS-based approach could be adapted to optimise monitoring strategies and support planning of testing and transportation infra-structure development. Such logistical challenges to monitoring in remote areas exist not only in Colombia but in other middle and low income countries, so the approach could usefully be applied elsewhere.

Conflicts of interests

Profs Gundry and Bartram and Dr. Wright have benefited from the grant Aquatest funded by Bill & Melinda Gates Foundation, whose main purpose is to develop a low cost, field test for microbial contamination of drinking water, suitable for use in developing countries. Bain and Crocker were employed on this grant. Prof SW Gundry was also the named, principal investigator for the grant. Professor Gundry is the sole inventor on granted European patent number 1960104 entitled 'Apparatus for determining the presence of a contaminant in a sample of water or other fluid'. This patent is also granted in South Africa and member countries of the African Intellectual Property Organisation (OAPI) and is pending in 9 other countries or groups of countries. Prof. Gundry and Bain are co-inventors on International Patent Applications PCT/GB2010/050728 and PCT/GB2012/050452 both entitled 'Apparatus for testing the quality of a fluid sample'. Other than these possible competing interests, there are no others known.

Acknowledgements

This research has been partially funded by the Bill & Melinda Gates Foundation, under a grant to the University of Bristol. The grant's purpose is to develop a low cost test of microbial water quality for use in developing countries. The Bill & Melinda Gates Foundation had no role in the design and conduct of this study.

References

Armenteras D, Rudas G, Rodriguez N, Sua S, Romero M. Patterns and causes of deforestation in the Colombian Amazon. Ecol Indic 2006;6:353–68. http://dx.doi.org/10.1016/j.ecolind.2005.03.014.

Aulenbach B. Bacteria holding times for fecal coliform by mFC agar method and total coliform and *Escherichia coli* by Colilert-18 Quantitray method. Environ Monit Assess 2010;161:147–59.

Bain RES, Bartram JK, Elliott M, Matthews RL, McMahan L, Tung R, et al. A summary catalogue of microbial drinking water tests for low and medium resource settings. Int J Environ Res Public Health 2012a;9:1609–25. http://dx.doi.org/10.3390/ijerph9051609.

Bain RES, Gundry SW, Wright JA, Yang H, Pedley S, Bartram JK. Accounting for water quality in monitoring access to safe drinking-water as part of the Millennium Development Goals: lessons from five countries. Bull World Health Organ 2012b; 90:228–35. http://dx.doi.org/10.2471/BLT.11.094284.

Bain RES, Cronk R, Wright JA, Yang H, Bartram JK. Fecal contamination of drinking water in developing countries: a systematic review and meta-analysis; 2014d (accepted).
Blyde J. Paving the road to export: assessing the trade impact of road quality. Int Econ J 2012;27:663–81. http://dx.doi.org/10.1080/10168737.2012.733721.
Castillo G. Water quality control Chile — phase II: final report. International Development Research Centre; 1994 [Accessed: Jan 2012. Available from:http://hdl.handle.net/10625/13856].
Chuang P, Trottier S, Murcott S. Comparison and verification of four field-based microbiological tests: H_2S test, Easygel®, Colilert®, Petrifilm TM. J Water Sanitation Hyg Dev 2011;1:68–85. http://dx.doi.org/10.2166/washdev.2011.026.
Crocker J, Bartram JK. Comparison and cost analysis of drinking water quality monitoring requirements versus practice in seven developing countries. Int J Hyg Environ Health 2014.
Cromley EK, McLafferty S. GIS and public health. Guilford Press; 2012.
Davis Jr CA, de Alencar RO. Evaluation of the quality of an online geocoding resource in the context of a large Brazilian city. Trans GIS 2011;15:851–68. http://dx.doi.org/10.1111/j.1467-9671.2011.01288.x.
de Barros RP, Ferreira FHG, Vega JRM, Chanduvi JS. Measuring inequality of opportunities in Latin america and the Caribbean. The World Bank; 2009. http://dx.doi.org/10.1596/978-0-8213-7745-1 [Accessed: Jan 2014].
Departamento Administrativo Nacional de Estadistica. Censo Basico 2005. 2013. [Accessed: Jan 2014. Available from: www.dane.gov.co].
Dobson J, Bright E, Coleman P, Durfee R, Worley B. Landscan: a global population database for estimating populations at risk. Photogramm Eng Remote Sens 2000;66:849–57.
Edberg S, Rice E, Karlin R, Allen M. *Escherichia coli*: the best biological drinking water indicator for public health protection. J Appl Microbiol 2000;88:106S–16S.
Google. The Google distance matrix API. 1 Nov 2013, 2013. Accessed: Jan 2014. Available from: https://developers.google.com/maps/documentation/distancematrix, 2013.
Gutierrez JM, Fan HW, Silvera CL, Angulo Y. Stability, distribution and use of antivenoms for snakebite envenomation in Latin America: report of a workshop. Toxicon 2009; 53:625–30. http://dx.doi.org/10.1016/j.toxicon.2009.01.020.
Instituto de Hidrologica Meteorologia y Estudios Ambientales. Lista de Laboratorios Ambientales Acreditados por el IDEAM. Bogota, Colombia: IDEAM; 2012 [Accessed: Jan 2014. Available from: www.andi.com.co/archivos].
Instituto Nacional de Salud. Programa de Vigilancia por Laboratorio de la Calidad de Agua para Consumo Humano 978-958-13-0147-8; 2011 [Bogota, Colombia].
Instituto Nacional de Salud. Estado de la vigilancia de la calidad del agua para consumo humano en Colombia, periodo 2007–2011. 2012. [Accessed: Jan 2013. Available from: http://www.ins.gov.co/sivicap/Documentacion/].
Jimenez A, Perez-Foguet A. Improving water access indicators in developing countries: a proposal using water point mapping methodology. Water Sci Technol Water Supply 2008;8:279–87. http://dx.doi.org/10.2166/ws.2008.072.
Luh J, Baum R, Bartram JK. Equity in water and sanitation: developing an index to measure progressive realization of the human right. Int J Hyg Environ Health 2013;216: 662–71. http://dx.doi.org/10.1016/j.ijheh.2012.12.007.
Martin D, Wrigley H, Barnett S, Roderick P. Increasing the sophistication of access measurement in a rural healthcare study. Health Place 2002;8:3–13. http://dx.doi.org/10.1016/S1353-8292(01)00031-4.
McDaniels A, Bordner R, Gartside P, Haines J, Brenner K, Rankin C. Holding effects on coliform enumeration in drinking-water samples. Appl Environ Microbiol 1985;50(4): 755–62.
Mennis J. Generating surface models of population using dasymetric mapping. Prof Geogr 2003;55:31–42. http://dx.doi.org/10.1111/0033-0124.10042.
Ministerio de Protección Social, Ministerio de Ambiente Vivienda y Desarrollo Territorial. Resolución 2115. Bogota, Colombia: Government of Colombia; 2007 [Accessed: Jan 2014. Available from: www.minambiente.gov.co/documentos/res_2115_220707.pdf].
Ministerio de Salud y Protección Social. Resolución 431. Bogota, Colombia: Government of Colombia; 2012 [Accessed: Jan 2014. Available from: www.dssa.gov.co/__media__/dssa/dssa.gov.co/documentos/resolucion-431-de-2012-laboratorios-de-agua-autorizados.pdf].
Miranda M, Aramburu A, Junco J, Campos M. Situación de la calidad de agua para consumo en hogares de niños menores de cinco años en Perú, 2007-2010. Rev Peru Med Exp Salud Publica 2010;27:506–11. http://dx.doi.org/10.1590/S1726-46342010000400003.
Onda K, LoBuglio J, Bartram JK. Global access to safe water: accounting for water quality and the resulting impact on MDG progress. Int J Environ Res Public Health 2012;9: 880–94. http://dx.doi.org/10.3390/ijerph9030880.
Pope M, Bussen M, Feige M, Shadix L, Gonder S, Rodgers C, et al. Assessment of the effects of holding time and temperature on *Escherichia coli* densities in surface water samples. Appl Environ Microbiol 2003;69(10):6201–7.
Rahman Z, Crocker J, Chang K, Khush R, Bartram JK. A comparative assessment of institutional frameworks for managing drinking water quality. J Water Sanitation Hyg Dev 2011;1:242–58. http://dx.doi.org/10.2166/washdev.2011.002.
Rivett U, Champanis M, Wilson-Jones T. Monitoring drinking water quality in South Africa: designing information systems for local needs. Water SA 2013;39:409–14. http://dx.doi.org/10.4314/wsa.v39i3.10.
Roongpiboonsopit D, Karimi HA. Comparative evaluation and analysis of online geocoding services. Int J Geogr Inf Sci 2010;24:1081–100. http://dx.doi.org/10.1080/13658810903289478.
SSPD. Diagnóstico de la calidad del agua suministrada por las empresas Prestadoras del servicio de acueducto en Colombia. 2009–2010; 2011 [Accessed: Jan 2014. Available from: www.superservicios.gov.co/home/c/document_library/].
UN-OCHA. Humanitarian response common and fundamental operational datasets registry. 2013. [Accessed: Jan 2014. Available from: https://cod.humanitarianresponse.info].
US EPA. Manual for the certification of laboratories analyzing drinking water: criteria and procedures — quality assuranceFifth ed. ; 2005 [EPA 815-R-05-004, Cincinnati, Ohio].
WHO. Guidelines for drinking-water quality. Surveillance and control of community supplies. 2. Geneva, Switzerland: World Health Organization; 1997 [Accessed: Jan 2014. Available from: http://www.who.int/water_sanitation_health/dwq/gdwq2v1/en/index2.html].
WHO. Guidelines for drinking-water quality. Geneva, Switzerland: World Health Organization; 2011 [Accessed: Jan 2014. Available from: http://whqlibdoc.who.int/publications/2011/9789241548151_eng.pdf].
WHO, UNICEF. Drinking-water: equity, safety and sustainability, New York, USA; 2011 [Accessed: Jan 2014. Available from: http://www.wssinfo.org/fileadmin/user_upload/resources/report_wash_low.pdf].
WHO, UNICEF. Progress of sanitation and drinking-water: 2013 update. 2013. [Accessed: Jan 2014. Available from: http://www.wssinfo.org/fileadmin/user_upload/resources/JMPreport2013.pdf].
Wright JA, Yang H, Walker K, Pedley S, Elliott J, Gundry SW. The H_2S test versus standard indicator bacteria tests for faecal contamination of water: systematic review and meta-analysis. Trop Med Int Health 2012;17:94–105. http://dx.doi.org/10.1111/j.1365-3156.2011.02887.x.
Yang H, Bain RES, Bartram JK, Gundry SW, Pedley S, Wright JA. Water safety and inequality in access to drinking-water between rich and poor households. Environ Sci Technol 2013;47:1222–30. http://dx.doi.org/10.1021/es303345p.