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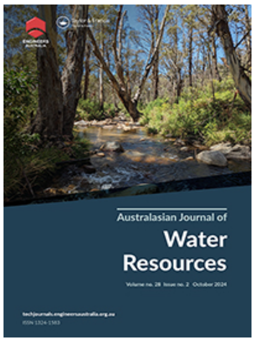

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A national assessment of the drinking water infrastructure deficit in New Zealand by territorial authority and sociodemographic characteristics

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ABSTRACT
The quality of drinking water reticulation networks is central to ensuring the provision of safe water. We conducted a national assessment of public drinking water reticulation condition in New Zealand (NZ) derived from information on pipe material and age and investigated regional and sociodemographic variations in the reticulation network. In total, 30.7% of the 57,174 km of drinking water pipes in NZ were in poor or very poor condition, while 18.5% were past their life expectancy. We identified wide variation in the proportion of pipes in poor or very poor condition amongst Territorial Authorities (TAs) and between areas of varying socio-economic deprivation within TAs. Using nationally consistent data, our findings suggest that the current drinking water infrastructure deficit in NZ may be larger than previously estimated. Our results also highlight potential challenges to TA-based amalgamation of water services under the new legislation.

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Drinking water; pipe network; New Zealand

1. Introduction

The provision of safe water is strongly dependent on the quality of the drinking water reticulation networks (World Health Organisation 2024). These networks may get contaminated during construction, installation or repair; from corrosion leading to accumulation of particles; leaking with low pressure or intermittent water supply; or inadequate chlorination (World Health Organisation 2024). There are an estimated 2,720 cases of gastrointestinal illness per 100,000 population and 1.2 cancer cases per 100,000 population attributable to drinking water in high-income countries per year (Lee et al. 2023). A systematic review of outbreaks in the USA from 1971 to 2006 found that 18% were caused by contamination of the distribution system (Craun et al. 2010).

The burden of waterborne disease in New Zealand (NZ) is largely unknown, with the latest (but slightly outdated) estimate in 2006 suggesting between 18,000 and 34,000 cases of gastrointestinal illness each year (Ball and Sheat 2007). NZ has experienced major waterborne outbreaks, including in Havelock North (Campylobacteriosis, 2016, with 5,500 probable cases) and Queenstown (Cryptosporidiosis, 2023, with 94 cases) (Gilpin et al. 2020; Te Whatu Ora 2023). In addition, 694 bacterial or chemical exceedances of the drinking water standards were reported in NZ in 2022–2023 (Taumata Arowai 2024a). However, epidemiological research into the full suite of public health risks associated with compromised drinking water reticulation is usually limited by the availability of reliable data on the quality of the water supply as well as linked individual-level health information.

Water infrastructure (drinking water, wastewater and stormwater) in NZ is believed to be worth around NZ$85bn, and it faces an investment deficit of approximately NZ$120–185bn over the next 30 years (Water Industry Commission for Scotland 2021). Public drinking water networks could be worth as much as 80% of all drinking water assets and 27% of all water assets in NZ (Water NZ 2022). Based on this, drinking water reticulation networks could be worth ~NZ$23bn and require ~NZ$32–50bn of investment over the next 30 years. However, these prior estimates have been based on incomplete and non-standardised data from the 67 Territorial Authorities (TAs) responsible for the majority of drinking water provision in NZ. A recent Government-commissioned report on NZ water infrastructure stated that 'there appears to be a high degree of optimism bias for the maximum asset lives' (Water Industry Commission for Scotland 2021, 25), particularly when considering NZ's challenging ground conditions and seismicity (Water Industry Commission for Scotland 2021). Consequently, there is limited understanding of the current state of drinking water infrastructure in NZ (Taumata Arowai 2024b), and of how it compares to other high-income jurisdictions.

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Historically, there has been limited regulatory obligation upon TAs relating to record-keeping and standardisation of drinking water reticulation information. The Local Government Act 2002 introduced the obligation for TAs to develop and implement long-term infrastructure plans, with section 101A mandating them to include financially sustainable strategies for service provision, and sections 101B and 125 mandating them to include an assessment of their drinking water assets and services (Local Government Act 2002). However, the Auditor General found in 2004 that TAs' attempts to achieve this were inadequate, noting that most TAs had a reasonable standard of base information but were missing other robust asset information, while some were missing the bare minimum information (Report of the Controller and Auditor General 2004). More recently, sections 141, 142 and 146 of the Water Services Act 2021 have introduced a new requirement for TAs to report information on the performance of their drinking water networks (Water Services Act 2021). However, there does not appear to be a data standard for this information, so comparison of asset information between jurisdictions or at a national level remains a challenge.

Following the Havelock North outbreak in 2016 (Gilpin et al. 2020), NZ has undertaken a major set of water reforms which included the establishment of the new water services regulator, Taumata Arowai. A contentious area of the water reforms has been how to deal with the significant current and future infrastructure deficits. The former Labour-led government enacted a set of policies that transferred possession of water assets from TAs to a set of separate amalgamated Crown-owned entities, aiming at achieving balance sheet separation and economies of scale, required to address the infrastructure deficit (Water Industry Commission for Scotland 2021). In response, the current Government repealed the legislation before it came into effect and proposed new policies in a set of three Bills under the banner of 'Local Water Done Well' (LWDW). Under LWDW water assets remain in TA ownership while creating opportunities for TAs to voluntarily create council-controlled organisations (CCOs) or joint local government arrangements to manage water assets (Local Government 2024). A key issue in the previous amalgamation attempt and future attempts is the parameters around CCO formation. In particular, the risk of poorly performing or smaller TAs being excluded from the benefits of amalgamation, and the newly created CCOs lack the economies of scale required to address the infrastructure deficit.

This study aims to 1) collate and standardise a national database on the location and condition of NZ's TA-owned drinking water reticulation while developing a methodological framework for future similar studies; 2) estimate the overall drinking water infrastructure deficit in NZ; 3) investigate differences in drinking water reticulation condition by TA; 4) assess inequities in drinking water reticulation quality by ethnicity and deprivation; and 5) evaluate potential barriers to CCO formation under the LWDW legislation.

2. Methods

2.1. Study design

National cross-sectional study of drinking water reticulation.

2.2. Population and study area

In NZ, drinking water is either provided by a registered water supplier or a private/domestic self-supply. The area served by a registered water supply is called a Water Distribution Zone (WDZ). Figure 1 shows the extent of the 629 TA-owned WDZs registered in Taumata Arowai's drinking water register. These 629 WDZs serve water to 4,135,000 people (~88% of the total population).

2.3. Data

Spatial data on the location, age, and material of the drinking water reticulation were retrieved directly from TAs (asset owners) via their online repositories, or through information requests between 2023 and 2024.

2.3.1. Data collation and standardisation

We aggregated spatial data from all 67 TAs in NZ. Data were inconsistently collected and stored between TAs (e.g. 258 and 722 different values for asset type and pipe material variables, respectively). The main variables we standardised and derived across the dataset are shown in Appendix S1.

2.3.1.1. Asset type. The asset type variable indicated the function of the water pipe section. We converted 262 different values to the main asset types commonly used in drinking water reticulation systems (American Water Works Association 2003), including transmission or trunk mains (3.0% of our dataset), distribution or rider mains (81.1%), service lines (12.2%), abandoned (2.0%), private (1.0%), other (0.5%) and unknown (0.3%). Abandoned pipes were discarded for further analysis, but private pipes were included when connected to a TA-owned WDZ (see Appendix S2 for more information).

2.3.1.2. Pipe material, age and length. Pipe material data were retrieved from 66 of the 67 TAs and 96.2%

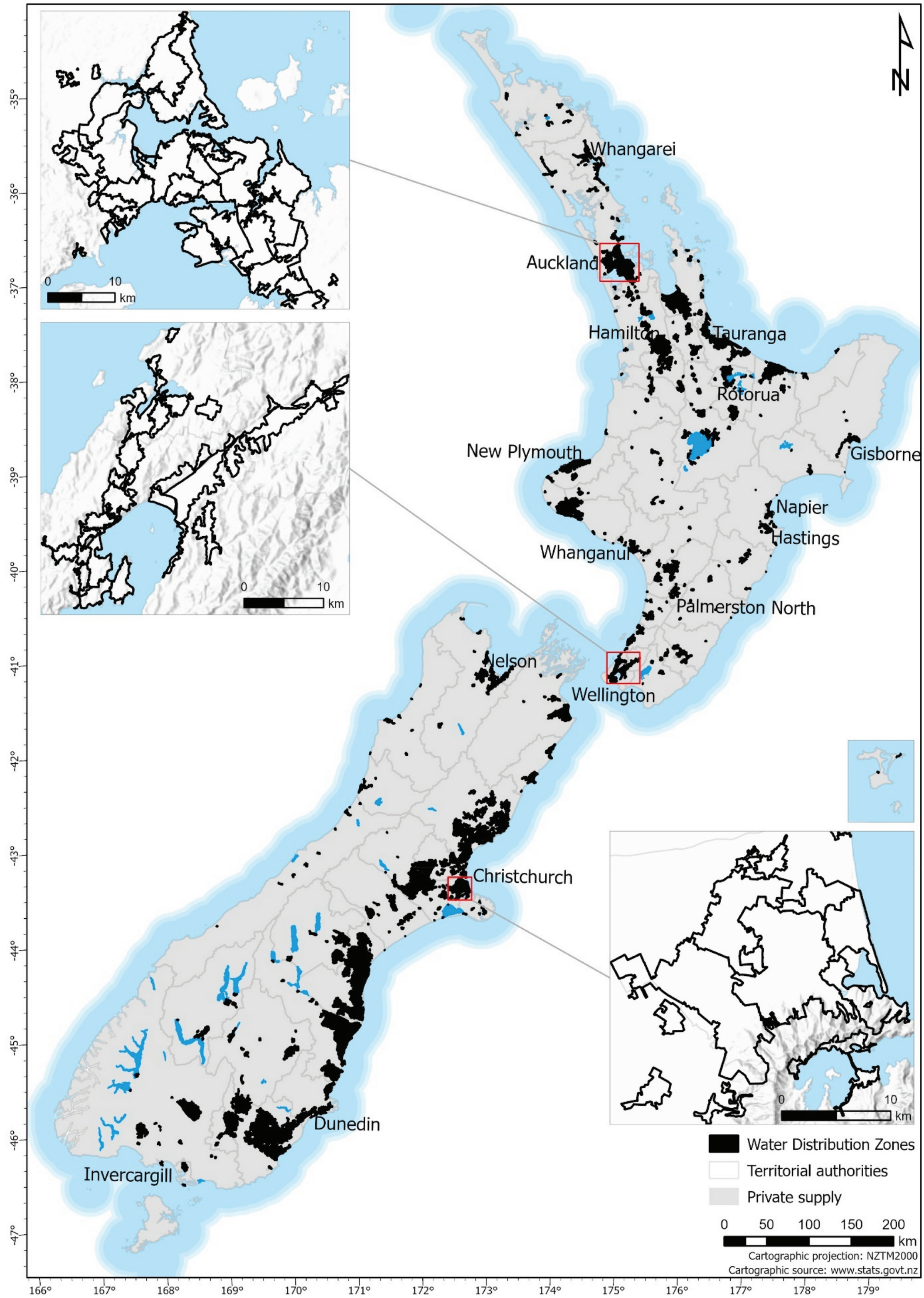

Figure 1. Extent of the 629 water distribution zones across New Zealand with insets for the three major urban areas of Auckland, Wellington and Christchurch.

of the reticulation length in the raw dataset had material information. We standardised 698 different values into materials present in NZ's reticulation (Ministry of Health 2010), including polyethylene, polyvinyl chloride, ductile iron, cast iron, copper, steel, galvanised iron, asbestos cement, and 'other' materials.

Installation date data were retrieved from 66 of the 67 TAs and were available for 96.9% of the reticulation length. The age of each pipe was calculated by subtracting the installation year from the current year (2024). We calculated the length of pipes in kilometres using ArcGIS Pro v3.0.1 (2022).

2.3.1.3. Pipe life expectancy. We determined material-specific pipe life expectancies (LE) from the evidence in the literature, as values provided by TAs had large variation and had been previously noted as overly optimistic (Water Industry Commission for Scotland 2021). Since the 'end conditions' of a water pipe are not universally well defined, we used the range of reported values in the literature to generate our low boundary (worst-case scenario), midpoint (most likely scenario) and high boundary (best-case scenario), all detailed in Appendix S3.

2.3.1.4. Pipe condition grading. Methods used to grade pipe condition vary in the literature and amongst individual TAs in NZ (Water NZ 2022). Pipe material and age are generally considered the most important factors when determining condition (Cabral et al. 2024). We considered the LE of each pipe and its current age to grade condition: excellent (100–76% remaining LE), good (75–51%), average (50–26%), poor (25–4%) and very poor (3%–past its LE).

2.3.1.5. Water distribution zone code. With our main outcomes assigned to the pipes (as shown in Figure 2 for Invercargill), we then spatially joined each pipe section with a WDZ in ArcGIS Pro (2022). The development of the WDZ dataset has been documented elsewhere (Puente-Sierra et al. 2023). Briefly, each WDZ has been spatially linked with 2018 census information to generate population estimates for the total population, population by ethnicity (prioritised ethnicity defined as Māori, Pacific, Asian and European) and area-level deprivation (Puente-Sierra et al. 2023). For each WDZ, we included the pipes that spatially intersected with that WDZ as well as any pipes that were connected to that WDZ but fell outside its boundary and did not intersect with any other WDZ (e.g. distribution pipes – long pipes from a treatment plant to an inland community – see Appendix S4) after a sensitivity analysis (Appendix S2).

2.3.2. Data aggregation

We aggregated data from each water pipe section by WDZ, TA and nationally. The populations from WDZs were used to estimate the total population and their sociodemographic characteristics exposed to suboptimal pipes (e.g. past LE). The variables available in the final dataset by WDZ are presented in Appendix S5.

2.3.3. Data exclusions

Figure 3 outlines the key exclusions for the final analytic dataset which included pipes defined as abandoned (1,216 km or 2.0% of the raw dataset); pipes not connected to a TA-owned WDZ (762 km or 1.2%); pipes missing data for pipe age or material (2,859 km or 4.6%). In total, the final dataset (referred further as TA-owned drinking water reticulation) included 57,174 km of pipe (92.2% of the raw dataset) with coverage for 625 of the country's 629 TA-owned WDZs as well as 66 of the 67 TAs. The four WDZs excluded due to missing pipe age or material data supplied water to less than 0.01% of the NZ population.

2.4. Spatial and statistical analyses

Descriptive statistics on all pipe variables were calculated at a national, TA and WDZ level for the three LE scenarios (worst-case, most likely and best-case scenarios) and the two main outcomes: 1) percentage of pipes past their LE and 2) percentage of pipes in poor or very poor condition (PVPC). Population measures used below refer to the total population on a TA-owned water supply.

We used SaTScan (Kulldorff 2021) to identify statistically significant spatial clusters of TAs (represented by their population-weighted centroids) based on the overall pipe condition represented by the two main outcomes. We utilised 'Purely Spatial' analysis scanning for clusters with a high or low proportion of pipes in suboptimal condition using the 'Discrete Poisson' model within circular windows, with up to 50% of the population (pipes) at risk. The model ran a spatial scan statistic to identify spatial clusters by comparing the structure of pipes within a dynamic window with the structure of pipes outside of this window, followed by testing each cluster for significance (Amin et al. 2020). We retained only statistically significant (p-value < 0.05) non-hierarchical, non-overlapping clusters. Statistical inference was based on 999 Monte Carlo simulations. We aggregated the identified clusters into high- and low-value clusters.

To explore differential exposure to suboptimal pipe condition by ethnicity and area-level deprivation, we conducted a descriptive population-weighted disparity analysis. We first normalised suboptimal pipe condition by multiplying suboptimal pipe length by the

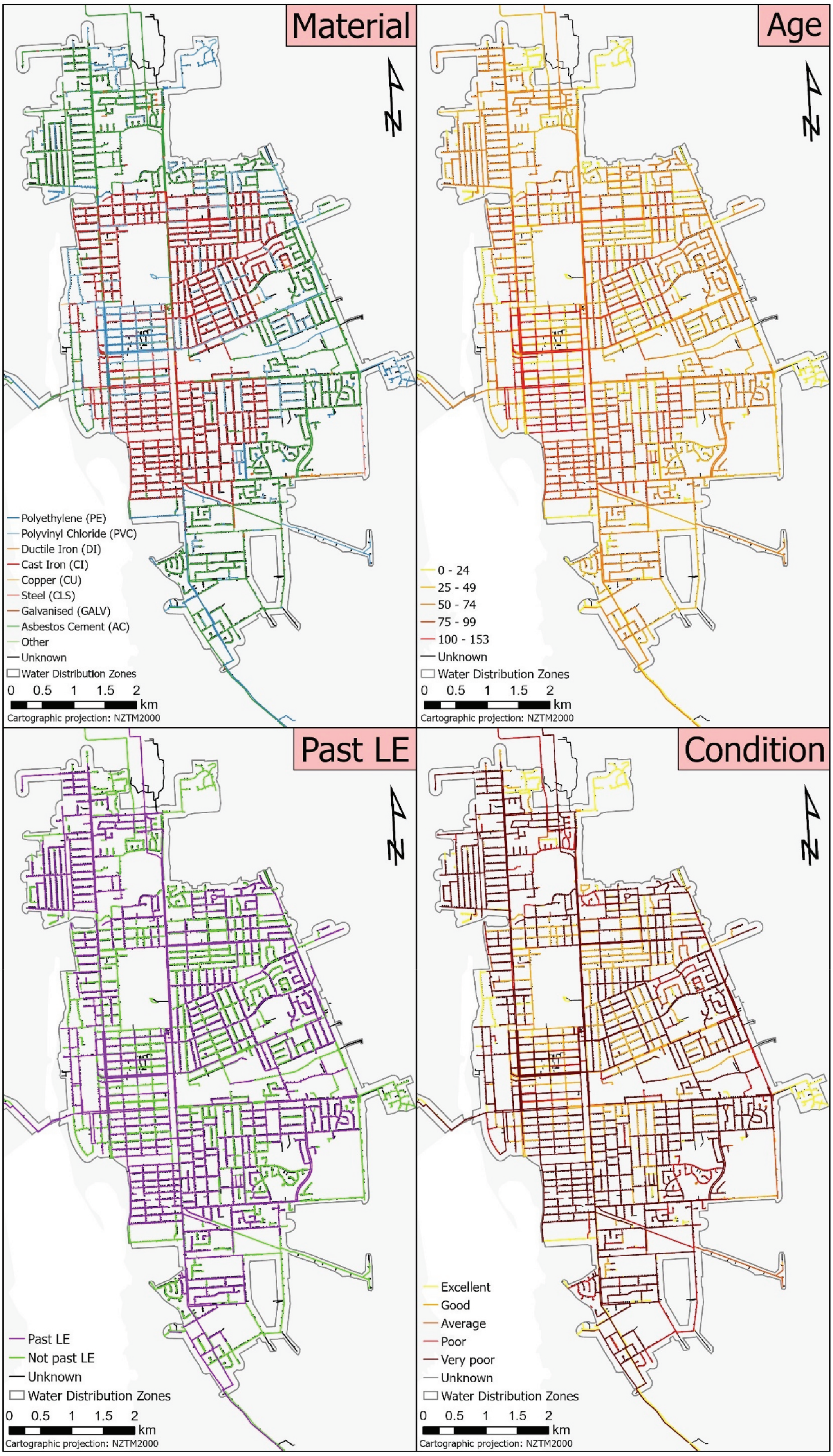

Figure 2. Invercargill as an example of drinking water reticulation and assigned outcomes.

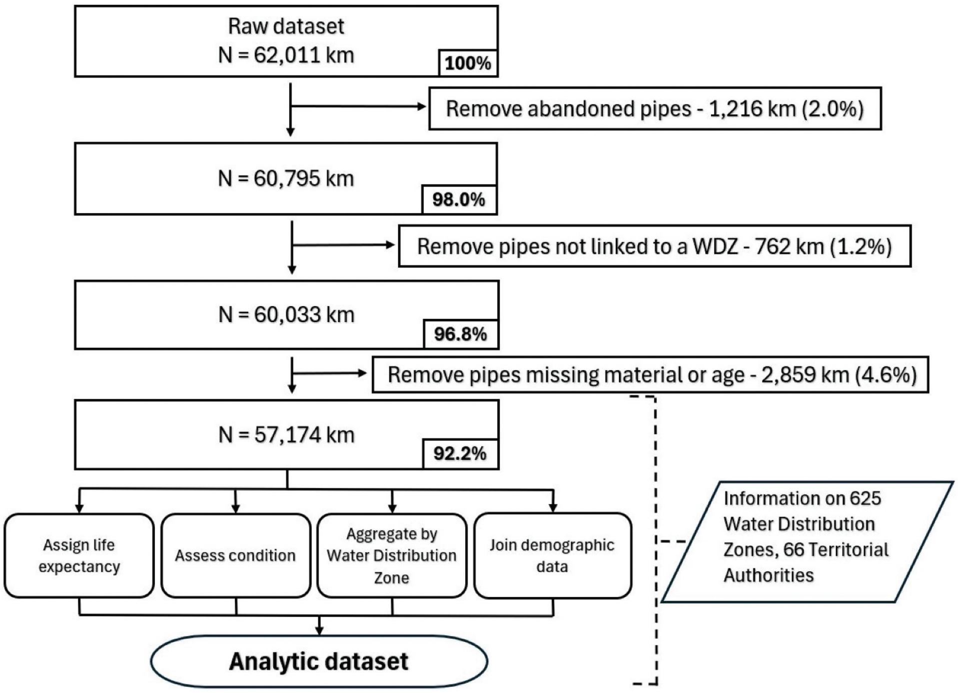

Figure 3. Data exclusion flow diagram.

population of each sociodemographic group for each WDZ. Second, we aggregated these values across all WDZ and divided this by the total population of each sociodemographic group to get a normalised suboptimal pipe length measure. Third, we repeated these two steps but for all pipe sections to get a normalised total pipe length value. After, we divided the normalised suboptimal pipe length by the normalised total pipe length to obtain a disparity ratio indicative of the relative condition of pipes weighted by sociodemographic group. Finally, we calculated relative disparity ratios by dividing the disparity ratios of different sociodemographic groups by the reference groups (European for ethnicity and low for deprivation).

Further, we investigated how the two main outcomes relate to the population living in individual WDZs. We applied a logistic mixed-effect model with a random intercept that enabled us to incorporate a spatial reference using the multilevel nesting of WDZs within TAs, as TAs may manage all their WDZs similarly. We used ethnicity and area-level deprivation as explanatory variables together with the total population of the WDZs. We did not use the percentage of European and low deprivation due to high collinearity with other variables. Furthermore, explanatory variables were scaled and centred around zero. This way we obtained fixed effects of the model that provided a general idea about relationships between outcomes and explanatory variables with the intercept being a baseline value. As random effects are differences between the intercept of individual (groups of) subjects and the overall intercept, random intercepts provide additional information about how individual TAs performed compared to the national average represented by fixed effects intercept. We transformed log-odds of both random and fixed intercepts into probabilities and subtracted the fixed intercept from the random intercept to map regional differences in probabilities (under the condition of comparable populations) of having suboptimal pipe conditions, where negative values represent TAs that are outperforming the national average and positive values show TAs underperforming it.

3. Results

3.1. Descriptive statistics

As shown in Table 1, the total length of NZ's TA-owned drinking water reticulation was 57,174 km, with a wide variability between TAs from a minimum of 70 km to a maximum of 11,767 km. The mean weighted pipe age of the national reticulation was 37.8 years, ranging from 20.4 to 54.2 years across TAs. In total, 18.5% of the national reticulation was classified as past its LE using the midpoint estimate, but it could range from 8.7% to 28.1% depending on the LE assumptions (case scenarios). For individual TAs, the minimum midpoint value for LE was 1.5%, while the maximum value was 49.5%. The national estimate was 21.2% for pipes in the very poor and 9.5% for pipes in poor condition, totalling 30.7% of the total reticulation. Most pipes were made of plastic (67.3%), while asbestos cement made up 19.8% of the network and various

Table 1. Characteristics of New Zealand's drinking water reticulation.

Pipe characteristic	Value		Total national		TA range (min – max)*
Pipe length	Kilometres		57,174		71–11,768
Mean weighted pipe age	Years		37.8		20.4–54.3
Pipe material (%)	Polyethylene		36.0		0.8–65.8
	Polyvinyl Chloride		31.3		5.4–73.1
	Asbestos Cement		19.8		0.0–61.9
	Cast Iron		4.8		0.0–29.9
	Steel		4.7		0.0–23.4
	Copper		1.3		0.0–16.6
	Galvanised		1.0		0.0–16.7
	Ductile Iron		0.6		0.0–4.1
	Other		0.5		0.0–26.0
Boundaries		Low	Midpoint	High	
Pipes past LE (%)		8.7	18.5	28.1	1.5–49.5
Pipe condition (%)	Very poor	11.4	21.2	30.1	1.8–56.2
	Poor	13.1	9.5	12.5	0.2–38.4
	Average	13.6	17.3	16.6	2.8–63.6
	Good	27.8	25.7	23.2	4.5–70.6
	Excellent	34.1	26.3	17.7	7.3–59.0

*Only midpoint boundary shown in TA.

metals contributed to the remaining ~13%. Breakdowns of the pipe materials' characteristics are in Appendix S6.

3.2. Spatial patterns in suboptimal pipe condition by territorial authority

Figure 4(A) presents the spatial distribution of the percentage of pipes in PVPC by TA. TAs in dark red (e.g. Kawerau, Hutt, Invercargill, Gisborne or Dunedin) have a high proportion of their pipes in PVPC (over 50%), while TAs with the lowest include Selwyn, Queenstown-Lakes, Ōpōtiki, Waimakariri, Clutha, Waimate and Waikato (below 10%). Regions in the North Island generally have more of their pipes in PVPC than areas in the South Island (36.3% against 22.1%). Figure 4(B) highlights (dark pink) TAs with a higher probability of having pipes in PVPC compared to the national average (e.g. Gisborne, Napier, Wellington, Dunedin or Invercargill). In contrast, TAs in green, such as Ōpōtiki and Selwyn, have a substantially lower probability of having pipes in PVPC than the national average. Figure 4(C) highlights clusters of TAs that either have a lower or higher proportion of their pipes in PVPC compared to the areas outside of those clusters, showing six main clusters of high values or worse outcomes (Invercargill-Dunedin, Wellington-Wairarapa-Palmerston, Taranaki, Gisborne-Hawke's Bay, Eastern Waikato and Northland) and four main clusters of low values or better outcomes (Canterbury-Otago-Tasman, Manawatū, Eastern Bay of Plenty and Tauranga-Coromandel-Western Waikato) that can be generally observed (detailed in Appendix S7). The outcomes and spatial patterns were relatively similar when looking at the proportion of pipes past their LE, as well as analyses using the optimistic and pessimistic LE assumptions, so we have chosen to present those in Appendix S8.

3.3. Differential exposure to suboptimal pipes by ethnicity and area-level deprivation

The results of the population-weighted disparity analysis for pipe age, percentage of pipes past their LE and percentage of pipes in PVPC are shown in Table 2 (see results for the low and high LE boundaries in Appendix S9). The results show that Māori have similar levels of exposure to suboptimal pipes (all outcomes) compared to European populations, while the Pacific and Asian populations have slightly higher exposure. Pipes serving Pacific populations were 6% older by length-weighted age, 19% more were past their LE and 16% more were in PVPC compared to European populations. Pipes serving populations in high area deprivation were 9% older by length-weighted age, 6% more were past their LE and 7% more were in PVPC compared to those living in low area deprivation.

The results produced by the multilevel models for pipes past their LE and pipes in PVPC are presented in Table 3 (see results for the low and high LE boundaries in Appendix S10). As independent variables were scaled and centred, the fixed effects were interpreted in the context of their standard deviation (SD). For example, a one SD increase in the proportion of Māori population reduces the odds of the percentage of pipes past their LE and the percentage of pipes in PVPC by 17% and 16%, respectively. A one SD increase in the Pacific population reduces the odds by 6% and 4%, while the Asian population raises them by 3% and 5%. The effect is more pronounced for the area-level deprivation where one SD increase in the proportion of people in moderate area deprivation raises the odds by 19% and 21%, and one SD increase in the population in high area deprivation raises the odds by 89%. Random effects are presented as their standard deviation (on the log scale) and show considerable differences by individual TAs that are visualised as differences in probabilities in Figure 4 and Appendix S8.

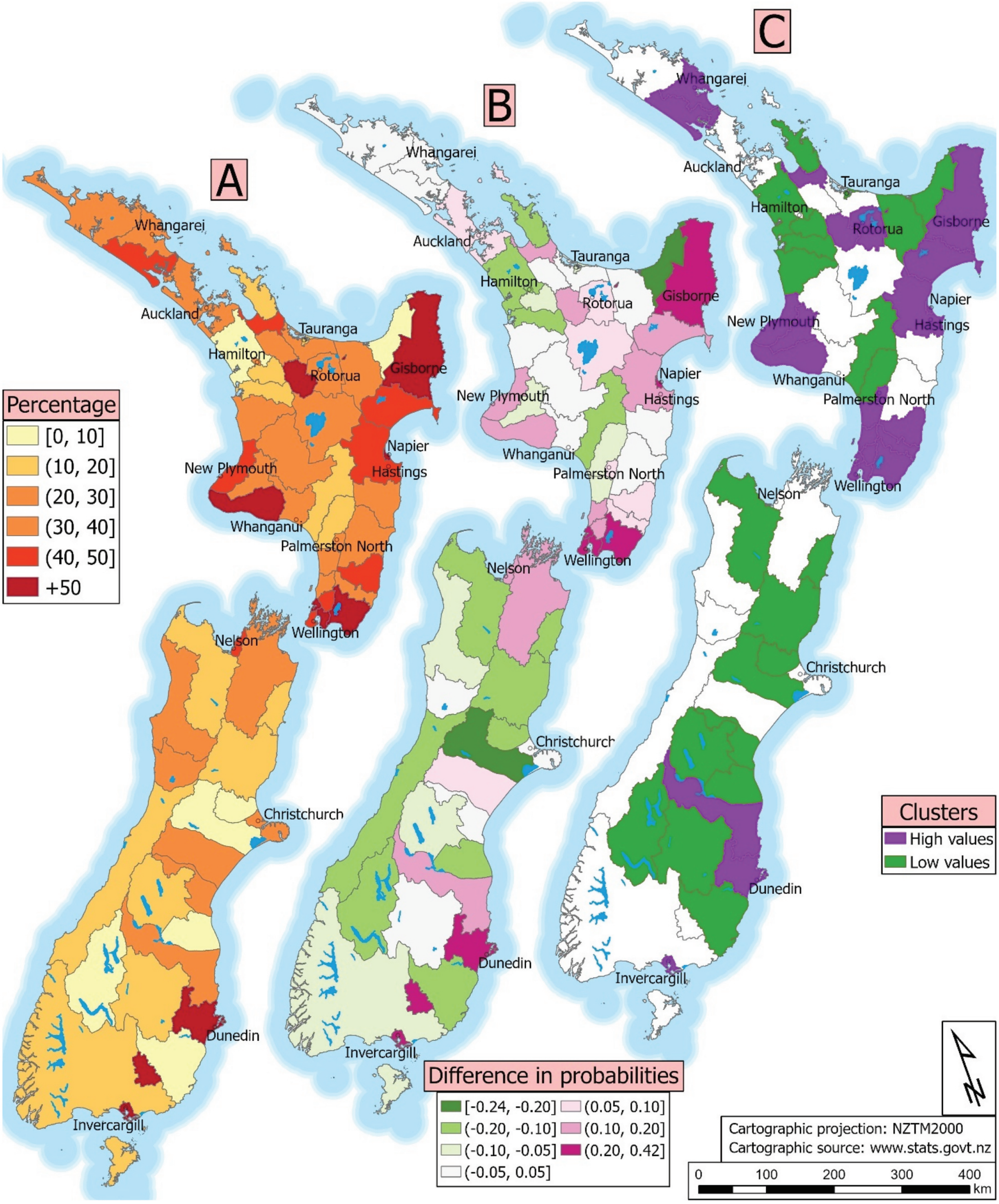

Figure 4. Spatial patterns in territorial authorities by percentage of pipes in poor or very poor condition (midpoint LE boundary).

4. Discussion

This study examined the drinking water infrastructure deficit in NZ by collating, cleaning and standardising the first national geospatial dataset of TA-owned drinking water reticulation. Our findings showed that a substantial proportion of drinking water pipes were in suboptimal condition, with just under a third (30.7%) in PVPC and 18.5% past their LE. We observed significant spatial differences between TAs in pipe condition, including spatial clusters of good- and poor-condition pipes. Finally, inequities by sociodemographic characteristics were

Table 2. Population-weighted disparity analysis results by sociodemographic groups (midpoint LE).

	Pipe age		% of pipes past their life expectancy		% of pipes in poor or very poor condition	
	N	RDR*	%	RDR*	%	RDR*
Overall	40.28	–	24.24	–	38.73	–
Ethnicity						
European**	39.75	1.00	23.25	1.00	37.63	1.00
Māori	40.12	1.01	23.24	1.00	38.02	1.01
Pacific	42.19	1.06	27.75	1.19	43.73	1.16
Asian	41.61	1.05	25.52	1.09	40.44	1.08
Area-level deprivation						
Low**	38.27	1.00	23.47	1.00	37.48	1.00
Moderate	40.45	1.06	24.06	1.03	38.51	1.03
High	41.73	1.09	24.84	1.06	40.13	1.07

*RDR – Relative Disparity Ratio.
**Reference value.

Table 3. Summary of fixed and random effects produced by multilevel models (midpoint LE).

	% of pipes past their life expectancy	% of pipes in poor or very poor condition
Intercept	0.18 [0.14,0.21]	0.37 [0.30,0.45]
Ethnicity		
Māori (%)	0.83 [0.83,0.83]	0.84 [0.83,0.84]
Pacific (%)	0.94 [0.94,0.94]	0.96 [0.96,0.96]
Asian (%)	1.03 [1.03,1.03]	1.05 [1.05,1.05]
Area-level deprivation		
Moderate (%)	1.19 [1.19,1.19]	1.21 [1.21,1.21]
High (%)	1.89 [1.88,1.89]	1.89 [1.89,1.90]
Total population	1.04 [1.04,1.04]	1.05 [1.05,1.05]
Random effect (SD)	0.80	0.85

observed, especially for those living in the highest area-level deprivation as well as WDZ serving higher Asian populations.

4.1. Infrastructure deficit

Of the 57,174 km of NZ's TA-owned drinking water reticulation, 18.5% (low estimate 8.7% – high estimate 28.1%) were past their LE, and 30.7% (24.5–42.5%) were in PVPC, with the mean weighted age being 37.8 years. The most recent estimate by Taumata Arowai relied on self-reported measures from TAs which might be prone to non-response and measurement misclassification biases (Taumata Arowai 2024b). Our estimates for pipe length and age were similar to those reported by Taumata Arowai (57,174 km compared to 54,057 km and 37.8 years to 32.0 years) (Taumata Arowai 2024b). However, our estimate of pipes in PVPC was substantially higher than that reported by Taumata Arowai (30.7% to 13.0%), which was calculated as an average of the responses provided by TAs rather than the percentage of total pipe length. Further, Taumata Arowai also included 16 zero responses provided by TAs as 'real' rather than missing values (e.g. Watercare reported 0% of pipes in PVPC, while our analysis estimated that 40% of their 12,000 km network was in PVPC). Due to a lack of data standardisation, there is wide variability in the reported percentage of pipes in PVPC between TAs, but also to our estimates. For 13 TAs, the reported estimate differs by less than 5% from our estimate, while six TAs have a higher estimate than ours. However, most TAs reported far lower estimates than those observed in our results, which may be representative of what the Water Industry Commission for Scotland (WICS) called 'a high degree of optimism bias for the maximum asset lives' amongst TAs (Water Industry Commission for Scotland 2021). (25) On balance, our results suggest that previously reported estimates of the infrastructure deficit for drinking water reticulation may be a substantial underestimate.

While not directly comparable due to diverse reporting methods, this deficit would be higher than in other high-income countries such as Australia, Canada, Hong Kong, Japan, Norway, South Korea or Spain, and similar to that of the USA (see Appendix S11). The percentage of drinking water pipes over 40 years in NZ (46.2%) compares to the USA (47.0% from a sample of around 20.0% of the USA reticulation) but surpasses Japan (20.7%), Spain (26.0%) and Canada (41.0%), while the percentage of pipes in poor or very poor condition is also greater in NZ (30.7%) than in Australia or Canada, 10.0% and 9.6%, respectively (13143: Water pipelines and inhabitants connected 2023; Asociación Española de Abastecimientos de Agua y Saneamiento, Asociación Española de Empresas Gestoras de los Servicios de Agua Urbana 2016; Australian Local Government Association 2024; Barfuss 2023; Canadian Infrastructure Report Card 2019; Korea Water 2024; Legislative Council of the Hong Kong Special Administrative Region 2006; Yamashita et al. 2023).

4.2. Spatial differences and clustering of reticulation in suboptimal condition by TA

While our approach to classifying pipe condition was relatively straightforward, it enabled a standardised comparison between TA, for which previous estimates in NZ had not provided. In our results, there was high variability between TAs regarding the proportion of pipes past their LE (1.5–49.5%), pipes in PVPC (2.4–-75.4%) and weighted age (20.4–54.3). Older cities (e.g. Dunedin, Wellington, Auckland, Napier, Invercargill), where greater development occurred earlier in NZ's history, generally have poorer quality pipes than younger or developing cities (e.g. Hamilton or Tauranga). While these larger cities may have suboptimal drinking water pipes, they also have a ratepayer base to potentially borrow or charge to replace them. More problematic are some smaller rural TAs that have a substantial proportion of their pipes in suboptimal condition and small ratepayer bases such as Kawerau (75.4% in PVPC, population on public supply 7,100), Gisborne (58.7%, 35000), South Wairarapa (57.5%, 7,100) Gore (54.2%, 10200), South Waikato (52.4%, 19400) or South Taranaki (51.0%, 21900).

Our results also demonstrated that there were spatial relationships between TAs in relation to their pipe condition. We identified six clusters of TAs with suboptimal pipes and four clusters of TAs with above-average pipes. These clusters highlight the potential feasibility of regional strategies to overcome any potential infrastructure deficit. Further, they outline the regional baseline of the collective condition of drinking water reticulation. In this context, our results suggest that regions with lower baseline pipe condition may face greater challenges in a regional effort to overcome their infrastructure deficit. The spatial clusters identified remained relatively constant when using different outcomes (LE or PVPC) and LE definitions (low, midpoint or high estimates), which suggests that clusters are unlikely a product of our selected outcome definition.

4.3. Inequities in exposure to suboptimal reticulation

Our population-weighted disparity analysis showed that exposure to suboptimal drinking water pipes was patterned by sociodemographic characteristics. Pacific and Asian populations had higher exposure to suboptimal pipes than European populations, as well as those living in higher area deprivation compared to those in lower area deprivation. However, our multilevel regression analysis suggested that deprivation was the major driver of inequitable exposure to suboptimal pipes when adjusting for the ethnic composition of a WDZ as well as the random effects by TA (e.g. the similarities between WDZ within a TA such as a TA's asset management strategy or a TA's financial capacity to upgrade infrastructure). It is possible the associations by deprivation are being driven by recent residential developments with new pipes and are likely to be classified as areas of low deprivation. However, we cannot rule out that these areas may have additional social and political capital (e.g. the capacity to alert TAs of failing pipes or the ability to influence decision-making) to facilitate the prioritisation of infrastructure replacement and upgrades in their area compared to people living in higher area deprivation. Inequities in water service provision by deprivation have been previously documented in NZ (Hales et al. 2003). Consequently, these existing inequities should be considered as part of asset management plans and in decision-making around renewals. For example, Figure 5 highlights water pipes in Invercargill past their LE that are also in areas of high deprivation (purple lines), which could be prioritised for renewal.

4.4. Policy implications

Our results suggest the reported water infrastructure deficit of NZ$120–185bn over the next 30 years (Water Industry Commission for Scotland 2021) could be substantially higher. Our estimate on the proportion of pipes in PVPC is more than 100% greater than that reported by TAs to Taumata Arowai (Taumata Arowai 2024b). If similar optimism and non-response biases are mirrored in TA responses to stormwater and wastewater assets, the reported infrastructure deficit may be substantially higher than reported. This underestimated infrastructure deficit is significant as multiple Government-initiated reports and analyses demonstrated that the status quo approach to water infrastructure development is financially unsustainable and was based on the NZ $120–185bn estimated infrastructure deficit (Department of Internal Affairs: Regulatory Impact Assessment 2021; Water Industry Commission for Scotland 2021). Further, the Local Government (Water Services Preliminary Arrangements) Bill (Local Government 2024) requires all TAs (either individually or jointly) to submit a Water Services Delivery Plan within 12 months after the Bill enactment (September 2024), which should provide detailed information on the current state of their water services arrangements for drinking water supply, wastewater, and stormwater and set out a strategy for how they will achieve the delivery of financially sustainable water services and meet regulatory quality standards. However, TAs only need to provide financial sustainability over the next 10 years (minimum) and can benchmark their projections against their Long-Term Plans (LTP) estimates, which are likely to be substantially lower than estimates provided by WICS (Department of Internal Affairs 2024). The WICS analysis stated that the LTP estimates provided by TAs 'contained substantial optimism bias' (Water Industry Commission for Scotland 2021, (85), while a 2021 Auditor-General's report on audits of 2021–2031 LTP concluded that there was substantial uncertainty around the nature and extent of the asset condition and performance information that some

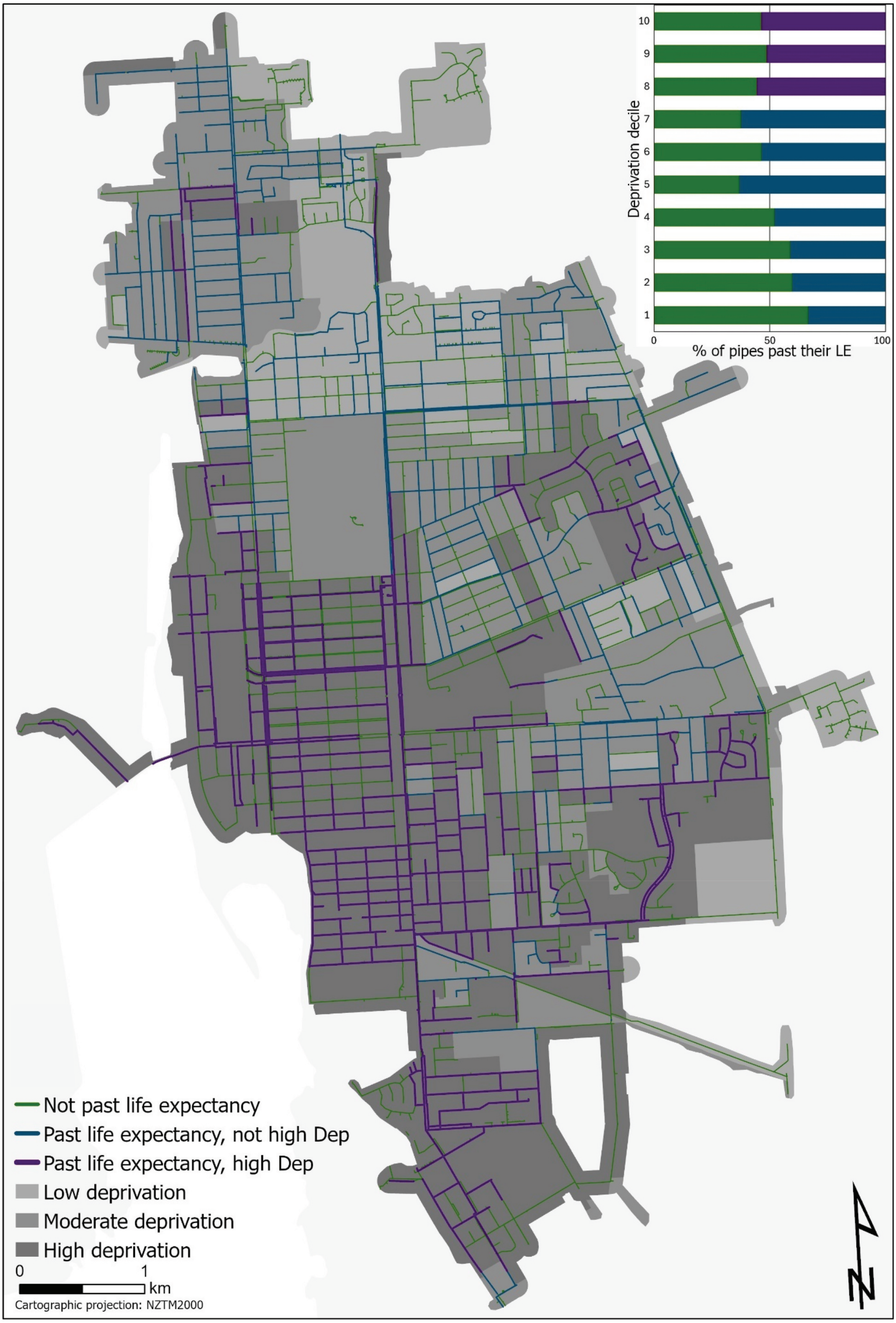

Figure 5. An example of suboptimal condition pipes in areas of high deprivation within Invercargill that could be prioritised for renewals to reduce inequities.

TAs used to inform their forecasts of three waters asset renewals and funding assumptions (Report of the Controller and Auditor General 2022). Our results are consistent with previous interpretations suggesting that using TA-derived LTP estimates in water services development plans may underestimate the required investment and call into question the financial sustainability of these plans.

A central issue facing the delivery of water services in NZ is that most TAs currently lack the economies of scale required for a financially viable model for water service delivery (Department of Internal Affairs: Regulatory Impact Assessment 2021). The Local Government (Water Services Preliminary Arrangements) Bill (Local Government 2024) created the levers to support TAs to form CCOs that could facilitate the required economies of scale. Our descriptive and spatial maps (Figure 4) highlight individual TAs that may struggle to convince their neighbouring TAs to form a CCO given their low baseline asset condition, while our spatial cluster maps highlight regions that may struggle to meet the infrastructure deficit even after forming a regional CCO. Geographically isolated areas (e.g. Northland, Gisborne) might find it harder to form CCOs than other areas with a greater number of options (e.g. Manawatū or Christchurch). It is estimated that between 600,000 and 800,000 people are required in NZ to achieve economies of scale (Department of Internal Affairs: Regulatory Impact Assessment 2021). Early indications from mayors of TAs in the South Island suggest that very few CCOs of adequate scale will be formed (Manch 2024). For example, Christchurch City Council has indicated they may proceed without a multi-TA CCO, which means the remaining 22 TAs in the South Island would need to join into a CCO to reach a supplied population above 600,000.

Another barrier to effective management of drinking water assets relates to wider systematic issues with long-term governance, in particular, around 'invisible' infrastructure. Strong political pressures exist for governments (including TAs) to focus on urgent and immediate issues, which results in those where the impacts are relatively hidden receiving lower priority (Boston, Bagnall, and Barry 2020). Hence, the limited temporal horizons of voters and politicians lead to short-term biases and to reactive, limited and unsystematic long-term governance (Boston, Bagnall, and Barry 2020). Water infrastructure is hidden by nature, while its longevity relative to the careers of most politicians predisposes it to be neglected by governments (Anand 2015). Systematic identification and assessment of such 'invisible' infrastructure can make it visible and is key for effective long-term governance.

4.5. Strengths and limitations

The current study has various strengths. The spatial dataset offers the first detailed overview of the public drinking water network in NZ, with almost complete coverage (<5% missingness on material or age data) and a standardised method applied throughout the country to obtain outcomes such as LE and condition (rather than each TA using a different method). The standardised approach enabled a comparative analysis by TA to highlight areas that are doing better and worse than others. Further, we provided estimates based on the most optimistic and pessimistic estimates of LE in the literature, which provide alternative estimates for pipe condition. The spatial dataset can easily be linked to other data, which was exemplified by linkage to the WDZ dataset that facilitated the analysis of differential exposure to suboptimal pipes by sociodemographic characteristics. Additionally, the framework followed in this study serves as an example for future standardised assessments of water infrastructure assets which could be implemented by researchers, particularly those without detailed water infrastructure maintenance information. Our simple methodological approach also facilitates comparisons between jurisdictions using a standardised approach given that the current methodologies used to assess pipe condition across jurisdictions vary widely.

The study also has a series of limitations that have important implications for interpreting the results. We assumed that the installation dates provided by the TAs were correct. However, there are multiple reports of inaccuracies in the original installation date which cannot be resolved without substantial contributions from TAs. For example, issues have occurred when TAs have migrated asset management systems, resulting in missing installation dates being replaced with of the data migration (e.g. 2010) or assigning a default date when the age is unknown. For the latter issue, some of these missing proxy dates have been identified due to their implausibility (e.g. 1840 or future dates); however, it appears that some TAs have used a range of plausible dates as their default missing date (e.g. 1970). It is likely that issues related to the reliability of the age variable would improve the overall condition grading of pipes as these biases would generally push the installation dates towards the current date. Further, if a date was unknown, and the installation date was prior to the imputed date (e.g. actual installation date of 1950 against the unknown imputed date of 1840), the pipe condition grading would likely still be the same.

Another limitation of this study was the arbitrary application of a fixed LE (or range) to the different pipe materials and the reliance on two variables (age and material) to infer pipe condition.

We acknowledge that other factors such as operational, environmental, and other physical factors influence the final LE and condition of a certain pipe (Cabral et al. 2024). Some TAs hold information on these factors and implement them in their own assessments, likely more accurate than the estimates generated within this paper. However, given the uncertainties in the metrics reported by TAs to the water services regulator (Taumata Arowai 2024b), it is unlikely that all TA-derived estimates are systematically more accurate than those contained in our assessment. In addition, LE is not universally well defined (e.g. date of the first break, date when the risk of failure is no longer tolerable, or date when it is no longer economically viable to continue repairing the pipe) and the methodology used to assess condition by TAs is heterogeneous, making their estimates not regionally comparable. Therefore, we believe our midpoint estimate is a reasonable approach without additional information on other factors that may influence pipe condition. Further, it has been regularly cited that TAs have an overly optimistic assessment of water asset lives (Water Industry Commission for Scotland 2021), particularly when considering factors common to NZ such as seismicity or water corrosiveness (soft waters and low pH waters). These limitations emphasise the need for a data standard across TAs to help with more accurate central reporting and the standardisation of these assessments.

5. Conclusion

In conclusion, our results have demonstrated that the drinking water infrastructure deficit may be higher than previously reported. We have also highlighted challenges to upcoming water reforms in NZ related to CCO formation and generating the economies of scale required to achieve the needed investment to replace and upgrade NZ’s drinking water infrastructure. Our results also highlight that areas of high deprivation are more likely to be exposed to poorer drinking water infrastructure which should be considered in asset replacement programmes.

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