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CHAMBERS, Tim <http://orcid.org/0000-0001-5856-5600>, PUENTE-SIERRA, Mario, MAREK, Lukas, MEAFOU, Brittany, KIM, Alice, KNOPICK, Michael and HOBBS, Matthew

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A national assessment of reticulation-level exposure risk indicators in drinking-water infrastructure in Aotearoa New Zealand

Tim Chambers [a,*], Mario Puente-Sierra [b], Lukas Marek [b], Brittany Meafou [a], Alice Kim [c], Michael Knopick [d], Matt Hobbs [e,f]

[a] Ngāi Tahu Research Centre, University of Canterbury, Te Whare Wānanga O Waitaha, Christchurch, Ōtautahi, New Zealand
[b] GeoHealth Laboratory, Te Taiwhenua O Te Hauora, University of Canterbury, Te Whare Wānanga O Waitaha, Christchurch, Ōtautahi, New Zealand
[c] Department of Public Health, University of Otago, Wellington, New Zealand
[d] ENGEO Ltd, Christchurch, New Zealand
[e] Faculty of Health, University of Canterbury, Te Whare Wānanga O Waitaha, Christchurch, Ōtautahi, New Zealand
[f] College of Health, Wellbeing and Life Sciences, Sheffield Hallam University, Sheffield, Yorkshire, United Kingdom

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ABSTRACT

Background: Drinking water reticulation networks are a critical yet understudied component of public health infrastructure. Despite recognition of microbial and chemical risks from ageing distribution systems, few studies have quantified these exposures or assessed associated population health burden nationally.

Objective: To assess public health risks from New Zealand's drinking water reticulation networks and identify demographic disparities.

Methods: We conducted a nationwide exposure risk assessment using spatial data on 57,000 km of municipal drinking water pipes across 629 Water Distribution Zones, covering 88% of the population. We developed key exposure metrics to assess enteric disease risk (proportion of pipes in poor/very poor condition), potential lead leaching (presence of metal pipes), and possible asbestos exposure (presence of asbestos cement pipes). Exposure was categorised into population-weighted tertiles to assess inequities by ethnicity and area-level deprivation.

Results: About 30.7% of New Zealand's pipes were in poor or very poor condition. Metal and asbestos cement pipes comprised 12.4% and 19.8% of the network, respectively, of which, 72.2% and 96.5% were in poor or very poor condition. Māori, Pacific Peoples, and those in high-deprivation areas were disproportionately exposed to the worst pipe conditions and asbestos pipes.

Significance: New Zealand's ageing drinking water infrastructure may pose microbial and chemical risks, with inequitable impacts across demographic groups. Our findings underscore the need for targeted infrastructure investment and regulatory reform to ensure safe, equitable access to drinking water.

1. Introduction

High-quality drinking water reticulation networks are an essential element for delivering safe drinking water. (Ercumen et al., 2014) Despite this, contamination can occur during construction, installation or repair; from corrosion leading to accumulation of particles; low pressure or leaking, intermittent water supply; or inadequate chlorination. (World Health Organization, 2014) Even in developed countries, compromised networks pose significant microbial and chemical risks with important public health implications. (Ercumen et al., 2014) However, attempts to quantify the attributable health burden of the distribution network are limited by inaccurate information on the location, condition and material of the pipes as well as the location and duration of network outages. (Ercumen et al., 2014) As such, epidemiological studies investigating direct health impacts of drinking water reticulation networks are sparse, often with major limitations. This study aims to: 1) quantify the population in New Zealand (NZ) exposed to drinking water reticulation potentially posing a public health risk; 2) investigate inequities in this exposure; 3) document the exposure assessment that can be used for future epidemiological research into the health impacts of these exposures. In this study, we examine three contamination risks within the drinking water distribution network:

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* Corresponding author.
E-mail address: tim.chambers@canterbury.ac.nz (T. Chambers).

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microbial pathogens, lead, and asbestos.

1.1. Microbial contamination risks

Microbial contamination within the reticulation (post-treatment) system remains a significant and often underappreciated public health risk. Such contamination can occur due to multiple deficiencies in the distribution system, which include breaches (e.g., cracks, leaks, or pipe breaks), loss of hydraulic integrity (e.g., pressure drops or backflow events), and deterioration of water quality within the system. (Ercumen et al., 2014) Network outages were the strongest predictor of enteric disease of all network system deficiencies in a 2014 systematic review. (Ercumen et al., 2014) Pipes in poor condition are particularly susceptible to both physical breaches and loss of pressure, which can enable the intrusion of pathogens from surrounding soil or water during periods of negative pressure or repair. (Barton et al., 2019) In Canada, an estimated 37% of all waterborne enteric diseases were attributable to the distribution system. (Murphy et al., 2016) Separately, a systematic review of waterborne outbreaks in the USA from 1971 to 2006 found that 18% were caused by deficiencies of the distribution system, however, such data do not capture the full burden of endemic disease.[5]

1.2. Lead contamination risks

Based on WHO guidelines, the *New Zealand Water Services Authority - Taumata Arowai* sets the NZ maximum acceptable value (MAV) for lead in drinking water at 0.01 mg/l, twice as high as the European Union MAV of 0.005 mg/l. (New Zealand Parliament, 2022) However, there is no known safe level of lead in the human body. (World Health Organization, 2016) Lead-contaminated drinking water can irreversibly impact cognitive development, IQ and behaviour in children as well as renal, cardiovascular and reproductive issues in adults. (Agency for Toxic Substances and Disease Registry, 2020) Children are particularly susceptible as they can absorb 40–50% of an oral dose of water-soluble lead compared to <10% for adults. (Agency for Toxic Substances and Disease Registry, 2020) In one study of children aged between one and five, every 0.001 mg/l (10% of the MAV) increase in water lead levels was associated with a 35% increase in blood lead levels. (Ngueta et al., 2016) However, precise dose-response curves between water lead and blood lead levels are still uncertain.

In Flint, Michigan (USA), lead leached into the town's drinking water from an aged reticulation system after a change to a more corrosive water source in 2014, which affected mostly disadvantaged communities. The number of children showing elevated blood lead levels (≥5 μg/dL) doubled from 2.4% to 4.9% after this change. (Hanna-Attisha et al., 2016) In NZ, lead exceedances of the drinking water MAV have been observed in Tokomaru, Waikouaiti, Karitane, Hawkesbury, Akaroa and Lyttelton. (Uwins-England and McKenzie, 2021; Arowai, 2024) The 2023 Taumata Arowai Drinking Water Regulation Report noted ten supplies had at least one lead exceedance in the 2023 reporting period. (Arowai, 2024) However, lead monitoring is infrequent (biannually for networks >500 people) and is only conducted on running water within the distribution network, so current reporting may not necessarily be representative of public exposure, particularly from lead leached from pipes and tapware past the shut-off valve operated by a water supplier.

Lead contamination can originate from various points within the distribution network. Metal-based pipes (e.g. cast iron, steel, ductile iron, copper, aluminium) tend to form scales with high affinity for heavy metals such as lead. (Stefan et al., 2023) Additionally, iron pipes can contain small amounts of lead, which can be released in the event of corrosion. (Stefan et al., 2023) Iron in combination with lead and organic matter can form colloidal particles which detach from pipe scale and mobilise through the water, being exacerbated by low pH and flow disturbances. (Stefan et al., 2023) In NZ, it is assumed, but not systematically confirmed, that metallic reticulation constructed before the mid-1980′s contains lead solder, which was only prohibited in the USA in 1986. (Aqua Works 2021; United States Environmental Protection Agency, 2024) It is evident that networks containing lead solder have higher lead levels (above WHO guidelines) than lead-free systems. (Chang and Lee, 2023) Given the outdated infrastructure and inconsistent monitoring, it is important to quantify which populations may be disproportionately affected. This study contributes to addressing that gap.

1.3. Asbestos contamination risks

Asbestos exposure through inhalation has long been associated with serious health risks, including cancer. (World Health Organization, 2021) In 2021, the WHO evaluated the risk associated with asbestos exposure through drinking water, concluding that while the carcinogenic risk of inhalation is well established, the overall evidence does not suggest a significant increase in cancer risk from asbestos exposure via drinking water. (World Health Organization, 2021) In 1992, the U.S Environmental Protection Agency (EPA) established a maximum contamination level (MCL) of 7 million fibres per litre (MFL) for long asbestos fibres (>10 μm) under the Safe Drinking Water Act of 1974. (World Health Organization, 2025; United States Environmental Protection Agency, 1992) The EPA's MCL was set as a precautionary measure to account for asbestos carcinogenicity and uncertainties in exposure from drinking water. (United States Environmental Protection Agency, 2016) Current evidence suggests that ingested asbestos fibres are largely excreted. Although some studies have found that some fibres can penetrate the gastrointestinal (GI) tract and enter the bloodstream, with small amounts accumulating in organs, (United States Environmental Protection Agency, 2001) and higher rates of GI cancers observed in populations with contaminated water. (Go et al., 2024)

Epidemiological evidence examining the health impacts of asbestos in drinking water is very limited and has produced mixed results. (Go et al., 2024) Some studies suggest an association between asbestos exposure and GI cancers, but these findings are inconsistent and limited by methodological challenges related to study design, inconsistent comparability protocols, and insufficient exposure data. (World Health Organization 2021; United States Environmental Protection Agency, 2001; ANSES, 2021) The majority of the epidemiological evidence is based primarily on ecological or cross-sectional observational studies. (Go et al., 2024) The best available epidemiological evidence appears to be the Lighthouse Keeper Cohort studies of 726 Norwegian lighthouse keepers, who were exposed to asbestos-contaminated water and observed an elevated risk of stomach cancer. (Andersen et al., 1993; Kjærheim et al., 2005) The overall evidence base is limited by study design, population size and assessment of asbestos exposure, which supports further epidemiological investigation into the potential health impacts of ingested asbestos.

The leaching of asbestos fibres from asbestos cement (AC) pipes into drinking water is driven by a combination of physical, chemical, and mechanical factors. Water quality parameters, such as pH, temperature, and the presence of disinfectants like chlorine, play a crucial role in the deterioration of AC pipes, particularly in ageing infrastructure. (Zavašnik et al., 2022) Low-pH water (pH < 7.5–8.0), low alkalinity, and low calcium content make water aggressive toward cement materials, accelerating the release of asbestos fibres, especially when high sulphate levels (>400 mg/l) are present. (Peña-Castro et al., 2023) Cement lime dissolves into the water, releasing calcium and hydroxide ions, which can significantly raise pH levels, depending on the buffering capacity of the water. (Peña-Castro et al., 2023) These chemical reactions weaken the structural integrity of the pipes and facilitate asbestos fibre release into the water supply. (Stefan et al., 2023) Mechanical stressors, such as vibrations from nearby roads, railroads, seismic instability or construction activities, also contribute to the degradation of AC pipes and increase the release of asbestos fibres. (Zavašnik et al., 2022) In addition to these physical forces, microbial activity within the pipes can create acidic conditions that further degrade the cement matrix, exacerbating the detachment of asbestos fibres. (Stefan et al., 2023) The complex interplay of these factors underscores the importance of regular monitoring, especially in older water systems that still rely on AC pipes.

Despite the recognised risks of airborne asbestos, water is not routinely tested for asbestos in many countries, including NZ. In one highly relevant study conducted in Christchurch (NZ), 19 of the 20 water samples taken across the city found long fibres (>10 μm), with an average contamination level of 0.9 MFL and short asbestos fibres (>0.5 μm), with an average contamination level of 6.2 MFL. (Mager et al., 2022) These results suggest that the city has an ageing AC water distribution network that is undergoing corrosion due to the soft and highly aggressive municipal water supply, leading to the release of both short (>0.5 μm) and long (>10 μm) asbestos fibres into the drinking water. This scarcity of testing, combined with the aggressive chemical dynamics of some water systems, raises concerns about the long-term integrity of AC pipes and the potential health risks posed by asbestos leaching into drinking water. Moreover, this Christchurch case study highlights the potential under-recognition of asbestos contamination nationally, further underscoring the need for more research/exposure mapping across NZ.

2. Methods

2.1. Population

The population included in this analysis consists of all people receiving water from a municipal drinking water supply in NZ. Municipal drinking water supplies in NZ are owned by 67 Territorial Authorities (TAs) who supply water to approximately 88% of the population. The remaining 12% of the population receives water from either unregulated domestic self-supplies (e.g. a bore or rainwater) or small non-municipal water suppliers. This study focuses on the population served by a registered supply owned by a TA.

2.2. Data

2.2.1. Water distribution zones (WDZ)

The area served by any registered water supply is called a Water Distribution Zone (WDZ). There are 629 TA-owned WDZs for which we have spatial information on the extent of these supplies. (Puente-Sierra et al., 2023) These 629 WDZs serve water to ~4135,000 people (88% of NZ's total population). (Puente-Sierra et al., 2023) WDZs vary substantially in size, ranging from small rural supplies serving a few hundred residents to large metropolitan supplies serving several hundred thousand people. A WDZ does not necessarily correspond to a city boundary, as some urban areas contain multiple WDZs while some rural WDZs span multiple settlements. Supplementary Table 1 provides an overview of the WDZs included in this analysis.

The collation and standardisation of the spatial extent of TA-owned WDZ has been documented elsewhere. (Puente-Sierra et al., 2023) In brief, data was received from TAs via official information requests. Data was standardised and the spatial extent of each WDZ was validated using a combination of data on building footprints, reticulation network location, and historical WDZ data. We then spatially intersected the WDZ boundaries with population data from census administrative boundaries. As such, for each WDZ, we estimated the total number of people served as well as the population served by ethnicity and deprivation. People reporting multiple ethnicities were assigned a single ethnicity prioritised in the following order: Māori (NZ indigenous population), Pacific Peoples, Asian and European. Deprivation was determined using the New Zealand Deprivation Index, which draws on multiple sources of census data to generate a deprivation decile from 1 (least deprived) to 10 (most deprived). In our analysis, we look at ethnic differences between Māori, Pacific Peoples and Europeans and differences by deprivation tertile (low = 1–3; moderate 4–7, high 8–10).

2.2.2. Drinking water reticulation networks

Spatial data on the location, age, and material of the drinking water reticulation was retrieved directly from all TAs between 2023 and 2024. The full process of collation and standardisation has been documented elsewhere. (Puente-Sierra et al., 2025) In brief, the dataset contains the spatial location of each drinking water pipe length in NZ as well as information on the installation date (age) and material of that pipe length. In total, 625 of the 629 WDZ from 66 of the 67 TAs had reticulation data for pipe material and age and are included in the analysis. A summary of pipe characteristics is provided in Supplementary Figure 1.

2.3. Exposure assessment

This study estimates reticulation-level exposure risk indicators rather than direct contaminant concentrations, individual doses, or observed health outcomes. The indicators were selected to identify WDZs where pipe condition or material composition may plausibly increase vulnerability to microbial intrusion or chemical leaching, based on existing literature and available national reticulation data. In addition, as outlined in the Introduction, the health risks associated with ingestion of asbestos fibres remain uncertain. We therefore interpret the asbestos cement pipe indicator as an exploratory measure rather than as a direct indicator of established disease risk.

The unit of analysis for this exposure assessment is WDZ, for which we aggregated the drinking water network data using a spatial intersection. We aggregated the total length of pipes, length of pipe by material type and length of pipe in poor or very poor condition. (Puente-Sierra et al., 2025)

We defined our **enteric disease risk indicator** using the proportion of pipe length in poor or very poor condition within each WDZ. (Puente-Sierra et al., 2025) Pipe condition was estimated using pipe material and installation year/age. For each pipe segment, remaining useful life was calculated using material-specific expected service life estimates (provided in Supplementary Table 2). Pipes with ≤25% of expected service life remaining were classified as being in poor or very poor condition. This classification represents a desktop proxy for pipe condition rather than a direct engineering inspection assessment. We used the proportion of pipe length in poor or very poor condition within each WDZ as a proxy indicator of potential enteric disease risk, based on the assumption that degraded pipes are more vulnerable to physical breaches, pressure loss, and intrusion of external contaminants.

We defined our **lead leaching risk indicator** by the presence of any metal pipe in the WDZ. While it is likely certain metal pipe materials are more prone to lead leaching than others due to the presence of lead-based components (e.g. lead solder), there is evidence that all metal pipes can pose some lead leaching risk. We defined our **asbestos leaching risk indicator** by the presence of AC pipes in the WDZ. We also assumed that the greater proportion of a WDZ made of AC was related to a higher proportion of leaching of asbestos fibres.

2.4. Statistical analysis

Descriptive statistics on all pipe variables were calculated at a national and WDZ level. For all analyses, we assumed that the proportion of the pipes within the WDZ was related to an increased risk. We provide statistics on the length (in kilometres) and proportion of the national reticulation network that comprises plastic, metal and asbestos pipes as well as the proportion of those pipes that are in poor or very poor condition.

Exposure indicators were calculated at the WDZ level. WDZs were then ranked by each exposure indicator and grouped into population-weighted tertiles, such that each tertile contained approximately one-third of the population served by TA-owned drinking water supplies. Consequently, the number of WDZs differed between tertiles, while the population size of each tertile was broadly similar. We then calculated the number of people that fell within those tertiles by ethnicity and neighbourhood deprivation to investigate if the exposure was patterned by sociodemographic characteristics. For each ethnic and deprivation group, we calculated the rate per 1000 for being in the highest tertile health risk indicator category. A gamma-distribution-based 95% confidence intervals were estimated for crude rates using epiR package in R version 4.3.1. (Stevenson et al., 2024) Rate ratios were estimated using the European and low deprivation groups as reference levels. Confidence intervals for rate ratios were computed using the Gaussian approximation for log-likelihood functions. (Clayton and Hills, 2013)

Additionally, we classified and mapped TAs by exposure to all three risk indicators. For each indicator, TAs were grouped into population-weighted quintiles of exposure, with each quintile containing approximately 20% of the population served by TA-owned WDZs (i.e. ~827,000 people per quintile).

3. Results

3.1. Pipe material and condition

Table 1 provides an overview of the national drinking water reticulation by material and percentage of pipes in poor or very poor condition. In total, there are 57,000 km of drinking water pipes in NZ, with an estimated 30.7% being in poor or very poor condition. Plastic pipes make up 67.3% of the entire reticulation network, followed by AC (19.8%) and metal pipes (12.3%). Under our assumptions about pipe condition, only 3.5% of plastic pipes are deemed to be in poor or very poor condition. In contrast, 72.2% of metal pipes and 96.5% of AC pipes are estimated to be in poor or very poor condition.

3.2. Demographic differences in exposure to potential reticulation risk indicators

Table 2 outlines the population-weighted tertiles of exposure for each pipe outcome, including by ethnicity and deprivation. The lowest tertile receives water from a WDZ that contains 0.0–29.0% of the pipes in poor or very poor condition, while the second tertile is between 29.1% and 47.7%, and the highest tertile is greater than 47.8%. Māori and Pacific Peoples have a greater proportion of their population residing in the highest tertile compared to European. In addition, the greatest proportion of the population living in the highest deprivation is present in the highest tertile of exposure. The lowest tertile of exposure to AC pipes is between 0.0% and 19.2% of the WDZ, while the second tertile is 19.3–30.1%, and the highest tertile is greater than 30.1%. Māori and Pacific Peoples, as well as those living in the highest neighbourhood deprivation, are overrepresented in the highest tertile of exposure.

Table 3 presents rate ratios of the population exposed to the highest tertile of potential public health risk indicators associated with drinking water reticulation by ethnicity and deprivation. Māori have a 3% (RR 1.03, 95%CI 1.02, 1.03) and Pacific Peoples have a 68% (RR 1.68, 95% CI 1.67, 1.69) higher rate of exposure to a WDZ in the highest tertile of pipes that are in poor or very poor condition compared to European. People living in moderate deprivation have a 6% (RR 1.06, 95%CI 1.06, 1.07) and people in high deprivation a 26% (RR 1.26, 95%CI 1.25, 1.26) higher rate of exposure to a WDZ falling in the highest tertile of pipes in poor or very poor condition. In contrast, Māori (RR 0.85, 95%CI 0.85, 0.86) and Pacific Peoples (RR 0.85, 95%CI 0.85, 0.86) have lower rates of exposure to WDZ that have the greater proportion of metal pipes. Māori have 50% (RR 1.50, 95%CI 1.49, 1.50) higher and Pacific Peoples a 104% (RR 2.04, 95%CI 2.03, 2.05) higher rates of exposure to WDZ falling in the highest tertile of WDZ with the greater proportion of AC pipes. People living in moderate deprivation have 14% (RR 1.14, 95%CI 1.14, 1.15) higher and those living in the highest deprivation have 77% (RR 1.77, 95%CI 1.76, 1.77) higher rates of exposure to asbestos pipes than those living in the lowest deprivation.

Sensitivity analyses using population-weighted quartiles and deciles produced broadly similar demographic patterns to the main tertile analysis (Supplementary Table 3). Associations were generally stronger when the highest exposure category was defined more narrowly, particularly for asbestos cement pipes and high-deprivation populations, suggesting that the main findings were not driven solely by the selected tertile cut-points.

Fig. 1 presents three maps of the population exposure to our enteric disease risk indicator (A), lead leaching risk indicator (B) and asbestos leaching risk indicator (C). The exposure in each of 67 TAs in NZ is visualised in population-weighted quintiles (Q1 – least exposed, Q5 – most exposed). Enteric disease risk indicator appeared to be concentrated in those large metropolitan cities such as Greater Wellington, Dunedin, Invercargill and Auckland, as well as a few smaller TAs such as Napier, Gisborne, Wairoa, Gore, South Taranaki and South Waikato. Lead leaching risk indicator showed a similar distribution to enteric disease risk indicator but also includes TAs such as New Plymouth, Hastings, Whanganui, Tararua, Masterton, Nelson and Buller. Finally, asbestos leaching risk indicator was higher in other zones, with TAs at the highest risk quintile, including Whangarei, Thames-Coromandel, Waitomo, South Waikato, South Taranaki, Wairoa, Napier, most of Greater Wellington and Invercargill.

4. Discussion

This study aimed to provide estimates of the population exposed to three potential public health risk indicators associated with public drinking water reticulation systems. The methodology used to generate

Table 1
Material, length and condition of New Zealand's drinking water reticulation network.

Pipe material		Total national		Percentage of pipes in poor or very poor condition		
		km	%	Midpoint estimate	Optimistic estimate	Pessimistic estimate
All pipes	**All pipes**	57,174	100	30.7	24.5	42.5
Plastic	**All Plastic**	**38,493**	**67.3**	**3.5**	**0.5**	**18.7**
	Polyethylene (PE)*	20,606	36.0	5.2	0.7	17.6
	Polyvinyl Chloride (PVC)	17,887	31.3	1.5	0.3	19.9
Metal	**All Metal**	**7113**	**12.4**	**72.2**	**57.9**	**80.6**
	Steel (CLS)	2695	4.7	72.1	60.2	77.0
	Cast Iron (CI)	2716	4.8	78.3	60.4	89.1
	Copper (CU)	741	1.3	74.3	59.1	90.0
	Galvanised (GALV)	573	1.0	86.0	70.9	93.4
	Ductile Iron (DI)	367	0.6	5.6	2.7	7.2
	Concrete Lined Steel (STCL)	16	<0.01	39.2	22.9	43.1
	Aluminium (AL)	5	<0.01	5.4	4.4	53.3
Asbestos Cement	**All Asbestos Cement (AC)**	**11,321**	**19.8**	**96.5**	**84.9**	**98.8**
Other**		248	0.4	56.5	37.7	82.3

[*] Includes: "Low Density Polyethylene (LDPE)", "Medium Density Polyethylene (MDPE)", "High Density Polyethylene (HDPE)", "Alkathene (ALK)")
**Includes: Concrete (CONC), Earthenware.

Table 2
Population exposed to quantiles of exposure to percentage (%) of pipe within WDZ for pipes in poor or very poor condition (enteric disease risk indicator), metal pipes (lead risk indicator) and Asbestos Cement pipes (asbestos fibre risk indicator).

Pipe outcome	% of pipe within WDZ	Total		Ethnicity						Area-level Deprivation					
		n	(%)	European, n (%)		Māori, n (%)		Pacific Peoples, n (%)		Low, n (%)		Moderate, n (%)		High, n (%)	
Enteric disease risk indicator (Ercumen et al., 2014)	0.0–29	1347,567	32.6	1011,526	36.0	201,020	29.8	55,807	15.0	451,528	39.6	557,831	34.7	338,212	24.4
	29.1–47.7	1360,594	32.9	930,692	33.1	259,653	38.4	122,541	33.0	334,216	29.3	518,840	32.3	507,530	36.6
	> 47.8	1426,413	34.5	868,785	30.9	214,912	31.8	192,537	51.9	353,866	31.1	531,906	33.1	540,640	39.0
Lead risk indicator (World Health Organization, 2014)	0.0–9.5	1376,682	33.3	1028,232	36.6	233,366	34.5	79,287	21.4	441,543	38.7	559,686	34.8	375,443	27.1
	9.5–19.3	1363,520	33.0	816,368	29.0	244,403	36.2	182,548	49.2	309,441	27.2	494,052	30.7	560,029	40.4
	> 19.3	1394,372	33.7	966,403	34.4	197,816	29.3	109,050	29.4	388,626	34.1	554,839	34.5	450,910	32.5
Asbestos risk indicator (Barton et al., 2019)	0.0–19.2	1345,552	32.5	1044,324	37.2	185,402	27.4	57,189	15.4	433,523	38.0	553,805	34.4	358,221	25.8
	19.3–30.1	1393,860	33.7	963,611	34.3	200,954	29.7	97,696	26.3	413,182	36.3	581,750	36.2	398,931	28.8
	> 30.1	1395,162	33.7	803,068	28.6	289,229	42.8	216,000	58.2	292,905	25.7	473,022	29.4	629,230	45.4

1 = Pipes in poor or very poor condition 2 = Metal pipes; 3 = Asbestos Cement pipes.

Table 3
Rate ratios of the population exposed to the highest tertile of potential public health risk indicators associated with drinking water reticulation by ethnicity and deprivation.

Characteristic	Total	Highest tertile of percentage of pipes within WDZ that are in poor or very poor condition			Highest tertile of percentage of pipes within WDZ that are metal			Highest tertile of percentage of pipes within WDZ that are Asbestos Cement		
	n	n	Rate per 1000 (95% CI)	Rate ratio (95% CI)	N	Rate per 1000 (95% CI)	Rate ratio (95% CI)	n	Rate per 1000 (95% CI)	Rate ratio (95% CI)
Total	4134,574	1426,413	345 (344–346)	-	1394,372	337 (337–338)	-	1395,162	337 (337–338)	-
Ethnicity										
European	2811,003	868,785	309 (308–310)	Ref	966,403	343 (343–344)	Ref	803,068	286 (285–286)	Ref
Māori	675,585	214,912	318 (317–319)	**1.03 (1.02–1.03)**	197,816	293 (292–294)	**0.85 (0.85–0.86)**	289,229	428 (427–430)	**1.50 (1.49–1.50)**
Pacific Peoples	370,885	192,537	519 (517–521)	**1.68 (1.67–1.69)**	109,050	294 (292–296)	**0.85 (0.85, 0.86)**	216,000	582 (580–585)	**2.04 (2.03–2.05)**
Deprivation										
Low	1139,610	353,866	311 (309–312)	Ref	388,626	341 (340–342)	Ref	292,905	257 (256–258)	Ref
Moderate	1608,577	531,906	331 (330–332)	**1.06 (1.06–1.07)**	554,839	345 (344–346)	**1.01 (1.01–1.02)**	473,022	294 (293–295)	**1.14 (1.14–1.15)**
High	1386,382	540,640	390 (389–391)	**1.26 (1.25–1.26)**	450,910	325 (324–326)	**0.95 (0.95–0.96)**	629,230	454 (453–455)	**1.77 (1.76–1.77)**

these estimates could be used as the foundation for future epidemiological studies investigating the health impacts associated with pipes in poor or very poor condition, lead leached from metal pipes, and asbestos fibres leached from AC pipes. The results also highlight inequities in exposure by ethnicity and neighbourhood deprivation. Māori and Pacific Peoples, and those living in the highest neighbourhood deprivation experienced disproportionate exposure to enteric and asbestos risk indicators, while European and those living in the least neighbourhood deprivation experienced disproportionate exposure to lead leaching risk indicator.

Overall, an estimated 30.7% of the entire reticulation network in NZ was estimated to be in poor or very poor condition based on the age and material. This is consistent with previous research demonstrating that pipes in poor or very poor condition are more vulnerable to breaches and loss of hydraulic pressure, which can lead to outages and contamination from exogenous sources. (Barton et al., 2019) While further validation analyses are required to better understand the relationship between condition and enteric disease risk, the results suggest that simple desktop condition grading may be a useful proxy at a population level. As mentioned, network outages, defined as interruptions to water supply or pressure within the distribution system, were the strongest predictor of enteric disease risk of all network system deficiencies in a 2014 systematic review of epidemiological studies. (Ercumen et al., 2014)

A total of 12.4% of the national network is comprised of metal pipes that are the most likely sources of lead leaching within the distribution system. (Stefan et al., 2023) While the primary source of lead in drinking water in most homes is tap fittings or service lines, our results provide a starting point for the identification of potential lead contamination issues associated with the reticulation.

AC is almost ubiquitous in NZ’s publicly owned water supplies, with only ~125,000 (3.0%) people being served by a WDZ that does not contain AC pipes (Supplementary Table 4). To date, epidemiological evidence that ingested asbestos poses a health risk remains limited and inconclusive. (Go et al., 2024) As such, the exposure assessment conducted in this study provides a platform for a future epidemiological study in NZ on the potential health risks associated with asbestos leached from AC pipes. NZ is a good locality for such a study due to: 1) its access to the Integrated Data Infrastructure, a national database of all routinely collected information from government agencies linked at the individual level, which facilitates national retrospective cohort studies at low cost; (Milne et al., 2019) 2) prevalence and differential exposure to AC pipes across WDZ; 3) high rates of gastrointestinal tract cancers. (Te Aho o Te Kahu 2021)

Given the biological complexities associated with asbestos-related diseases, the success of such epidemiological research will depend critically on the availability of comprehensive exposure data. This

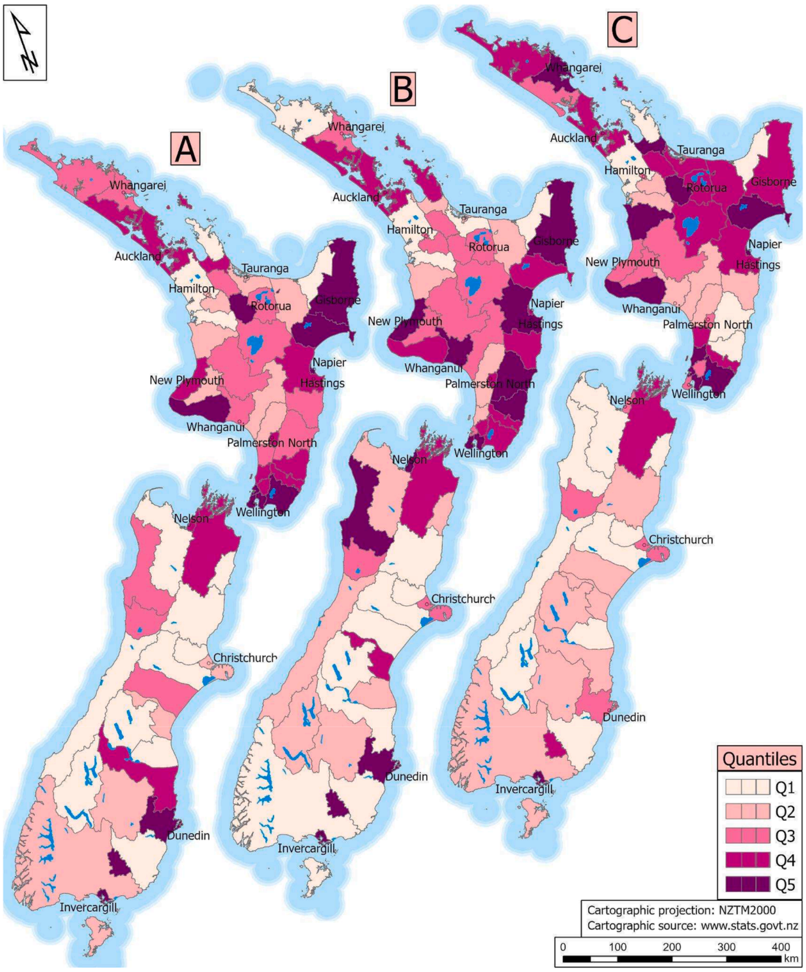

Fig. 1. Map of exposure on TAs by population-weighted quintiles for our categories - enteric (A), lead (B) and asbestos (C) risk indicators.

highlights the need for routine monitoring of asbestos fibres in drinking water to enable robust study design and meaningful interpretation of health outcomes. At the very least, improved asbestos monitoring in drinking water could facilitate a better understanding of the factors influencing fibre leaching, which then could be integrated into predictive models and used as a proxy for exposure.

Our results also highlighted inequities in exposure to different pipe materials and conditions by demographic characteristics. For example, people living in the most deprived areas had higher rates of exposure to pipes in poor or very poor condition and AC pipes. Inequities in water service provision by deprivation have been previously documented in NZ. (Hales et al., 2003) One explanation could be that modern residential developments come with new infrastructure, including pipes, and are also likely to be classified as areas of low(er) deprivation. Similarly, Māori and Pacific Peoples had higher exposure to pipes in poor or very poor condition and AC pipes. However, European people have greater exposure to metal pipes. One plausible explanation could be that many Europeans often in less deprived/more affluent neighbourhoods near metropolitan centres (but not in the CBD), (Marek et al., 2023) that are older and thus rely on the older infrastructure consisting of metal pipes.

4.1. Strengths and limitations

A major strength of this study is that it pulls on a national dataset of reticulation condition and materials to inform a national-level exposure assessment. We were also able to highlight inequities in these exposures by linking our WDZ dataset to census information for future epidemiological studies.

A major limitation of our analysis was that our condition assessment was based entirely on the age and material of the pipe, using estimates from literature on the life expectancy of a particular pipe material. We did not have access to pipe diameter or pressure, which are also important factors in pipe condition assessments. Likewise, multiple additional factors such as water softness, pH, soil conditions and seismic activity, which we could not include in our assessment, influence the leaching of pipe materials (lead and asbestos).

The exposure indicators used in this study are screening-level proxies and should not be interpreted as direct measures of contaminant concentrations, individual exposure, or disease risk. Actual lead and asbestos exposure depend on additional factors not available nationally, including water chemistry, stagnation time, pipe position within the network, premise plumbing, fittings, and temporal variation in flow or pressure. Similarly, enteric disease risk depends not only on pipe condition but also on pressure dynamics, outages, repair events, source contamination, treatment performance, and pathogen presence. These limitations may lead to exposure misclassification within WDZs and mean that the indicators are best interpreted as identifying areas where reticulation characteristics may plausibly increase public health vulnerability.

Our exposure assessment and analysis by demographic characteristics assumes that exposure is proportional within a WDZ, that is, each person is equally exposed to asbestos within a WDZ. However, it is likely that exposure within a zone is unlikely to be proportional, given that risk factors for that exposure are not equally distributed (e.g. water stagnation, water quality characteristics changing throughout the network, such as pH) as well as the physical location of the potential hazard (e.g. the actual location of the asbestos pipe). The implications for inequity estimates are uncertain. If pipes with associated risk indicators are concentrated in areas where Māori, Pacific Peoples, or socioeconomically deprived populations are overrepresented, our WDZ-level approach may underestimate inequities. Future studies may want to consider proximity to the hazard within the WDZ as well as other risk factors for leaching or physical breaches in their exposure assessments.

5. Conclusions

Attempts to quantify the attributable health burden from the distribution network have been limited primarily by the data available for epidemiological exposure assessments. Our study highlights a pathway forward for exposure assessments for national epidemiological studies investigating the potential health impacts of pipes in poor or very poor condition, as well as pipes made from metal or asbestos. The results suggest that high-quality and large epidemiological studies into these risk factors is feasible, and that NZ could be a suitable locality for these studies.

Ethical approval

Ethics approval for this study was granted by the University of Otago Human Ethics Committee as part of the project "A national burden of disease analysis of water-borne disease in Aotearoa New Zealand from community drinking water infrastructure", Ethics Committee reference number HD24/006

CRediT authorship contribution statement

Tim Chambers: Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Mario Puente-Sierra:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Lukas Marek:** Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation. **Brittany Meafou:** Writing – review & editing, Writing – original draft, Conceptualization. **Alice Kim:** Writing – review & editing, Methodology, Formal analysis. **Michael Knopick:** Writing – review & editing, Project administration, Methodology, Formal analysis, Data curation. **Matt Hobbs:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Tim Chambers reports financial support was provided by Te Niwha - Infectious Disease Research Platform. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sste.2026.100825.

Data availability

Data will be made available on request.

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