Supply system factors associated with microbiological drinking water safety in regional New South Wales, Australia, 2001–2007

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ABSTRACT

Aim: To determine factors associated with microbiological safety of public drinking water systems in regional New South Wales (NSW), Australia.

Method: We analysed 107,000 end-user drinking water samples for an association between detection of *Escherichia coli* and drinking water system features, sample year and season using NSW Health Drinking Water Monitoring Program data, 2001–2007. We used negative binomial generalized estimating equations with adjustment for autocorrelation and clustering.

Results: We detected *E. coli* in over 2% of samples from 40% (129/323) of systems. *E. coli* detection was significantly more common in earlier years and during summer ($p < 0.001$). On multivariate analysis *E. coli* detection was significantly associated with smaller systems; watercourse sources; no disinfection or disinfection with ultraviolet only; and higher post-treatment mean turbidity (all $p \leq 0.01$). Detection was most strongly associated with lack of disinfection (incidence rate ratio 12.6, $p < 0.001$) and smaller supply systems (1% reduction in *E. coli* detection for each 1,000 person increase in supply population, $p = 0.004$). Ultraviolet disinfection alone was the least effective disinfection method ($p < 0.001$).

Conclusion: Even in developed countries, drinking water systems without disinfection or serving small populations appear vulnerable to the effects of faecal contamination, which presents a risk of waterborne disease outbreaks.

Key words | compliance, disinfection, drinking water, *Escherichia coli*, regional, water supply

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ACRONYMS

IQR	interquartile range
NSW	New South Wales
NTU	nephelometric turbidity unit

INTRODUCTION

Drinking water can pose serious health risks through microbiological and chemical contamination, or inadequate disinfection and treatment (Hunter *et al.* 2003; Hrudey & Hrudey 2004). Microbiological contamination poses an ongoing risk of sporadic gastrointestinal illness and a risk of acute waterborne gastrointestinal disease outbreaks. Illness related to drinking water can lead to substantial morbidity and mortality, community anger and detrimental economic impacts (Hunter *et al.* 2003; Hrudey & Hrudey 2004).

Australia uses the *Australian Drinking Water Guidelines 2004* as a model of best practice for the management of drinking water (NHMRC & NRMMC 2004). These guidelines provide a risk management framework for drinking water supply systems, which includes

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a multiple barrier 'catchment-to-tap' approach (the *Framework for Management of Drinking Water Quality*). A single-barrier approach to managing drinking water risks is vulnerable to failure (Reason 1997). There is growing international evidence that *Escherichia coli* (*E. coli*) is the most appropriate bacteriological indicator of faecal contamination (Edberg *et al.* 2000; World Health Organization 2006). In line with this evidence, the *Australian Drinking Water Guidelines 2004* recommend the use of *E. coli* rather than thermotolerant coliforms as the main indicator of microbiological contamination.

A drinking water monitoring program has been operating comprehensively in New South Wales (NSW), Australia, since 2001. Drinking water quality samples are taken from taps in public locations and private residences within the distribution system and are representative of the water supplied to the consumer. The NSW Department of Health recommends the minimum number of samples that should be used for each water supply system to monitor its drinking water quality, and provides testing for bacteria and health-related chemicals in these samples free of charge. Each water utility is responsible for monitoring its supply systems.

The number of drinking water samples allocated is based on the minimum sampling frequency recommended in the *Guidelines*, the population served and the complexity of the system (NSW Health 2005). These recommendations align with the *Australian Drinking Water Guidelines 2004*.

The laboratories that participate in analysis of drinking water samples in NSW are all National Association of Testing Authorities (NATA) accredited. The employees who take the water samples have been trained in the collection of drinking water samples. The sample collection procedure is outlined in the *Australian Drinking Water Guidelines 2004*, which include precautions necessary to avoid contamination of the sample. The laboratories and water utilities participating in the program enter the results of drinking water monitoring samples directly into the NSW Drinking Water Database, which is password protected and accessible over the internet.

Drinking Water Monitoring Program data were reviewed for sampling adequacy and microbiological compliance to assess the safety of public drinking water supplies in regional NSW. The review included all public drinking water supplies in NSW, except for the large metropolitan drinking water supply systems operated by Sydney Water Corporation and Hunter Water Corporation, which are monitored separately (Figure 1). Private (independent, non-water utility) drinking water supplies and Aboriginal communities with independent drinking water supplies were also excluded from the analysis.

METHODS

We used data from the NSW Drinking Water Database for samples collected from 1 January, 2001, to 30 June, 2007, inclusive. Microbiological sampling adequacy was assessed by comparing the number of samples tested for *E. coli* or thermotolerant (faecal) coliforms with the number of microbiological samples allocated to each supply system annually. Microbiological compliance was assessed by calculating the proportion of samples in which *E. coli* were detected. The results for microbiological non-compliance included tests for *E. coli* only, as *E. coli* is a more specific indicator of faecal contamination of drinking water than thermotolerant coliforms. The *Australian Drinking Water Guidelines 2004* guideline value for *E. coli* of two detections per 100 samples was used as the upper acceptable threshold for *E. coli* detection.

The association between supply system characteristics, time period and monthly microbiological non-compliance for each supply system was modelled for the review period using generalized estimating equations (Liang & Zeger 1986; Hardin & Hilbe 2003). All samples tested for *E. coli* were included. The model used a negative binomial model, with a correlation matrix defined using a one-month lagged autocorrelation. The number of non-compliant samples (i.e. the number of samples where *E. coli* was detected) was used, and exposure was incorporated by using the total number of samples taken each month for each supply system. All 323 supply systems were included in the univariate analysis, except for the turbidity and free chlorine analysis. The 305 systems with turbidity readings were included in the turbidity analysis, while the 132 systems that used chlorine for disinfection and reported residual free chlorine concentrations were included in the free chlorine analysis.

Figure 1 | New South Wales Drinking Water Monitoring Program coverage, 2001–2007.

Supply system features that were modelled included size of the population supplied, water source, disinfection method, clarification method, chemical treatment status, mean turbidity and mean free chlorine residual. Monthly means were used for all features except population size, where annual population was used. Time characteristics included the sample year and the season. The analysis was conducted using the supply system as the unit of analysis. Estimates were adjusted for clustering within supply systems using robust variance estimates. The association between microbiological non-compliance and system characteristics was expressed using the incidence rate ratio. The same modelling strategy was used to examine all of the significant supply system features in a multivariate negative binomial model. Eighteen supply systems were excluded from the multivariate analysis, due to lack of turbidity measurements. Variables that did not reach a significance of <0.2 were excluded from the model, and then individually re-introduced. The most parsimonious multivariate model was selected as the final model.

RESULTS

For the period 1 January, 2001, to 30 June, 2007, 104 regional water utilities responsible for 349 drinking water supply systems reported to the NSW Health Drinking Water Monitoring Program. Twenty-six drinking water supply systems were excluded from the analysis, as they were no longer considered to be supplying potable drinking water (17 systems), had no permanent residential population (7 systems) or were not suitable for analysis for other reasons (1 private system, 1 system with minimal samples).

The remaining 323 supply systems and their 110,274 microbiology samples were used to review the quality of drinking water in regional NSW. These supply systems cover all regions of NSW outside the Sydney and Newcastle metropolitan regions, and serve a population of approximately 1.7 million people (Figure 1). Only two supply systems served populations of over 100,000 people. Most of the supply systems were much smaller.

Table 1 | Proportion of supply systems with populations defined by the NSW Health Drinking Water Monitoring Program recommended frequency of microbiological sampling

Population served	Minimum number of samples	No. of supply systems	% of supply systems
≥100,000	Six samples per week, plus one additional sample per month for each 10,000 above 100,000	2	0.6
5,000–99,999	One sample per week plus one additional sample per month for each 5,000 above 5,000	62	19.2
500–4,999	One sample per week (52 samples per year)	129	39.9
100–499	One sample per fortnight (26 samples per year)	102	31.6
<100	One sample per month (12 samples per year)	28	8.7

The median population served by regional water supply systems was 900 people (IQR 250–3150). The supply population and sampling recommendations are presented in Table 1.

The 104 water utilities responsible for the quality of drinking water in regional NSW generally had a small number of supply systems under their authority (median 2, interquartile range [IQR] 1–4 supply systems per water utility). Most of the water utilities in NSW were local government councils, with the remainder consisting of larger water utilities or water county councils and small water trusts. Most supply systems (288/323, 89%) had participated in the NSW Health Drinking Water Monitoring Program since 2001. The median duration of participation was 6.4 years (interquartile range 6.2–6.4 years).

Most samples (89%) were analysed by the three NSW Health laboratories, with the remainder analysed by nine other laboratories. In addition, onsite testing for other characteristics (chlorine, pH and turbidity) was conducted by a number of water utilities.

Water treatment includes the use of clarification (for example, sedimentation, coagulation, filtration), disinfection (for example, chlorination, ultraviolet treatment) and other chemical treatment of water (for example, pH treatment, hardening, softening). The majority of drinking water supplies were treated using at least one of these treatments (318/323, 98.5%).

Five public drinking water supplies (serving a population of 12,785) used completely untreated water for the duration of the review period. Apart from these five systems with no treatment, there were an additional five systems that used no disinfection process. In total, 10 public drinking water supplies (10/323, 3.1%) serving approximately 17,485 people used no disinfection process for the duration of the review period January 2001 to July 2007.

During the review period, 36 supply systems (11.2%) upgraded their treatment of drinking water. The treatment upgrade most commonly included the introduction of chlorination. By mid 2007, the majority of supply systems used chlorination, chloramination or both (chlorination 82.4%, chloramination 2.5%, both 0.9%) to disinfect their drinking water supply. The next most common disinfection method used was ultraviolet light alone (9.9%). Smaller supplies were more commonly not disinfected, with 9 of the 10 systems without disinfection serving populations of fewer than 5,000.

Clarification includes procedures such as sedimentation, coagulation, flocculation and filtration. Just over half (51.1%) of the drinking water supply systems were clarified by mid 2007. Groundwater systems were commonly not clarified, with 80.2% (77/96) of these systems having no clarification process. Apart from disinfection, the majority (205/323, 63.5%) of regional drinking water supplies in NSW received no further chemical treatment.

The most common single source of water was a watercourse (for example, a river or creek, 41.5%). The next most common single source was groundwater (for example, a bore, spring or well, 29.7%), and the third most common was surface storage (for example, a dam, reservoir or lake, 15.5%). Some supply systems used more than one source of water (Table 2).

Of the total number of microbiological samples tested for *E. coli* and/or thermotolerant coliforms, 3186/110,278 (2.9%) were tested for thermotolerant coliforms only. The remaining 107,092/110,278 samples (97.1%) were tested for *E. coli* alone or in combination with thermotolerant

Table 2 | Water source for drinking water supply systems in regional NSW

Water source	No. of supply systems	%
Watercourse	134	41.5
Groundwater	96	29.7
Surface storage	50	15.5
Mixed*	43	13.3
Total	323	100.0

*Mixed—a combination of two or more water source categories.

coliforms. A total of 110,278 samples (107,105 tests for *E. coli* and 36,881 tests for thermotolerant coliforms) were included in the analysis.

Frequency of microbiological sampling

The median time between microbiological sampling (of samples tested for *E. coli* and/or thermotolerants) for all 323 regional supply systems included in the analysis was 9 (IQR 7–14) days. Even though more than one sample per week was routinely collected for the larger supply systems, multiple samples were collected on a single day rather than on separate days. This resulted in a median time between repeated sets of samples of one week for all systems serving more than 500 people. As recommended by the NSW Health Drinking Water Monitoring Program, the median time between sampling for systems of 100 to 499 people was 14 days, while for systems serving less than 100 people the median time between microbiological samples was 28 days.

The median time between collection of a repeat sample following a non-compliant sample or set of samples was 7 (IQR 7–14) days. The median time between repeat microbiological sampling following a non-compliant result was significantly longer for smaller supply systems (Figure 2).

Microbiological sampling adequacy (of samples tested for *E. coli* and/or thermotolerants)

The majority of supply systems submitted an adequate number of samples for microbiological testing of drinking water quality when compared against the annual sampling recommendations from the NSW Department of Health. The median proportion of allocated samples taken was 88.8%. The median number of samples taken by supply systems ranged from 2606 samples for the largest systems to 60 samples for the smallest systems during the review period (2001–mid 2007). The corresponding number of allocated samples ranged from 2592 for the largest to 78 for the smallest supply systems. However, the smaller supply systems were significantly more likely to under-sample for microbiological quality ($p < 0.001$, non-parametric trend test; Figure 3). In total 272/323 supply systems (84.2%)

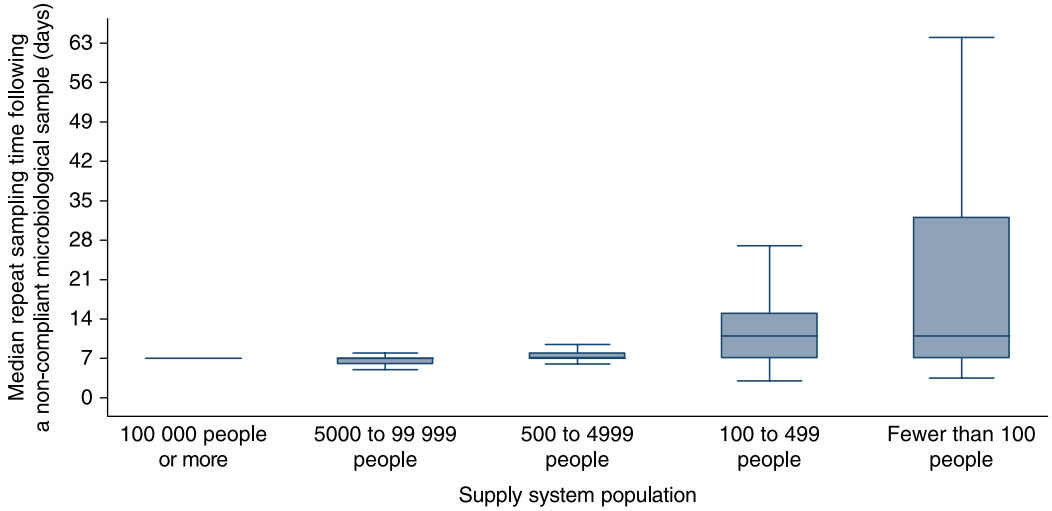

Figure 2 | Median time between repeat microbiological sampling after a non-compliant sample by supply system population. Box indicates median, lower and upper quartiles. Cross bars indicate lower and upper octiles. Outliers are not shown. Time between samples represents time between one or more samples taken on the same day.

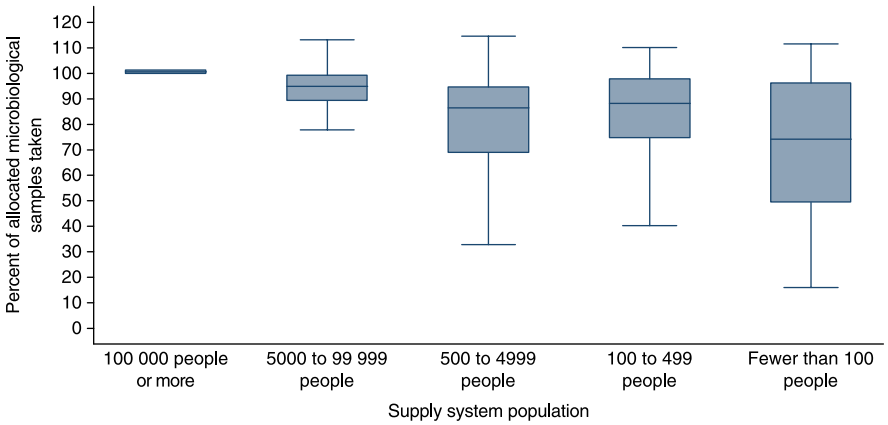

Figure 3 | Percent of allocated microbiological samples taken, using samples tested for either *E. coli* or thermotolerant coliforms, by supply system population. Box indicates median, lower and upper quartiles. Cross bars indicate lower and upper octiles. Outliers are not shown. *P* for trend <0.001.

submitted fewer than their allocated number of microbiological samples for testing over the review period.

There was an annual pattern to the adequacy of microbiological sampling, with fewer samples taken during summer than any other season (Figure 4). There were significant differences in the adequacy of sampling by season ($p < 0.001$, Kruskal Wallis test). Microbiological sampling adequacy improved significantly over the review period (Figure 5).

The median time between a sample being taken and the sample being received by the laboratory was one day. The median time between a sample being received by the laboratory and a sample result being available was also one day, providing a median delay between sampling and result reporting of two days.

Microbiological non-compliance (of samples tested for *E. coli* only)

Almost 40% (129/323) of regional drinking water supply systems in New South Wales did not comply with the *Australian Drinking Water Guidelines* during 2001–2007, as they detected *E. coli* in over 2% of microbiological samples. Further, 82/323 (25%) of regional drinking water systems registered rates of *E. coli* detection of more than twice the guideline value during this period of review.

Smaller supply systems were significantly more likely to have higher rates of *E. coli* detection ($p < 0.001$, non-parametric trend test, Figure 6). The overall median rate of *E. coli* detection for regional drinking water supply systems in NSW was 1.37 per 100 samples (IQR 0.31–4.07 per 100 samples).

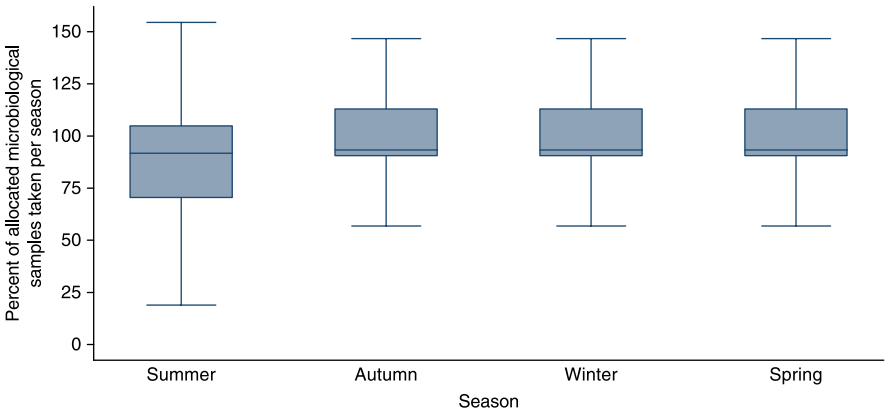

Figure 4 | Seasonal pattern of microbiological sampling. Box indicates median, lower and upper quartiles. Cross bars indicate lower and upper octiles. Outliers are not shown.

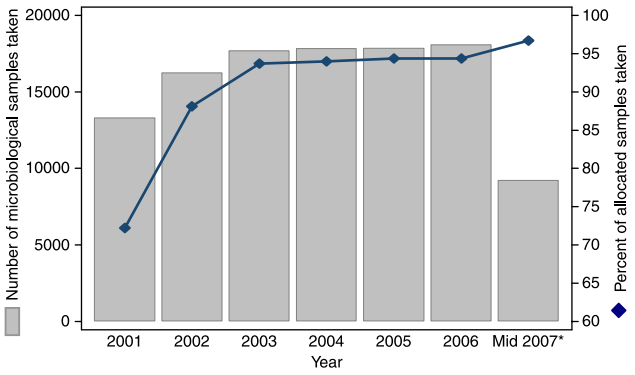

Figure 5 | Trend in microbiological sampling adequacy by calendar year, using samples tested for either *E. coli* or thermotolerant coliforms. *P* for trend = 0.02, trend test for ordered groups. Number of microbiological samples for the period to 30 June 2007.

There was significant improvement in microbiological compliance over the period 2001 to mid 2007 (Figure 7).

Univariate modelling of monthly microbiological non-compliance

There was a statistically significant association between all the drinking water supply system features and microbiological non-compliance (Table 3). On univariate analysis, smaller supply systems, watercourse and groundwater, undisinfected and ultraviolet disinfected systems and higher mean turbidity levels were associated with a higher risk of microbiological non-compliance. Higher mean free chlorine residual levels were associated with lower microbiological non-compliance levels. The strongest association with non-compliance was seen with: supply systems serving populations of fewer than 500 people, undisinfected systems and 'sedimentation only' systems.

Microbiological non-compliance was significantly associated with sampling year, confirming the significant trend in improved compliance over the review period (Table 4). Microbiological non-compliance was also significantly associated with season. Greater microbiological non-compliance was associated with earlier sampling years and with autumn, spring and summer each year. Summer periods (December to February) were associated with over three times the incidence of microbiological non-compliance than winter periods (June to August).

Multivariate modelling of monthly microbiological non-compliance

On multivariate analysis the supply system population, water source, disinfection method and mean turbidity levels were significantly associated with microbiological non-compliance (Table 5). Clarification status was no longer significantly associated with non-compliance after controlling for mean turbidity levels.

There was a 1% reduction in risk of microbiological non-compliance for each 1,000 person increase in the size of the supply system population ($p = 0.01$). The strongest association with microbiological non-compliance was seen in undisinfected supply systems, with an incidence of

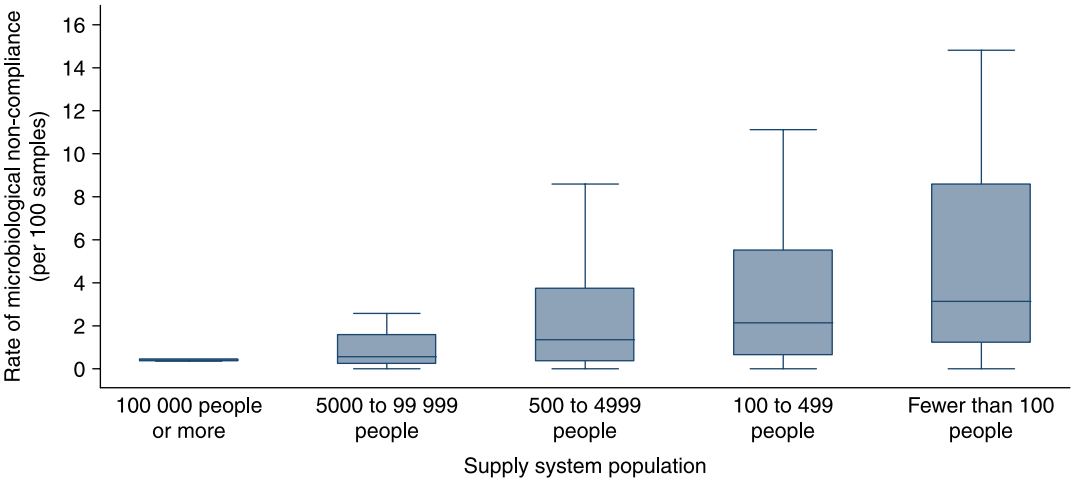

Figure 6 | Rate of microbiological non-compliance per 100 samples by supply system population. Box indicates median, lower and upper quartiles. Cross bars indicate lower and upper octiles. Outliers are not shown. *P* for trend <0.001.

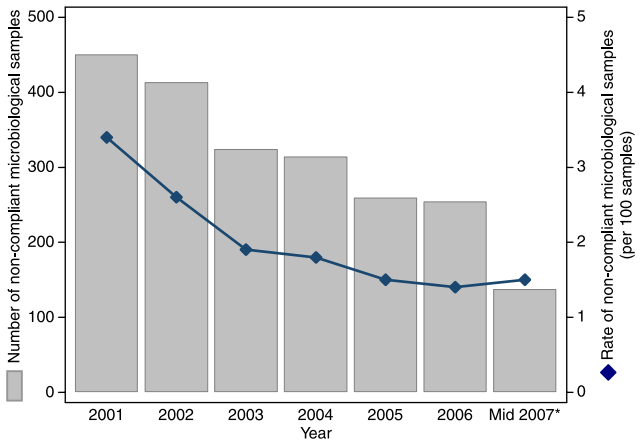

Figure 7 | Trend in microbiological compliance by year, samples tested for *E. coli* only. *P* for trend = 0.02, trend test for ordered groups. *Number of non-compliant samples for the period to 30 June 2007.

microbiological non-compliance over 12 times higher than for disinfected systems ($p < 0.001$). Ultraviolet disinfection consistently performed the worst of all disinfection methods, presenting a risk of microbiological non-compliance almost three times greater than chlorinated systems ($p = 0.001$; Table 5).

After controlling for disinfection method, groundwater was the lowest risk water source, with watercourses presenting a risk of microbiological non-compliance 2.3 times that of groundwater. Mean turbidity also remained significant, presenting a 17% increased risk for each one nephelometric turbidity unit increase in mean monthly turbidity (Table 5).

DISCUSSION

The NSW Health Drinking Water Monitoring Program has promoted improved management of water supply systems in regional areas. Local Public Health Units regularly review data and where necessary follow up with water utilities that do not comply with sampling or water quality targets.

Despite the trend for significantly improved compliance by year, almost 40% of regional public drinking water systems in New South Wales, Australia, had rates of *E. coli* detection above the *Australian Drinking Water Guidelines 2004* guideline value during 2001–2007. One quarter of regional drinking water systems had rates of *E. coli* detection more than twice the guideline value. Further, ten drinking water systems in NSW did not supply disinfected water at the time of the review.

Smaller supply systems in regional NSW posed considerably higher risks of waterborne illness for the communities they served, as evidenced by substantially higher rates of *E. coli* detection in the drinking water. Further, smaller supply systems were found to have significantly lower rates of microbiological sampling adequacy, even though the measure of sampling adequacy incorporated fewer allocated samples for supply systems with smaller populations. Levels of *E. coli* detection may have been greater if the allocated numbers of samples had been taken.

Even supply systems serving over 100,000 people did not perform daily microbiological monitoring. The median monitoring frequency was weekly for systems serving more than 500 people, while smaller systems sampled less frequently. This calls into question the intent of the *Guidelines 2004* recommendation for more than one sample a week for systems serving greater than 10,000 people (NHMRC & NRMMC 2004). The NSW Department of Health recommends that sampling should be distributed in both time and place, (NSW Health 2005) but water utilities commonly collected multiple samples on a single day, and then waited the maximum period before collecting the next sample.

The median time taken to perform repeat microbiological sampling after *E. coli* detection was similar to the usual time between routine samples. This indicates that most water utilities wait for the next scheduled microbiological sample to determine whether any corrective action taken had been successful in removing the microbiological risk. The Drinking Water Monitoring Program recommends immediate re-sampling and provides response protocols to guide Public Health Units and water utilities when managing contamination. Corrective action may have included emergency maintenance, increasing disinfection or the issuing of boil water alerts. While acknowledging the practical difficulties in obtaining repeat unscheduled samples, particularly for small, remote supply systems, the delays between taking the sample and receiving the result of the sample, and the lack of availability of water testing services on weekends, make this situation less than ideal. Delays in obtaining a sample result may partially, but

Table 3 | Univariate association between microbiological non-compliance and drinking water supply system features

Supply system feature	Incidence rate ratio	95% confidence interval	*P*
Supply system population (for each 1,000 person increase)	0.98	0.96–0.99	<0.001
Population 100,000 or more	1.00		
Population 5,000–99,999	2.88	2.00–4.14	<0.001
Population 500–4,999	6.40	4.72–8.67	<0.001
Population 100–499	11.60	8.08–16.65	<0.001
Population fewer than 100	12.95	8.12–20.66	<0.001
Water source			
Mixed sources	1.00		
Surface storage	1.41	0.80–2.47	0.23
Watercourse	2.21	1.34–3.66	0.002
Groundwater	2.65	1.54–4.57	<0.001
Disinfection method			
Chlorination, chloramination or both	1.00		
Other or mixed disinfection methods	0.71	0.27–1.82	0.47
Ultraviolet treatment	2.68	1.74–4.12	<0.001
No disinfection	5.72	3.72–8.80	<0.001
Clarification method			
Membrane clarification	1.00		
Standard clarification*	1.24	0.63–2.41	0.53
Sedimentation only	5.60	1.56–20.16	0.008
Not clarified	2.76	1.45–5.28	0.002
Other chemical treatment	0.43	0.32–0.60	<0.001
Mean turbidity (NTU)†	1.19	1.14–1.24	<0.001
Mean free chlorine‡	0.46	0.21–1.01	0.05

*Includes any one of: filtration, flocculation, clarification, coagulation.
†Using the 305 supply systems with turbidity measurements available.
‡Using the 132 supply systems that used chlorination and measured free chlorine.
NTU—nephelometric turbidity unit.

cannot fully, explain the delays between repeat sampling after a non-compliant sample.

Despite these deficiencies, there have been significant improvements in both microbiological compliance and adequacy of microbiological sampling during the review period. There may be many explanations for this, including improved reporting to the Drinking Water Monitoring Program, improved monitoring and maintenance of the regional drinking water systems, improved disinfection and treatment of public drinking water supplies, as well as real improvements in sampling frequency.

During the review period, no outbreaks of waterborne disease were associated with public water supply systems in NSW. It is possible that some outbreaks were prevented by prompt action such as the issuing of boil water alerts following system failure or contamination. Twelve such alerts were issued in 2007.

However, a number of concerns remain. Our results indicate that there is still a risk that a waterborne outbreak of disease could lead to morbidity and mortality in regional NSW. The overall median non-compliance level of 1.4% for regional drinking water systems was up to 70 times higher than the level for utilities serving metropolitan areas (Hunter Water Corporation and Sydney Water Corporation). Hunter Water reported *E. coli* detection in 0.2% of samples, while Sydney Water reported *E. coli* detection in

Table 4 | Univariate association between microbiological non-compliance and time

Time period	Incidence rate ratio	95% confidence interval	*P*
Sample year (per one-year increase)	0.85	0.80–0.91	<0.001
2007 (mid year)	1.00		
2006	0.99	0.71–1.38	0.95
2005	1.01	0.75–1.37	0.94
2004	1.26	0.94–1.70	0.12
2003	1.28	0.92–1.77	0.15
2002	1.84	1.37–2.47	<0.001
2001	2.31	1.64–3.25	<0.001
Season			
Winter	1.00		
Autumn	1.88	1.56–2.27	<0.001
Spring	1.95	1.56–2.43	<0.001
Summer	3.11	2.55–3.79	<0.001

0.02% of samples for the year 2006–2007 (Hunter Water 2007; Sydney Water 2007). It is important to note that the level of risk to communities served by the smallest water supply systems is substantially greater than the median for all regional areas.

Apart from the size of the population served by the drinking water system, a number of factors were associated with an increased risk of *E. coli* detection. These included the type of disinfection used, water source, method of clarification, post-treatment turbidity level, sampling year and season.

There was a significant difference in the effectiveness of different disinfection methods. A lack of disinfection presented a risk of *E. coli* detection of over 12 times that of chlorinated systems. Ultraviolet disinfection performed relatively poorly when used as the sole disinfection method, with rates of *E. coli* detection almost three times higher than rates for chlorinated systems.

Although chlorination and/or chloramination provided the best results, 1.2% of samples were non-compliant even with this method of disinfection. This highlights the need

Table 5 | Multivariate association between microbiological non-compliance and system features

Supply system feature	Incidence rate ratio	95% confidence interval	*P*
Supply system population (for each 1,000 person increase)	0.99	0.98–1.00	0.01
Water source			
Groundwater	1.00		
Surface storage	1.41	0.86–2.31	0.17
Watercourse	2.34	1.40–3.92	0.001
Mixed sources	1.64	0.88–3.07	0.12
Disinfection method			
Chlorination, chloramination or both	1.00		
Other or mixed	2.13	0.45–10.08	0.34
Ultraviolet	2.93	1.57–5.47	0.001
No disinfection	12.62	7.44–21.41	<0.001
Mean monthly turbidity (NTU)	1.17	1.12–1.22	<0.001

NTU—nephelometric turbidity unit.

for regular monitoring and maintenance of all disinfection systems, especially ultraviolet systems. Properly operated ultraviolet disinfection systems are effective in inactivating pathogens; however, ultraviolet disinfection is particularly dependent on an adequate process of clarification prior to disinfection (US Environmental Protection Agency 2006). Water disinfected using ultraviolet light alone also remains vulnerable to contamination after being treated, while chlorination provides ongoing disinfection in the distribution system if there is an adequate chlorine residual (NHMRC & NRMMC 2004).

The level of clarification as measured by the post-treatment turbidity provided a stronger measure of microbiological risk than the method of clarification used. However, more sophisticated clarification techniques were associated with lower risks of microbiological non-compliance. Maintaining consistently low turbidity is desirable to reduce the pathogen risk and achieve good disinfection. Even in filtered supplies fluctuations in turbidity have been associated with an increase in gastrointestinal illness (Schwartz *et al.* 1997, 2000).

As expected, water courses provided the greatest risk of *E. coli* detection, more than twice the risk posed by groundwater systems. However, it is worth emphasizing that supply systems that were not disinfected posed the greatest single risk of microbiological non-compliance after controlling for the water source. This finding is consistent with reviews of outbreaks in the United States, where contamination is commonly associated with untreated or inadequately treated groundwater systems (Liang *et al.* 2006; Yoder *et al.* 2008).

The seasonal association with microbiological non-compliance was possibly a result of higher rainfall in summer, and lower rainfall in winter in NSW during the review period (Bureau of Meteorology 2008). High rainfall can cause contamination of water supplies. A review of United States data found that almost 70% of waterborne disease outbreaks were preceded by extreme rainfall events (Curriero *et al.* 2001). Microbiological risks converged during summer, as this season was also associated with less adequate sampling practice on average.

This review had limitations. We only used data from the NSW Health Drinking Water Monitoring Program, which is a routinely collected source of data that may contain inaccuracies. Further, the data only contained information on public drinking water systems that report to the Program. There may have been additional potable supplies in NSW that were excluded because they do not participate in the monitoring program.

In addition, the Program only collects data on the quality of drinking water that is supplied to consumers. This meant that our ability to assess risk mitigation strategies and processes was limited. We could not report on the adequacy of corrective actions taken as a result of a non-compliant sample, as this information is not available from the Program's database. This review was limited to an analysis of microbiological quality, although the chemical quality of drinking water is also associated with both acute and chronic health risks.

Finally, although monitoring is an important part of quality control, monitoring end-user drinking water quality has a number of inherent limitations, including:

- intermittent sampling cannot detect all contamination events,
- exposure of the supply population to contaminated water may occur days before a non-compliant sampling result is available, and
- contamination with pathogens such as protozoa and viruses may not be identified unless the contamination is accompanied by the indicator organism (*E. coli*) or elevated turbidity.

To ensure that drinking water is safe, the *Guidelines* recommend assessment of the risks to drinking water supply, and implementation of a preventive risk-management framework which seeks to manage hazards before system operation or water quality is compromised. Such risks include potential contamination from septic wastes, animal faeces and effluent. Water catchments should be carefully protected from such contamination.

CONCLUSION

Drinking water systems that are not disinfected, and systems serving small populations, are particularly vulnerable to the effects of faecal contamination. All drinking water systems should be adequately treated and continuously

disinfected, regardless of water source, to reduce the risk of waterborne disease. The disinfection method of choice is chlorination. Treatment performance should be carefully monitored.

Communities cannot rely solely on end-user drinking water monitoring programs to prevent waterborne outbreaks of infectious disease. Even in developed countries such as Australia, where drinking water monitoring programs exist, the presence of *E. coli* above guideline levels in many drinking water supplies indicates that there is still a risk of outbreaks of waterborne disease in regional areas. It is necessary for each water utility to fully implement a preventive risk-management framework to protect the community from risks associated with drinking water.

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