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Review paper

A review of drinking water quality issues in remote and indigenous communities in rich nations with special emphasis on Australia

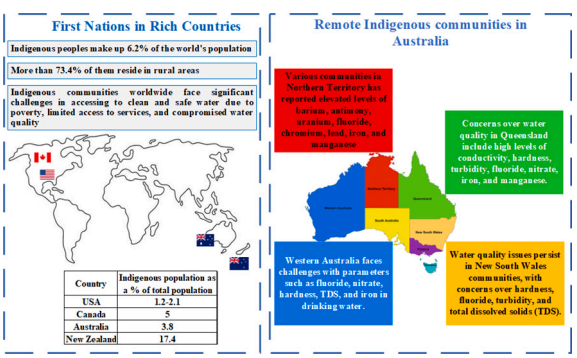
B.M.J. Kalpana Balasooriya [a], Jay Rajapakse [b,*], Chaminda Gallage [a]

[a] School of Civil and Environmental Engineering, Faculty of Engineering, Queensland University of Technology (QUT) Brisbane QLD 4001, Australia
[b] School of Civil and Environmental Engineering, Faculty of Engineering, Queensland University of Technology (QUT), 2 George Street, GPO Box 2434, Brisbane, QLD 4001, Australia

HIGHLIGHTS

- Extensive drinking water quality analysis of remote/Aboriginal people in Australia
- High levels of conductivity, hardness, turbidity, F, nitrate, Fe, Mn in Queensland
- High levels of hardness, fluoride, turbidity, and TDS in NSW
- 19 communities affected by high nitrates (>50 mg/L as nitrate) in WA
- Elevated levels of Ba, Sb, U, F, Cr, Pb, Fe, and Mn in Northern Territory.

GRAPHICAL ABSTRACT



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ABSTRACT

This review paper examines the drinking water quality issues in remote and Indigenous communities, with a specific emphasis on Australia. Access to clean and safe drinking water is vital for the well-being of Indigenous communities worldwide, yet numerous challenges hinder their ability to obtain and maintain water security. This review focuses on the drinking water-related issues faced by Indigenous populations in countries such as the United States, Canada, New Zealand, and Australia. In the Australian context, remote and Indigenous communities encounter complex challenges related to water quality, including microbial and chemical contamination, exacerbated by climate change effects. Analysis of water quality trends in Queensland, New South Wales, Western Australia, and the Northern Territory reveals concerns regarding various pollutants with very high concentrations in the source water leading to levels exceeding recommended drinking water limits such as hardness, turbidity, fluoride, iron, and manganese levels after limited treatment facilities available in these

Abbreviations: WHO and UNICEF JMP, World Health Organization and United Nations Children's Fund Joint Monitoring Program; SDG, Sustainable Development Goals; DWQMP, Drinking Water Quality Management Plan; WSS, water and sanitation services; PFAS, *Per-* and polyfluoroalkyl substances; AGI, acute gastrointestinal illness; CRC, colorectal cancer; AI, American Indian; NNDSS, National Notifiable Diseases Surveillance System; ADWG, Australian Drinking Water Guidelines; LGQA, Local Government Association of Queensland; TDS, total dissolved solids; NSW, New South Wales; TAS, Treatment as a State; WQSs, Water Quality Standards; IK, Indigenous knowledge; WS, Western science; SWP, Source Water Protection; WSP, Water Safety Plan; RICES, Remote and Isolated Communities Essential Services; WASH, water, sanitation, and hygiene; RAESP, Remote Aboriginal and Torres Strait Islander Environmental Health Program.

* Corresponding author.
E-mail addresses: jay.rajapakse@qut.edu.au (J. Rajapakse), chaminda.gallage@qut.edu.au (C. Gallage).

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communities. Inadequate water quality and quantity contribute to adverse health effects, particularly among Indigenous populations who may resort to sugary beverages. Addressing these challenges requires comprehensive approaches encompassing testing, funding, governance, appropriate and sustainable treatment technologies, and cultural considerations. Collaborative efforts, risk-based approaches, and improved infrastructure are essential to ensure equitable access to clean and safe drinking water for remote and Indigenous communities, ultimately improving health outcomes and promoting social equity.

1. Introduction

Ensuring access to safe drinking water is a critical health and development concern that must be addressed at the national, regional, and local levels (World Health Organization, 2022). The quality of drinking water in numerous countries, particularly in developing nations, is substandard, which has led to the emergence of numerous waterborne diseases (Li and Wu, 2019). According to the latest data from the World Health Organization and United Nations Children's Fund Joint Monitoring Program (WHO and UNICEF JMP), two billion people across the globe lack access to safely managed services. Of this number, 1.2 billion people only have access to basic services, with an additional 282 million individuals only having access to limited services. Furthermore, 367 million people rely on unimproved sources for their daily water needs, while 122 million individuals are left with no choice but to consume surface water, which can pose serious health risks. It is concerning that eight out of ten people who still lack basic water services in 2020 lived in rural areas (WHO and UNICEF, 2021).

Despite significant investments in water and sanitation infrastructure have notably enhanced public health in high-income countries, achieving universal access to safe water and sanitation remains an ongoing challenge. This is primarily due to historical disparities and the marginalization of specific population groups (Brown et al., 2023). Persistent problems, such as inadequate water quality, insufficient quantity, and ineffective waste management, disproportionately affect remote and minority communities, often escaping the notice of authorities.

To exemplify, Indigenous households in Canada face a stark disparity, being 90 times more likely than non-Indigenous households to lack access to running water. Furthermore, the issue of water insecurity experienced by Indigenous Peoples at the household level in Canada remains underexplored (Duignan et al., 2022).

Additionally, the difference in life expectancy at age 1 between Indigenous and non-Indigenous individuals surpasses a decade (2011), highlighting significant health inequalities (Durand-Moreau et al., 2022). Likewise, American Indians and Alaska Natives exhibit a life expectancy 4.4 years shorter than that of all US races (Rajapakse et al., 2022). In Australia, the discrepancy in life expectancy between Indigenous and non-Indigenous Australians is estimated to be 8.6 years for males and 7.8 years for females (Australian Institute of Health and Welfare, 2023a) while Aboriginal Australians carry a disease burden 2.3 times higher than that of non-Indigenous people, resulting in diminished life expectancies that decline as remoteness increases. This trend remains consistent for non-Indigenous Australians (Rajapakse et al., 2022). Correspondingly, the disparity in life expectancy at birth between Māori and non-Māori individuals was 7.5 years for males and 7.3 years for females during the years 2017–2019 (Stats NZ, 2021).

While water and sanitation coverage in these nations generally surpasses 98 %, the remaining 2 % frequently goes unnoticed or unaddressed. Unfortunately, these challenges within high-income countries tend to be overshadowed in the global discourse on water and sanitation, which predominantly centres on lower-income nations (Mattos et al., 2021). Thus, continuing to prioritize and allocate resources to improve access to these services is imperative to addressing the broader social and economic implications of this issue (Tortajada and Biswas, 2018).

Investing in water supply and sanitation can have a positive economic impact in certain areas, as research has demonstrated. The expenses associated with implementing these interventions are outweighed by the benefits of reducing negative health outcomes and the corresponding costs of healthcare (World Health Organization, 2022). In recent years, significant investment in drinking water services has led to substantial improvements in access to safe drinking water, with approximately two billion people now having access to safely managed drinking water services. As a result, 74 % of the global population used safely managed drinking water in 2020 compared to 62 % in 2000 (WHO UNICEF World Bank., 2022).

Various factors influence the quality of drinking water, including the initial quality of the water source, the treatment process at water treatment plants, the water distribution system, storage containers, household filters, and more (Li and Wu, 2019). In urban areas with high population density, treated surface water is crucial for meeting the drinking water needs of the community. Conversely, rural and remote areas, as well as livestock, heavily rely on untreated groundwater as a vital water source. It is imperative to prioritize the protection and management of groundwater resources to ensure their quality and availability, considering the specific requirements of different communities and promoting sustainable water supply systems (Pang et al., 2021). Climate-related hazards also affect the safety of drinking water, and their likelihood and severity are predicted to increase due to rising mean sea levels, an increase in the number of heatwaves, an increase in the frequency and intensity of heavy rainfall, and an increase in the risk of drought in some regions (Kohlitz et al., 2020). Extreme weather is identified as one of the top five most severe global risks over the next decade, along with climate action failure (McLennan, 2022). Other primary causes of the worldwide water issue include rising standards of living, shifting consumption habits, and increased agricultural production (Reddy et al., 2022).

1.1. Indigenous communities across the globe

Indigenous Peoples form distinctive social and cultural communities, united by shared ancestral connections to their lands and natural resources within their present habitats, territories, or locations that have undergone historical displacements (The World Bank, 2023). Their possession of unique cultures and traditional knowledge shapes their interactions with both society and the environment, setting them apart from dominant societies in terms of social, cultural, economic, and political traits (United Nations, 2023c).

Indigenous peoples make up 6.2 % of the world's population, totalling 476.6 million individuals worldwide. Asia and the Pacific have the largest concentration of indigenous people, comprising 70.5 % of the global population. The rest of the indigenous population is distributed across Africa, Latin America and the Caribbean, Northern America, Europe, and Central Asia. However, >73.4 % of the world's indigenous peoples reside in rural areas, although this percentage varies significantly across regions (International Labour Organization., 2019). Indigenous Peoples have a significant presence on a quarter of the Earth's surface through ownership, occupation, or utilization. Notably, they also serve as crucial guardians protecting 80 % of the world's remaining biodiversity (The World Bank, 2023). Despite their significant numbers, indigenous peoples remain the most disadvantaged and marginalized groups, consistently facing disproportionate poverty. They account for 18.7 % of the population living in extreme poverty across 23

countries, which collectively make up 83 % of the world's indigenous population (International Labour Organization., 2019).

Indigenous peoples are particularly vulnerable to the health impacts of environmental pollution. This is because many indigenous communities rely on the natural environment for their livelihoods and traditional practices. Pollution can directly impact the quality of the air, water, and soil that they rely on. The health impacts of pollution on indigenous peoples are often mediated through the consumption of polluted water and food. For example, pollution from mining, agriculture, or industry can contaminate water sources and affect the fish and wildlife that indigenous communities rely on for food. This can lead to a range of health impacts, including respiratory illness, cancer, and neurological damage (Fernández-Llamazares et al., 2020).

1.2. Remote and indigenous Australian communities

The Indigenous Australian population has a rich and storied history, with a cultural lineage that extends over 65,000 years, making it one of the world's most ancient civilizations. Australia's Indigenous population is characterized by exceptional diversity, encompassing over 250 distinct language groups and approximately 800 dialectal variations spoken throughout the continent during the period of European settlement in 1788 (Moggridge and Thompson, 2021). This fact has earned Indigenous Australians the distinction of being referred to as Australia's 'first people' and 'traditional owners of the land'. The Aboriginal and Torres Strait Islander designation encompasses two distinct groups of people, with the Aboriginal population having primarily inhabited mainland Australia and Tasmania, while the Torres Strait Islanders are native to the islands located between Australia and Papua New Guinea (Statista, 2023).

As of 30 June 2021, there were 984,000 Aboriginal and Torres Strait Islander people residing in Australia, which constitutes 3.8 % of the country's total population. The number of individuals has increased by 185,600 (23.2 %) since June 30th, 2016, with most residing in New South Wales, followed by Queensland (Australian Bureau of Statistics., 2021). However, persistent economic, health, and social disparities continue to marginalize Indigenous Australians, presenting them with significant challenges (Mazel, 2018).

In light of this, the focus of this paper is centred on addressing disparities within the nation, as evidenced by indigenous communities in the USA, Canada, New Zealand, and Australia. It aims to leverage the advanced infrastructure of developed countries to potentially create successful models for enhancing safe drinking water access. Importantly, this approach is not exclusive, as it acknowledges similar challenges in other regions like Africa, Asia, or South America. By establishing this strategic foundation for change and fostering global collaboration, the leadership of developed countries in addressing water accessibility within their remote areas can serve as a catalyst for progress and inspire other regions to follow suit.

2. Review methodology

This article provides a comprehensive review of academic literature in English that pertains to water pollution, water quality issues, and their impact on indigenous communities around the world and specially in Australia. The literature search was conducted by using several online databases and applying keywords related to drinking water, such as quality, pollution, impacts, regulation, economics, social, and political aspects. The search yielded a total of 101 publications spanning from 2018 to 2023, complemented by 5 additional publications dating back 1978. Most of the publications found were journal articles that were accessible through the online library of the Queensland University of Technology. Moreover, 31 pertinent government-related websites were consulted to obtain the most current information. In the interest of comprehensively assessing the evolution of water quality from its source to the consumer's tap, an in-depth scrutiny was conducted using annual water quality reports for each state, with the exception of Queensland. It is worth noting that these reports are dated back to 2015. Since a consolidated report was not accessible for Queensland, an analysis and summary were derived from the "Drinking Water Quality Management Plan" (DWQMP) reports of all 45 Regional councils and 16 Aboriginal Councils. All the aforementioned reports were obtained by downloading them from the respective council websites or from the water supplier's websites.

For the purposes of this paper, water pollution is defined as the contamination of water sources by substances that render the water unsuitable for drinking. Water quality issues are defined as changes in the chemical, physical, and biological characteristics of water according to drinking water standards, while impacts refer to any changes in the local environment or the health of an indigenous community that result from consuming polluted water. While a bibliography is provided, the aim of this article is not to conduct a quantitative assessment of the literature, but rather to highlight the global impact of polluted water on indigenous populations.

3. Effect of Indigenous water issue on Sustainable Development Goal 6 (SDG 6)

3.1. Global view

The realisation of the Sustainable Development Goals (SDGs) requires prioritizing investment in physical infrastructure and essential services, while also promoting social inclusion, fostering global cooperation, and ensuring universal access to public services, to combat significant challenges such as security crises, pandemics, and climate change (Sachs et al., 2022).

The pursuit of universally accessible and safe drinking water began in the 1950s, with the world categorized into two groups - the developed world with universal access to safe drinking water and sanitation, and the developing world without access, making them more susceptible to waterborne diseases. Despite some progress made by a few countries, the situation remains largely unchanged for many people worldwide (Huang et al., 2021). While high-income countries committed to achieving universal water access as part of the United Nations Sustainable Development Goals, significant disparities in access to basic necessities such as clean water, indoor plumbing, and safe waste management persist among low-income and marginalized communities worldwide. These disparities are particularly acute among minority populations, including American Indian, Alaskan Native, Black, and Hispanic households in the United States, as well as Indigenous Canadian communities, remote and Indigenous communities in Australia, Roma communities in Europe, and others (Mattos et al., 2021).

The management of water has become a critical issue for Indigenous communities globally, given the unprecedented rate of reforms in the water sector in recent decades (McFarlane and Harris, 2018). Although the improvement of drinking water quality is often perceived as a technical issue that focuses on water treatment and monitoring technologies, small communities face significant operational and governance challenges that increase their vulnerability to water contamination events (Jackson, 2018). Therefore, Indigenous peoples are focused on political action aimed at reforming state-based institutions as a primary strategy to access and safeguard water resources and fulfill their management responsibilities (McFarlane and Harris, 2018).

In line with the United Nations Sustainable Development Goal 6 (SDG 6), it is crucial to address the issue of pathogens in water. Poor sanitation practices and improper disposal of waste contaminate surface and groundwater, exposing humans to harmful pathogens. This highlights the need for effective management of sanitation and waste to prevent waterborne diseases and ensure a safe environment for all (Mraz et al., 2021). However, it appears that the challenges encountered in water and sanitation services (WSS) worldwide are not primarily due to

technological or natural limitations but rather stem from a governance crisis (Ballabh, 2008; Grigg, 2010). This crisis is characterized by inadequate financial management, insufficient economic regulation, and poorly drafted legislation (Pereira and Marques, 2021).

3.2. Australia

According to the Sustainable Development Report 2022, Australia ranks 38 out of 163 countries in terms of overall progress towards sustainable development. While the country is moderately improving in SDG 6, which focuses on Clean Water and Sanitation for all, challenges remain in this area (Sachs et al., 2022). It is important to highlight that while the percentage of the population utilizing basic drinking water services and safely managed water services is marked at 100 % in the report, this does not accurately reflect the experience of Australians residing in remote and Indigenous communities. Roughly 8 % of Australia's population, which amounts to around two million individuals, are not accounted for in the reporting on the United Nations Sustainable Development Goals (SDGs) pertaining to the objective of providing clean water for all (Australian National University, 2023).

Australia's vast geography and changing climate create a significant challenge in ensuring access to water and sanitation services for all communities. This spatial disconnect is especially pronounced in rural and remote areas, where the availability of water resources may be limited, and infrastructure for water distribution and storage may be insufficient. As a result, residents of these communities may face unique challenges and difficulties accessing clean water and sanitation services, compared to their urban counterparts (Department of Foreign Affairs and Trade., 2018; Hall et al., 2020).

Continued action is needed to ensure access to safe and clean water for all Australians, as part of the country's efforts towards sustainable development.

4. Inadequate access to safe water in remote and Indigenous communities

4.1. Rich countries (USA, Canada, New Zealand)

The Indigenous population in the United States is estimated to range between 4 million and 7 million individuals, representing between 1.2 % and 2.1 % of the total population (Statista, 2022). In the American West, a persistent struggle over limited water resources has become a defining feature of the region and has made Alaska the most populous state for Indigenous people, followed by Oklahoma, New Mexico, South Dakota, and others (United States Census Bureau., 2021). Disparities in universal access to water have been identified in high-income countries such as Canada and the United States, primarily due to the scale and geography of drinking water systems, racial disparities in wealth, issues of citizenship status and belonging, and institutionalized structures of marginalization (Meehan et al., 2020). Moreover, a study by Mueller and Gasteyer (2021) establishes a connection between increased water-related challenges and social factors such as rural living, poverty, Indigenous identity, low educational attainment, and advanced age, indicating a pervasive environmental injustice across the United States (Mueller and Gasteyer, 2021). The combination of a growing population, climate change effects, and extended droughts has exacerbated the gap between water demand and supply, further complicating the situation (Sanchez et al., 2020). Research continues to unveil the health implications of climate change, exposing vulnerabilities like heightened exposure to infectious diseases, aggravated water and food insecurity, increased natural disaster risk, and population displacement (Ford, 2012).

The adoption of more intensive cultivation and grazing practices, deviating from traditional land use, has resulted in a notable rise in surface water runoff and a heightened level of microbial pollution in surface water sources. Such sources are occasionally utilized for drinking purposes, thus posing a potential risk to human health. On the other hand, groundwater contamination has emerged as a ubiquitous issue across various land covers, owing to the widespread prevalence of pit latrines, cows, and pigs in the vicinity. As a result, human users are consistently exposed to health hazards, given the possible presence of pathogenic microorganisms in the water sources (Esselman et al., 2018). Access to water remains a pervasive issue for Indigenous communities throughout the South American Chaco, leading to significant challenges and health risks. The issue cannot be attributed solely to geographical or natural factors but also arises from the ways in which settler waterscapes have redefined hydro social relations, creating a situation of water scarcity that disproportionately affects Indigenous communities in the Bajo Chaco region (Correia, 2022).

According to the 2021 Census data, the Indigenous population in Canada is composed of 1,807,250 individuals, representing 5.0 % of the total population. Ontario has the highest number of Indigenous people, followed by British Columbia, Alberta, and Manitoba, in descending order (Statistics Canada, 2022). Although tap water is the primary source of drinking water in Canada, many individuals from rural and Indigenous communities lack access to sufficient quality tap water at home. Nevertheless, a study conducted in eight Indigenous communities in Saskatchewan found that despite being satisfied with the quality of their tap water, only 35 % of participants consumed it (Bermedo-Carrasco et al., 2018). In the province of Alberta, approximately 11 % of households, equivalent to around 114,000 homes, rely on private wells as their primary source of drinking water. However, hand-dug wells and springs are often constructed without proper design and construction practices, resulting in increased permeability of enteric pathogens into the well water. This indicates that localized contamination specific to the water source is a significant contributor to groundwater contamination, rather than contamination affecting the entire aquifer or a significant portion of it (Pang et al., 2021). The issue of human exposure to perfluoroalkyl and polyfluoroalkyl substances (PFAAs), including perfluorooctane sulfonate (PFOS) and perfluorooctanoate (PFOA), has garnered significant attention due to their detrimental effects on various aspects of human health, such as development, metabolism, immune system, and endocrine function (Zhang et al., 2019). In line with this concern, a large-scale study in Quebec, Canada analysed tap water samples from 376 municipalities. The results showed that 99.3 % of samples tested positive for *Per-* and polyfluoroalkyl substances (PFAS), with concentrations ranging from below detection limits to 108 ng/L. On average, surface water had 12 times higher PFAS levels than groundwater. However, six of the top ten most contaminated locations relied on groundwater for their tap water supply (Munoz et al., 2023).

Besides, Indigenous communities in Ontario face some of the most severe drinking water challenges in the province, ranging from a decline in water quality to regulatory obstacles and inadequate assistance. Communities are subjected to a Drinking Water Advisory when water is known or suspected to be hazardous for human consumption (Lucier et al., 2020). Boil water advisories are a persistent problem in numerous communities, particularly in rural and Indigenous areas, with some advisories lasting for decades. Despite government efforts, many of these advisories remain in place, posing a serious threat to the health and safety of local residents (Arsenault et al., 2018). However, the lack of a detailed breakdown of water quality risks at the household level in these advisories makes it difficult to determine which individuals or communities are most in need of support, limiting the effectiveness of interventions aimed at improving water quality and security for Indigenous peoples (Duignan et al., 2022). In addition, the Mackenzie River Basin of Northern Canada faces a significant challenge with respect to drinking water in First Nations communities due to both the infrequency of testing and cleaning of cisterns as well as contamination caused by flooding. This lack of access to clean drinking water compels many individuals within these communities to rely on bottled water as a necessity. Unfortunately, the costs associated with acquiring bottled water can prove to be an excessive financial burden for First Nations

communities that are already vulnerable to poverty and poor health (Spicer et al., 2020).

As of June 30, 2022, it was reported that approximately 892,200 individuals identifying as Māori were estimated to make up 17.4 % of the overall population in New Zealand (Stats NZ, 2022). The majority of New Zealand's drinking water is obtained from underground aquifers and rivers, and it undergoes testing and treatment by local authorities. Some households and communities obtain their drinking water from nearby sources like rivers, lakes, and aquifers through wells, and it is their responsibility to ensure its safety (Ministry for the Environment and Stats NZ, 2020). In the previous year, a report published by the government revealed that approximately 60 % of the nation's rivers were contaminated with pollutants exceeding acceptable levels. Furthermore, the report indicated that between 95 % to 99 % of rivers located in pastoral, urban, and non-native forested areas were polluted (Melhem, 2021). It also highlighted the potential risks associated with polluted water sources and the accumulation of pollutants in freshwater environments, which can pose health hazards to humans through the consumption of certain food sources. While the risk of contamination is generally low for most New Zealanders, certain Māori communities may face a higher risk due to their dietary preferences. The contamination and degradation of freshwater sources pose significant risks not only to the public health and wellbeing but also undermining the country's tourism industry and the lifestyle of its citizens (Pirsoul and Armoudian, 2019).

The long-term availability of safe and clean drinking water in New Zealand is being challenged by several stressors, including climate change, contamination, water-dependent industries, and the requirements of neighbouring regions. These stressors have created a major threat to public health, as indicated by the presence of these challenges in most of the monitored groundwater sources throughout the country (Armoudian and Pirsoul, 2020).

4.2. Remote and indigenous Australian communities

Indigenous communities have a deep connection to water, including groundwater, surface water, and their interactions with the atmosphere and land. Therefore, preserving and managing water landscapes are crucial to them (Moggridge and Thompson, 2021). However, access to water and sanitation services is not equitable across rural and remote communities, particularly for remote Aboriginal and Torres Strait Islander communities. This lack of access leads to significant impacts on health outcomes (Department of Foreign Affairs and Trade., 2018). Despite the challenges, providing clean and safe drinking water and adequate sanitation is a necessity and a human right that many remote and Indigenous communities struggle to access (Hall et al., 2021a, 2021b; Wyrwoll et al., 2022).

Besides, inadequate water quality is also a growing concern in remote and First Nations communities and has the potential to exacerbate health disparities between Indigenous and non-Indigenous populations, causing severe health consequences (Water Services Association of Australia, 2022a). There is substantial evidence indicating that numerous remote communities do not meet the United Nations' Sustainable Development Goal (SDG) 6, which aims to provide clean water and sanitation to all individuals (as explained in Section 3.2). This inadequacy in services impedes the attainment of more comprehensive national objectives, such as the Australian Government's Closing the Gap targets (Infrastructure Australia, 2019).

To meet the Australian Drinking Water Guidelines, an investment of at least $2.2 billion is necessary, according to Adam Lovell, the Executive Director of the Water Services Association of Australia. This estimate does not include the cost of replacing old pipes and plumbing, which would further increase the required investment (Water Services Association of Australia, 2022b).

Despite efforts to improve access to safe water in remote, Aboriginal and Torres Strait Islander communities, consultations have identified several barriers that hinder the provision of potable water. The quality of water sources in remote regions is often suboptimal and necessitates additional treatment to meet safety standards for human consumption (Productivity Commission, 2021a).

4.3. Connection between pollution and water infrastructure

Water insecurity arises due to limited access and poor water quality, emphasizing the need for robust infrastructure. In the United States, inadequate water systems pose significant environmental and health risks, highlighting disparities in environmental and social justice. Notably, compliance with water regulations varies between tribal lands and the broader population (Khalsa, 2022; Redvers et al., 2021).

The relationship between pollution and water infrastructure is evident in Aotearoa New Zealand's freshwater crisis, with global implications. Indigenous Maori view freshwater bodies as integral to their ancestral ties, traditional knowledge, and wellbeing. The degradation of these water systems, ranked among the world's worst, is fueled by energy development and agriculture. A significant portion of the country's export earnings comes from primary industries, which contribute to pollution through increased agricultural land. This pollution impacts water quality, marked by elevated nitrogen, phosphorus, and *Escherichia coli* concentrations (Stewart-Harawira, 2020).

Lead exposure remains a persistent issue, particularly in marginalized communities where millions are connected to lead pipes and exposed to lead-based paint hazards (The White House, 2021). In response to unmet water advisory goals in Canada, there have been increased federal investments aimed at rectifying advisories and providing stable funding for water and wastewater infrastructure in First Nations communities (Office of the Parliamentary Budget Officer, 2021). Similarly, Australia's National Water Grid Fund is dedicated to water infrastructure investment, with a specific allocation of $150 million for First Nations communities (United Nations, 2023b).

5. Impact of poor water quality on the health and well-being

5.1. Rich countries (USA, Canada, New Zealand)

The availability of safe, easily accessible water is crucial for maintaining human health. Whether it's used for drinking or any other household purposes, having access to sufficient quantities of clean water at homes, schools, and healthcare facilities has a direct positive impact on health in numerous ways (WHO UNICEF World Bank., 2022). Diseases such as cholera, diarrhea, dysentery, hepatitis A, typhoid, and polio are closely associated with contaminated water and poor sanitation, and inadequate water and sanitation services increase the risk of preventable health issues. An alarming estimate suggests that inadequate drinking water, sanitation, and hand hygiene contribute to around 829,000 annual deaths due to diarrhea (World Health Organization (WHO), 2022a). As such, addressing enduring health disparities has remained a consistent health priority, manifesting in areas like life expectancy, disease prevalence, chronic disease risk factors, and overall quality of life (Stanley et al., 2020).

Regrettably, Indigenous communities across the globe face significant challenges with poverty and limited access to services, leading to inferior health outcomes and a greater number of unmet health and social service needs (Harfield et al., 2018; World Health Organization (WHO), 2022b). These challenges are exacerbated by compromised water quality and water-related issues, coupled with socio-cultural complexities, particularly for dispersed rural Indigenous communities, which are among the most vulnerable populations exposed to toxic metal(*oid*)s (Navarro-Espinoza et al., 2021; Rowles III et al., 2018). These vulnerabilities are a consequence of the colonial state's structural framework, rather than inadequate capacity or lack of interest from the communities (Baijius and Patrick, 2019).

Significant health issues, including chronic kidney disease, acute

gastrointestinal illness (AGI), and colorectal cancer (CRC), disproportionately affect remote Indigenous areas. AGI outbreaks contribute to morbidity, mortality, and economic costs, with indigenous populations bearing a disproportionate burden (Harper et al., 2015; Wright et al., 2018). Notably, Inuit communities in the Canadian Arctic report one of the world's highest self-reported AGI incidence rates, potentially due to consuming water contaminated with *Escherichia coli* and coliforms during transportation (Wright et al., 2018).

Despite similar incidence rates, CRC exhibits higher mortality rates among indigenous groups (D'onise et al., 2020; Rawla et al., 2019). Besides, a significant number of First Nations communities in Canada depend heavily on cisterns to obtain their drinking water supply. However, bacterial contamination is common in these systems, leading to boil water advisories (Bradford et al., 2018a). The origin of contamination remains unclear, but households using concrete underground cisterns in Manitoba, Canada, exhibited a significant prevalence of fecal bacteria compared to those with above-ground cisterns (Mi et al., 2019). Illustrated in Fig. 1 is the possible water distribution methods from source to consumer in remote areas while Fig. 2 is a prevalent water distribution methodology in Manitoba, spanning from the water source to the end consumer (Khan et al., 2022).

Meanwhile, tracers found in wastewater in southern Ontario, such as nitrate, *E. coli*, total coliforms, and artificial sweeteners, have the potential to move into groundwater, where many First Nations reserves were under drinking water advisories in the area (Marshall et al., 2019).

A significant proportion of the New Zealand population is also exposed to elevated or undetermined levels of nitrates in their drinking water. The New Zealand government has set the current national policy statement limit for nitrates at 2.4 mg. However, in many cases, the concentration of nitrates in freshwater is four times higher than this limit. The government claims that by setting the bottom line at 2.4 mg/L, the limit would be considered non-toxic for 95 % of species (Riverwatch, 2023). Considering the findings of international epidemiological research on the link between cancer and nitrate ingestion through drinking water, this exposure may result in a substantial burden of preventable cases of colorectal cancer (CRC), as well as associated fatalities and economic expenses (Richards et al., 2022). It is also noteworthy that in 2016, New Zealand witnessed its most significant documented waterborne disease outbreak. During this incident, a drinking water supply became contaminated with Campylobacter sp., leading to the diagnosis of over 5500 individuals with this pathogen and tragically resulting in four fatalities (Phiri et al., 2020).

Additionally, various issues have been reported in five rural and regional communities across British Columbia, including elevated metal (loid) concentrations, the presence of coliforms, and poor aesthetic properties (Hu et al., 2022). In addition to reporting high levels of lead in their drinking water that exceed health-based maximum acceptable concentrations, certain First Nations communities have also been found to have other metals in their water that surpass the 2019 Guidelines for Canadian Drinking Water Quality (Schwartz et al., 2021). These metals include manganese at 4.0 %, uranium at 1.6 %, aluminum at 1.3 %, and copper at 0.2 % in flushed water. Enteric parasites are also prevalent in Canada and can cause waterborne diseases (Masina et al., 2019).

Further investigations are necessary to determine the links between various toxic exposures, such as uranium, and chronic health conditions in Indigenous communities worldwide. Uranium mining and milling activities on or near American Indian (AI) reservations and lands in United States have been ongoing for decades, raising concerns about the potential health effects of exposure to uranium and other radioactive materials (Redvers et al., 2021).To date, arsenic has been identified in 15 Latin American countries. The rural population is frequently unaware of the toxic effects of arsenic due to the fact that many instances of exposure are linked to the consumption of arsenic-contaminated drinking water, which is both odorless and tasteless (Kumar et al., 2019). The following Table 1 presents a summary of water quality challenges that are particularly prevalent in indigenous communities in rich countries.

5.2. Remote and indigenous Australian communities

Australia is home to a total of 537 councils, distributed across different regions. Approximately 55 % of these councils are situated in regional, rural, or remote areas (Australian Local Government Association, 2023b). The Australian Classification of Local Governments

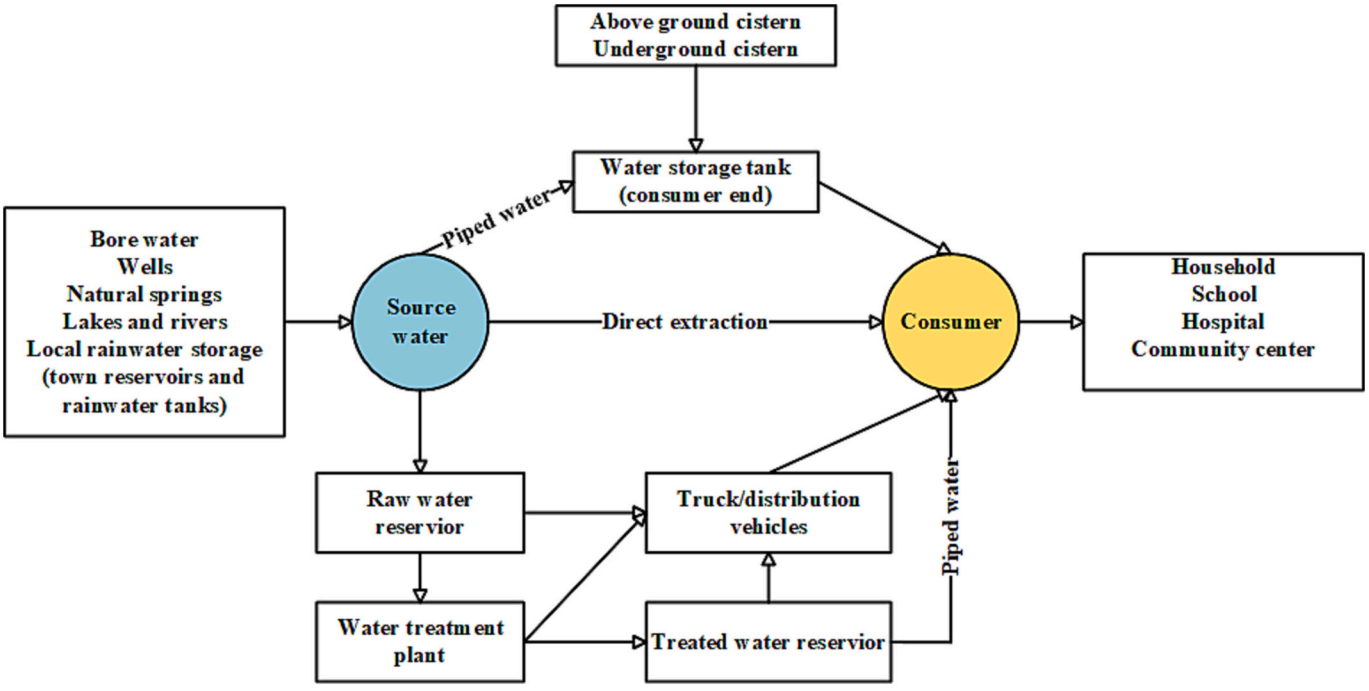

Fig. 1. Possible water distribution methods from source to consumer in remote areas.

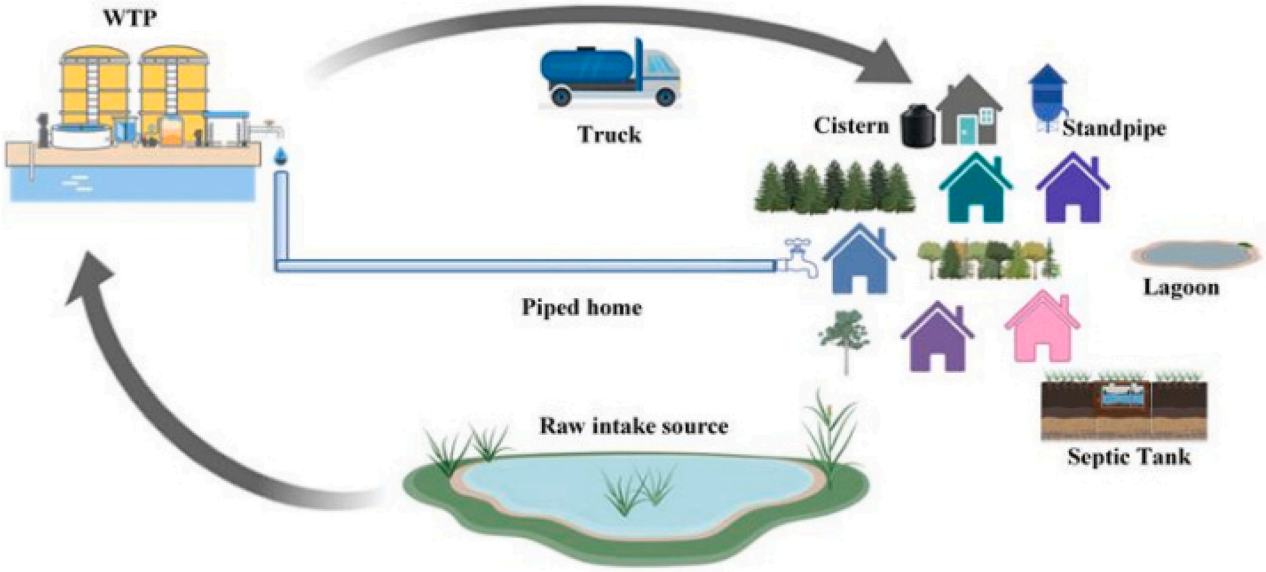

Fig. 2. Schematic diagram of water distribution at two First Nation communities in Manitoba, Canada (Khan et al., 2022).

Table 1
Indigenous health issues associated with drinking water in some rich countries (USA, Canada, New Zealand).

Indigenous community	Reported contaminants	Identified stage of contamination in water cycle	Health impacts	References
AI communities, America (New Mexico)	High levels of uranium, arsenic, and radium	Unregulated and unmonitored wells (groundwater)	Kidney disease, diabetes, cancers, low life expectancy compared to Whites.	Redvers et al. (2021)
Beardy's and Okemasis First Nation Reserve, Saskatchewan	Bacterial contamination	Trucks, cisterns and taps (distribution, storage, consumer tap)	Household boil water advisories	Bradford et al. (2018a)
Manitoba, Canada	*E. coli* and total coliforms	Storage systems (underground cisterns)	Waterborne infectious diseases (gastroenteritis)	Mi et al. (2019)
First Nations across Canada	Trace metals (lead, manganese, uranium, aluminum, copper)	Distribution system/consumer tap	Neurodevelopmental effects, neurotoxicity, kidney effects, diarrhea	Schwartz et al. (2021)
Northern Canada	Total coliforms	Collection and storage (containers)	Acute gastrointestinal illness	Wright et al. (2018)
Iqaluit, Canada	Waterborne parasites	Sylvia Grinnell and Apex Rivers (untreated surface water)	Gastrointestinal illness	Masina et al. (2019)
(Māori) New Zealand	Nitrate	Unregistered (private) supplies	Colorectal cancer (CRC)	Richards et al. (2022)
Alberta, Canada	Water pathogen (viruses)	Private wells (groundwater)	Gastroenteritis	Pang et al. (2021)
Quebec, Canada	PFAS	Consumer tap	Adverse effects on human health in development, metabolism, immune, and endocrine function	Munoz et al. (2023); (Zhang et al., 2019)

(ACLG), introduced in September 1994, serves as a framework to categorize local governing bodies across Australia, utilizing criteria like population size, density, and urban composition (Department of Infrastructure Transport Regional Development and Communications, 2020). The Local Government Area (LGA) Structure represents the comprehensive geographic jurisdiction of incorporated Local Government Councils or Aboriginal Councils in Queensland where "Aboriginal Council" refers to an entity established in accordance with the provisions outlined in Section 31 of the Aborigines Act 1971–1975 (Queensland Parliament, 1978). The responsibility for forming and defining LGAs rests with State and Territory Governments, resulting in variations in their count, nomenclature, and boundaries over time. In Queensland, these entities are organized into distinct categories, including Cities (C), Shires (S), Towns (T), and Regional Councils (R) (Australian Bureau Of Statistics, 2023).

Small rural-remote and Indigenous councils operate in a distinct context compared to urban and provincial counterparts, often grappling with resource constraints and reliance on grants for funding. These councils are expected to provide crucial services to their communities despite limited resources (Morton Consulting Services Pty Ltd., 2012).

Historically, Aboriginal communities would have selected their settlements based primarily on cultural, survival, and social factors. Nowadays, permanent Aboriginal settlements have replaced the traditional nomadic way of life, with many communities now housing more than a thousand people. However, most of these settlements are located in remote areas and depend on groundwater accessed through boreholes, posing an ongoing challenge to the provision of safe and reliable water supplies (Moggridge and Thompson, 2021). This is especially true when using subpar or low-grade groundwater as a primary source and when sophisticated treatment methods are not feasible for implementation (Water Services Association of Australia, 2022a).

Water supplies sourced from deep artesian (bore) sources are susceptible to both microbial and chemical contamination. The microbial risk associated with these sources is attributed to the lack of maintenance of infrastructure as well as poor hygiene practices. This poses a potential health hazard due to waterborne illnesses that may result from consuming contaminated water (Hall, 2019).

Cryptosporidium, an enteric parasite, is not only a major cause of infectious diarrhea globally but also one of the most prevalent waterborne parasitic infections. In Australia, cryptosporidiosis is recognized as a national notifiable disease (Zahedi et al., 2018). According to the National Notifiable Diseases Surveillance System (NNDSS) in Australia, the average notification rate is 12.8 cases per 100,000 population. However, vulnerable populations often experience significantly higher

notification rates. For instance, in Western Australia, Aboriginal children in a specific age group had notification rates 20.5 times higher than their non-Aboriginal counterparts over an 11-year period from 2002 to 2012 (Ryan et al., 2022). In addition to the challenge of microbial contamination in drinking water, Indigenous communities in remote areas of Australia also face the risk of high levels of chemical contaminants in drinking water (Rajapakse et al., 2022).

These communities also confront heightened exposure to climate change impacts due to residing in rapidly changing environmental regions influenced by latitude, topography, proximity to the sea, and soil quality (Hill et al., 2020). Climate change leads to direct public health consequences, including the contamination of drinking water with saltwater and pollutants, intensified by droughts. These factors can lead to altered water quality, promoting algal blooms and salinity increase, ultimately affecting dissolved oxygen concentrations (Productivity Commission, 2021a). The Aboriginal population in New South Wales (NSW) experiences disproportionate impacts from extreme climate events, a trend projected to intensify with anticipated climatic shifts (Standen et al., 2022). Reports also highlight the consequences of climate change on the health of Aboriginal and Torres Strait Islander peoples encompass a spectrum of direct and indirect effects on morbidity and mortality (Lowitja Institute, 2021). Indirect health impacts are mediated by natural systems, including sewage-contaminated drinking water. Additionally, reduced groundwater recharge exacerbates water contamination issues, compounding the challenges posed by saltwater intrusion (Hall and Crosby, 2022).

In Australia, >500 communities lack consistent water quality testing, and those in remote regions are supplied with water that contains levels of uranium, arsenic, fluoride, nitrate, manganese, iron, and microbial contamination that exceed the thresholds set by the Australian Drinking Water Guidelines (ADWG) and prolonged exposure to these substances can lead to severe health problems with detrimental effects (Power and Water Corporation., 2021; Rajapakse et al., 2019; Water Services Association of Australia, 2022a, 2022b). Contamination concerns in remote Indigenous communities sharply contrast with urban safe water standards. For instance, around 30 % of 274 communities in Western Australia exhibited irregular compliance with drinking water standards. *E. coli* and Naegleria were consistently found in at least one community each month, indicating fecal contamination (Hall et al., 2020). Australia remains the only developed nation with endemic Trachoma eye infections among indigenous communities, a consequence of Water, Sanitation, and Hygiene (WASH) issues such as limited clean water access and crowded housing (Rajapakse et al., 2022).

Notably, Chronic kidney disease presents a significant and chronic condition, particularly affecting indigenous communities in Australia, with higher rates compared to non-indigenous populations (Genereux et al., 2021). Hypertension and diabetes contribute to the high burden of chronic diseases among Indigenous Peoples, leading to faster progression to kidney failure and elevated mortality rates in these populations (Hoy et al., 2020; Kerr et al., 2022). By December 31, 2021, 2568 Indigenous Australians received kidney replacement therapy, 85 % on dialysis, 15 % with transplants. From 2019 to 2021, 1063 Indigenous Australians began replacement therapy. Kidney failure incidence was six times higher than non-Indigenous counterparts, with 279 Indigenous deaths attributed to kidney disease from 2015 to 2019 (Australian Institute of Health and Welfare, 2023b).

The results of the study of Wyrwoll et al. (2022), provide valuable insights into the state of drinking water quality in remote and indigenous communities in Australia. The data reveals significant exceedances of the health limits specified by the Australian Drinking Water Guidelines (ADWG). Nitrate concentrations were found to exceed acceptable limits in 19 communities, highlighting the potential risks to vulnerable populations such as infants and pregnant women. Similarly, *E. coli* contamination was observed in 13 communities, indicating the presence of fecal contamination and the associated health risks. Uranium concentrations were found to exceed the defined basic level in 8 communities, while Fluoride concentrations exceeded acceptable limits in 6 communities. Manganese concentrations were also found to be elevated in 3 communities, suggesting potential neurological health risks. Additionally, the presence of antimony and barium above acceptable levels in one community each highlights the importance of addressing toxic elements in drinking water sources. These findings underscore the urgent need for targeted interventions, resources, and support to ensure access to clean and safe drinking water in remote and indigenous communities.

5.2.1. Queensland

Queensland lacks a comprehensive consolidated report regarding the annual state drinking water quality. Consequently, authors have conducted an analysis of the Drinking Water Quality Management Plans (DWQMP) for all 45 rural and remote councils identified by the Local Government Association of Queensland (LGAQ) on June 25, 2021. Additionally, the DWQMPs of the 16 Indigenous councils in Queensland were also examined and where drinking water quality parameters exceed ADWG values for all 61 remote and aboriginal councils in Queensland are summarized below in Table 2.

The analysis of the drinking water quality data has revealed a concerning trend across the studied regional and Aboriginal councils in Queensland. In all cases, the recorded maximum values for the parameters in the table exceeded the recommended limits set by the Australian Drinking Water Guidelines (ADWG), both in raw water and finished water samples. This indicates significant concerns regarding the quality of drinking water in these areas. Among the 61 councils studied, it is noteworthy that Isaac and Quilpie regional councils exhibited particularly poor water quality. Although there is no specific ADWG recommended limit for conductivity, the recorded value of 2500μS in treated water is considerably high, indicating the presence of dissolved

Table 2
Recorded maximum drinking water quality values in regional and Aboriginal councils in Queensland (Blackall-Tambo Regional Council, 2021-22; Burdekin Shire Council, 2021-22; GBA Consulting Engineers, 2021-22, 2022; Goondiwindi Regional Counci, 2021-22; Isaac Regional Council, 2021; South Burnett Regional Council, 2021-22; Tablelands Regional Council, 2021-22).

Parameter	ADWG	Max value in Raw water	Location	Max value in treated water	Location
Conductivity	N/A	5100	Quilpie SC (2022)	2500	Quilpie SC (2022)
Total Hardness	200 as CaCO3	1145	Isaac RC (2021)	510	Isaac RC (2021)
TDS	600 mg/L	2970	Quilpie SC (2022)	1500	Quilpie SC (2022)
Colour	15	1940	Isaac RC (2021)	120	Isaac RC (2021)
Turbidity	5 NTU	2242	Isaac RC (2021)	30.1	Isaac RC (2021)
Silica	80 mg/L	88	Quilpie SC (2022)	147	Goondiwindi RC (2021−22)
Sodium	180 mg/L	640	Quilpie SC (2022)	350	Quilpie SC (2022)
Chloride	250 mg/L	1300	Quilpie SC (2022)	560	Quilpie SC (2022)
Fluoride	1.5 mg/L	1.8	Boulia SC (2021–22)	1.9	Boulia SC (2021–22), Quilpie SC (2022)
Nitrate	50 mg/L	46	Burdekin SC (2021–22)	53	Goondiwindi RC (2021–22)
Iron	0.3 mg/L	13.6	Tablelands RC (2021–22)	6.33	Blackall-Tambo RC (2021–22)
Manganese	0.1 mg/L	61	South Burnett RC (2021–22)	4.5	Isaac RC (2021)

substances in the water. This suggests the need for further investigation into the sources of these dissolved substances and the implementation of appropriate treatment measures.

Furthermore, it is concerning that 15 councils out of the 61 exceeded the ADWG limits for hardness in either their raw water or treated water. The maximum total dissolved solids (TDS) values ranged from 610 mg/L to 2970 mg/L, indicating a significant variation in water quality across the councils. Turbidity, an important parameter indicating water clarity, was also found to exceed the ADWG limits in 21 councils. This highlights the need for improved filtration and treatment processes to address these turbidity issues. Of notable concern is the fluoride content in the water. Boulia, Diamantina, Maranoa Paroo, and Quilpie councils all exceeded the ADWG limit of 1.5 mg/L for fluoride. This necessitates urgent action to implement appropriate measures to regulate and reduce fluoride levels in these areas.

The analysis also revealed significant exceedances in iron and manganese levels. Eighteen councils recorded iron levels surpassing the ADWG limit, ranging from 0.32 mg/L to 13.6 mg/L. Similarly, manganese levels exceeded the ADWG limit in 16 councils, ranging from 0.1 mg/L to 61 mg/L. These findings underscore the need for improved treatment processes to address the presence of iron and manganese in the drinking water, as their elevated levels can impact water quality and pose potential health risks.

5.2.2. New South Wales

Based on the data collected from 18 water supply systems in remote aboriginal communities in New South Wales (NSW), it is evident that there are still water quality issues despite the presence of treatment measures. The data presented in Table 3 demonstrates that the concentration of certain contaminants, such as hardness, fluoride, turbidity, and total dissolved solids (TDS), continue to be a concern for consumers at the tap. Additionally, it is important to note that there has been an increase in turbidity levels at the consumer tap in recent years 2021–22 (SA Water Corporation, 2020, 2022).

Besides, inadequate water supplies in numerous rural communities in New South Wales, Australia, can lead individuals to consume sugar-sweetened beverages, which are known to have adverse health effects (Perry et al., 2022), particularly for Indigenous Australians who have higher rates of type 2 diabetes. Recent research suggests that SSBs account for 48 % of total sugar intake among children and adolescents, and their consumption is associated with an increased risk of developing type 2 diabetes (Pan et al., 2021).

5.2.3. Western Australia

In the remote areas of Western Australia, nitrate-N levels were sampled on a limited basis, with only 48 samples being taken and levels ranging from 6.2 to 107 mg/L where ADWG for nitrate as nitrate is 50 mg/L for infants under 3 months and 100 mg/L for others. In addition, uranium levels in the groundwater were tested 212 times, and these levels ranged from 0.0001 to 1.46 mg/L where ADWG is 0.02 mg/L (NHMRC and NRMMC, 2022; Rajapakse et al., 2019).

Table 4 presents a comparison between the recorded maximum values of drinking water quality data of Western Australia (Perth, Mandurah and >220 regional towns and communities throughout Western Australia) for the years 2015 and 2022 (Water Corporation, 2015, 2022). It is evident that certain parameters, such as nitrate levels, water hardness, and fluoride content, continue to pose issues in the region over the span of eight years.

Table 4
Changes in drinking water quality parameters in Western Australia from 2015 to 2022 (Water Corporation, 2015, 2022).

Parameter	ADWG	2014–15		2021–22	
		Max. Value (consumer tap)	Location/s	Max Value (consumer tap)	Location/s
Fluoride	1.5 mg/L	1.1	Laverton, Collie	1.3	Collie
Nitrate (as nitrate)	50 mg/L	19.2	Yalgoo	61.6	Meekatharra
Hardness	200 mg/L	380	Jurien Bay	370	Salmon Gums, Munglinup, Grass Patch, Esperance
TDS	600 mg/L	1357	Horrocks	1518	New Norcia
Iron	0.3 mg/L	0.86	Tincurrin	0.6	Augusta

According to the 2015 Auditor General's report of Western Australia, four out of five communities experienced issues with their water supply meeting the required microbiological quality standards in the two-year period leading up to June 2014, due to the detection of E.coli or Naegleria (Office of the Auditor General Western Australia, 2015). It has also come to attention that eleven regional towns in Western Australia have not been following the Australian drinking water guidelines for the past decade due to excessive nitrate contamination. The water from bores in these areas has not been properly filtered, leading to naturally occurring uranium and nitrate contamination (Rajapakse et al., 2022). However, new assets and water management plans have had a positive impact on the drinking water in around half of the communities examined in 2015, contributing to its improvement in microbial contamination where 37 out of 84 communities still remained at risk from unsafe water in 2015 due to contamination from microbes, nitrates, or uranium. Testing confirmed the presence of *E. coli* or Naegleria species in 21 communities, high nitrate levels in 19 communities, and high uranium levels in 4 communities in the two years leading up to 2019–20 and the results are compared with values of 2015 Auditor General's Report in Table 5 (Office of the Auditor General Western Australia, 2015, 2021). The situation with nitrates, there had been a deterioration; an increase from 14 to 19 high-nitrate communities since the issue was reported in 2015.

5.2.4. Northern Territory

Indigenous people from the remote community of Ngukurr in northern Australia have expressed concerns about the safety of drinking water from freshwater billabongs due to the possibility of microbial contamination together with turbidity from feral ungulates (Russell and

Table 3
Changes in remote aboriginal community source water quality and consumer tap water quality in NSW against ADWG (SA Water Corporation, 2020, 2022).

Parameter	ADWG	2019–20			2021–22		
		Source water	Consumer tap	Location	Source water	Consumer tap	Location
TDS	600 mg/L	10,200	126	Yalata	9530	228	Yalata
		1310	1260	Kanpi	705	857	Watinuma
Hardness	200 mg/L	4050	87	Yalata	3430	121	Yalata
		587	516	Kanpi	334	451	Watinuma
Fluoride	1.5 mg/L	3.2	3.1	Murputja	1.8	1.6	Pukatja
Turbidity	5 NTU	200 N	<0.1	Mimili	16	<0.10	Mimili
		N/A	8.5	Gerard	0.45	34	Nepabunna

Table 5
Comparison of the changes in examined parameters Auditor General's report for Western Australia in 2014 and 2020.

Examined parameter	ADWG	No. of communities experience the exceedance concentrations compared to ADWG in the two-year period leading up to June 2014 (total of 84 communities)	No. of communities experience the exceedance concentrations compared to ADWG in the two-year period leading up to June 2020 (total of 84 communities)	Difference
E. coli or Naegleria	Nil	68	21	+56 %
Nitrate (safe level for bottle-fed babies under three months old)	50 mg/L as nitrate	14	19	−6 %
Uranium	0.02 mg/L	4	4	0

Ens, 2020). The turbidity values have exhibited an increase across all sites during the transition from early to late dry season, with values reaching up to 550 NTU. Moreover, in the late dry season, the presence of waterborne pathogens, specifically Giardia cysts, was detected within a range of 0–12.24. The inadequate provision of water quality testing and maintenance resources exacerbates these challenges, leading to high staff turnover rates and making it difficult to monitor water quality effectively (Hall et al., 2021a, 2021b).

The maximum levels of manganese measured in Bulla, Nauiyu, and Nganmarriyanga in Northern Territory have all exceeded the recommended health-based guideline. Also, Bulla's groundwater contains high concentrations of barium, a naturally occurring metallic element, which is present at levels eight times higher than the health-based guidelines specified by the ADWG (Power and Water Corporation., 2021). Elevated concentrations of antimony have also been reported in the Beswick community. There have been documented cases of elevated levels of uranium and fluoride exceeding safe limits in that particular area. Moreover, changes in the aesthetic parameters of drinking water can also influence people's willingness to consume it. If water has an unpleasant taste, odor, or appearance, people may be less inclined to drink enough water to maintain proper hydration, potentially leading to health complications like dehydration. Table 6 provides a summary of the changes in water quality parameters between 2017 and 2021 in the remote communities of the Northern Territory (Power and Water Corporation., 2017, 2021).

Overall, ensuring safe drinking water for remote and First Nations communities in Australia remains a complex and multifaceted issue that requires coordinated efforts to address biological, chemical, and environmental challenges.

6. Current remedial measures to improve drinking water quality

6.1. Approaches in rich countries

Indigenous communities place great significance on safeguarding the waters on their ancestral territories. Their efforts to protect water resources are motivated by multiple factors, including concerns over public health and the pursuit of equitable access to clean water (Diver, 2018). To ensure effective water supply in rural communities and among indigenous populations, it is crucial to implement universally applicable measures that prioritize the use of simple and affordable technologies tailored to the specific local context. The focus should be on identifying solutions that are not only cost-effective but also easy to implement, ensuring accessibility and sustainability in providing clean water (Medeiros et al., 2020). Scholars and media outlets have reported on the unfortunate disregard for water quality on tribal lands in the United States. To address these issues, Treatment as a State (TAS) provisions were introduced as part of the Clean Water Act's 1987 amendments, alongside tribal Water Quality Standards (WQSs) programs (Diver, 2018). Attaining water security within a community necessitates a comprehensive grasp of the local water resources, encompassing their present condition, potential risks, accessible resources, and investment prospects. However, Canadian Indigenous communities encounter difficulties in achieving this objective. Nonetheless, a possible resolution involves fair involvement of Indigenous knowledge (IK) and Western science (WS) through a complementary multi-disciplinary approach that integrates participatory, scientific, and cultural methodologies (Latchmore et al., 2018). Further, a theoretical framework for effectively utilizing local governance to promote water security among First Nations in Canada is presented by the Institute of Public Administration of Canada. The approach to governance outlined requires sufficient financial resources to support the maintenance, operation, and renewal of water systems, as well as a regulatory framework to prevent the tragedy of the commons (Alcantara et al., 2020). Additionally, it entails formalizing public administration to establish clear lines of responsibility between elected officials and band staff. The proposed framework emphasizes the importance of collaborative efforts among different actors, such as First Nations communities, government agencies, and non-governmental organizations, to achieve water security for all. Bradford et al. (2018b) highlights the effectiveness of co-design as a promising approach to developing water infrastructure that meets both the technical requirements and community values in Indigenous Canada.

In many First Nation communities, poorly designed community infrastructure services have led to undrinkable water. These services include inadequate housing, water supply and delivery, wastewater disposal, and solid waste management. To address this issue, First Nation communities are reclaiming indigenous planning through source

Table 6
Remote water quality comparison results for Northern Territory in 2017 and 2021 (Power and Water Corporation., 2017, 2021).

Parameter	ADWG	2017 (consumer tap)		2021 (consumer tap)	
		Maximum value	Location/s	Maximum value	Location/s
Antimony	0.003 mg/L	0.007	Beswick	0.008	Beswick
Barium	2 mg/L	10	Bulla	5.0	Bulla
Chromium	0.05 mg/L	0.06	Wallace Rockhole	0.1	Bulla
Fluoride	1.5 mg/L	1.9	Nyirripi	1.7	Alpurrululam
Lead	0.01 mg/L	0.01	Amanbidji	0.03	Yuendumu
Iron	0.3 mg/L	0.97	Numbulwar	2.0	Bulla, Minyerri, Numbulwar
Manganese	0.5 mg/L	0.3	Nauiyu, Nganmarriyanga, Numbulwar, Amanbidji, Amoonguna	2.0	Nganmarriyanga
Uranium	17 μg/L	47	Laramba	57	Laramba
Hardness (as $CaCO_3$)	200 mg/L	745	Ngukurr	700	Jilkminggan, Ngukurr, Wilora
Total Dissolved Solids	600 mg/L	1360	Wilora	2000	Imanpak, Wilora
Turbidity	5 NTU	11.4	Numbulwar	30	Nganmarriyanga

water protection plans. This type of planning has the potential to improve water security and promotes constructive dialogue, trust-building, and reciprocity between participants, including community members and university researchers (Patrick et al., 2019). However, in Canada, Indigenous communities have limited participation in these programs, which has led to their source waters being vulnerable to contamination (Marshall et al., 2018). Consequently, there is a pressing need for risk assessment tools that reflect Indigenous perspectives and can be utilized by Indigenous training programs, such as the Ontario First Nations' Source Water Protection (SWP) program managed by OFNTSC (Marshall et al., 2019). The Water Safety Plan document of WHO 2023 states that water safety plans should be developed in collaboration with the community and stakeholders, considering local conditions, traditions, and perspectives. It also highlights the importance of understanding the social, cultural, and economic factors that affect water use and management in a community. Therefore, it is reasonable to conclude that incorporating Indigenous perspectives in the development of risk assessment tools would be consistent with the principles outlined in the Water Safety Plan (WSP) document who seek to implement SWP or WSP (World Health Organization, 2023).

While modern water treatment processes effectively mitigate many risks associated with contaminated water sources, recent incidents of drinking water contamination underscore the necessity for water managers to extend their focus beyond treatment facilities. It is crucial for them to also address the management of the entire water supply catchment to ensure the provision of safe drinking water. By considering factors such as source water protection, watershed management, and effective monitoring, water managers can enhance their efforts in safeguarding the quality of drinking water for the community (Phiri et al., 2020).

Indigenous communities grapple with pollution from various sources, including oil and gas extraction, mining, waste disposal, and traditional practices like burning (Fernández-Llamazares et al., 2020). Water contaminants encompass sewage, food waste, oil, pesticides, and even radioactive materials (Australian Indigenous HealthInfoNet, 2023). In New Zealand, colonial-era urban and industrial development introduced non-native species, disrupted waterways, and diverted rivers underground (Stewart-Harawira, 2020). Environmental governance involves regulatory processes and institutions shaping water-related decisions, including community input (Wilson et al., 2018). This underscores the intricate management of pollution within Indigenous contexts.

The 2017 revisions to the national policy for freshwater highlighted Te Mana o Te Wai and Ki Uta ki Tai concepts, emphasizing the relationship between freshwater and the environment, and including the wellbeing of freshwater ecosystems and communities into legislation. A 5-year plan was released by the government to restore the waterways, and the revised NPS-FM aimed to prioritize Te Mana o Te Wai by safeguarding the health and mauri of the water, catering to essential human needs like drinking water, and permitting other consumptive uses, as long as it did not harm the mauri of freshwater (Stewart-Harawira, 2020). Nelson et al. (2022) discusses the challenges faced by villages in accessing clean water due to population growth, contamination, and limited water supply during the dry season. It suggests that adopting a participatory approach that involves local communities in decision-making is critical to addressing contamination sources and improving water quality. Empowering villagers with knowledge about the health risks associated with water-related diseases can enable them to advocate

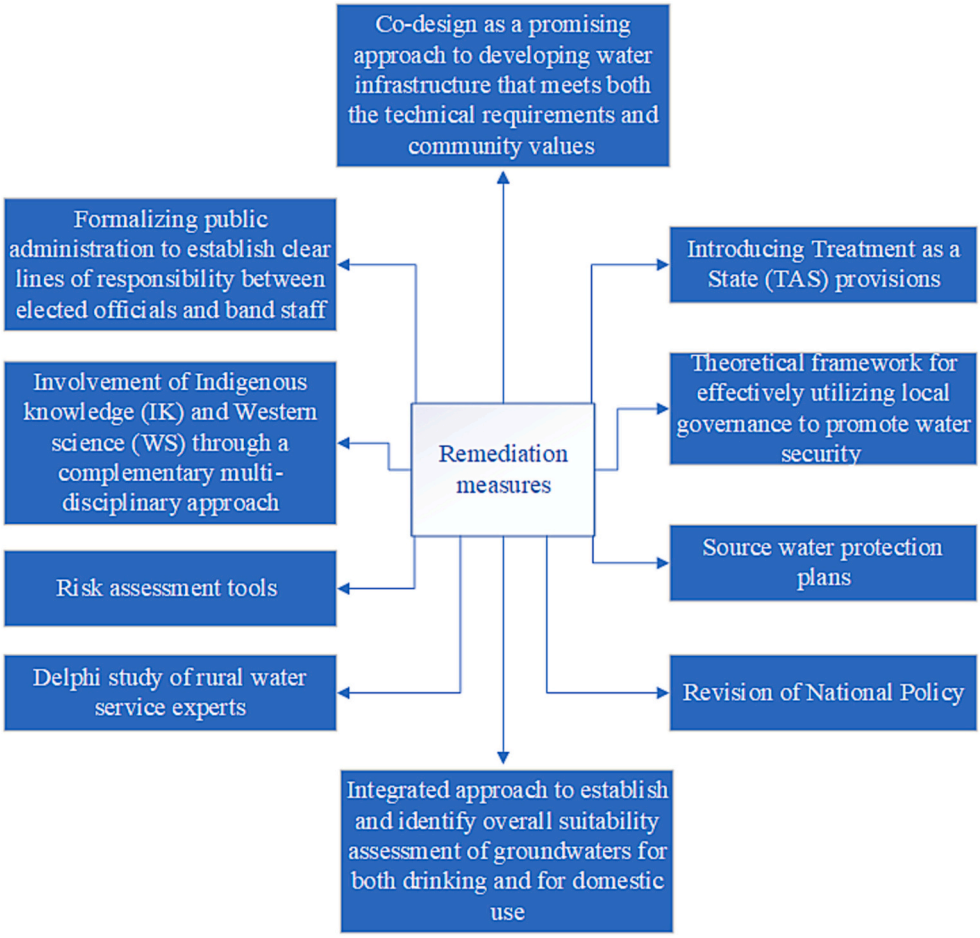

Fig. 3. Remediation measures currently using in Indigenous areas.

for improvements in water quality. Fig. 3 summarises the remediation measures currently being implemented in remote aboriginal areas in rich countries.

6.2. Approaches in Australian context

To ensure the preservation of water and sanitation rights in remote and Indigenous communities, a continued emphasis on investment is paramount. This entails, enhancing policies, adequate funding for water and sanitation services, addressing governance structures to avoid siloed government services, infrastructure development using technology fit for purpose, utilization of data and understanding cultural and historical aspects of the communities (Brown et al., 2023; Hall et al., 2022; United Nations, 2023a).

However, despite global progress, challenges persist due to local governance issues not only within the targets of SDG 6 but also across other goals within the broader SDG framework (Herrera, 2019). Many targets outlined in the SDGs fall under the jurisdiction of sub-national levels of government. In response, the Australian Government has adopted a strategic approach that aligns with the country's specific conditions. This approach involves delegating government policy responsibilities and priorities to relevant agencies and administrative tiers (Australian Local Government Association, 2023a; Department of Foreign Affairs and Trade., 2018). Proposed models like “joint boards” for sharing functions among local councils, as suggested in South Australia, could enhance efficiency if implemented effectively. Collaboration for cost efficiency can be achieved by adjusting optimal scales for municipal functions, although policy success can vary contextually (Fellows et al., 2022).

The ongoing challenges associated with supply of safe and readily available water in remote Australia can be framed shown in Fig. 4 (Water Services Association of Australia, 2022a). To manage water demand effectively, it is essential to understand the volume and nature of water use. Beal et al. (2018) have identified the main drivers of high outdoor water use in Stage 1 of Remote and Isolated Communities Essential Services (RICES) project and proposed a targeted demand management plan based on empirical data for RICES Stage 2. Additionally, encouraging families to commit to reducing their water use as part of a community-supported initiative could be an effective strategy.

Wyrwoll et al. (2022) aimed to measure disparities in drinking water quality and policies across regional and remote areas of Australia. The study provided three main contributions, including defining and applying basic levels of service for drinking water quality, improving the understanding of drinking water quality in regional and remote Australia, and showing that exceedances beyond ADWG guideline values are most prevalent in small and remote towns and settlements. The study suggests that policy initiatives seeking to improve drinking water services should consider cultural and geographic contexts and incorporate training, improvements to source water quality, and other non-capital investments.

A successful co-design program for safe water delivery was achieved through inter-agency collaboration in the outer Torres Strait Islands, which indicates three critical components for success: suitable infrastructure that meets the needs of the location and population, mentoring and technical assistance for water operators working in remote areas, and cooperation among relevant state and local government agencies (Hall et al., 2021a, 2021b). A systems-based approach to deliver WASH within households and communities, utilizing technology tailored to the specific needs of each community, its people, and the stage of water and wastewater treatment required, was also identified as an effective strategy (Hall, 2019).

Howey and Grealy (2021) draw attention to the inequitable governance of drinking water in the Northern Territory of Australia, which is detrimental to Indigenous communities. Despite the National Water Initiative's aim to ensure safe and reliable water supplies, it has failed to rectify structural inequalities. The article recommends integrating water policy with other policy domains and collaborating with land councils to adopt a strategic, transparent, and risk-based approach to water

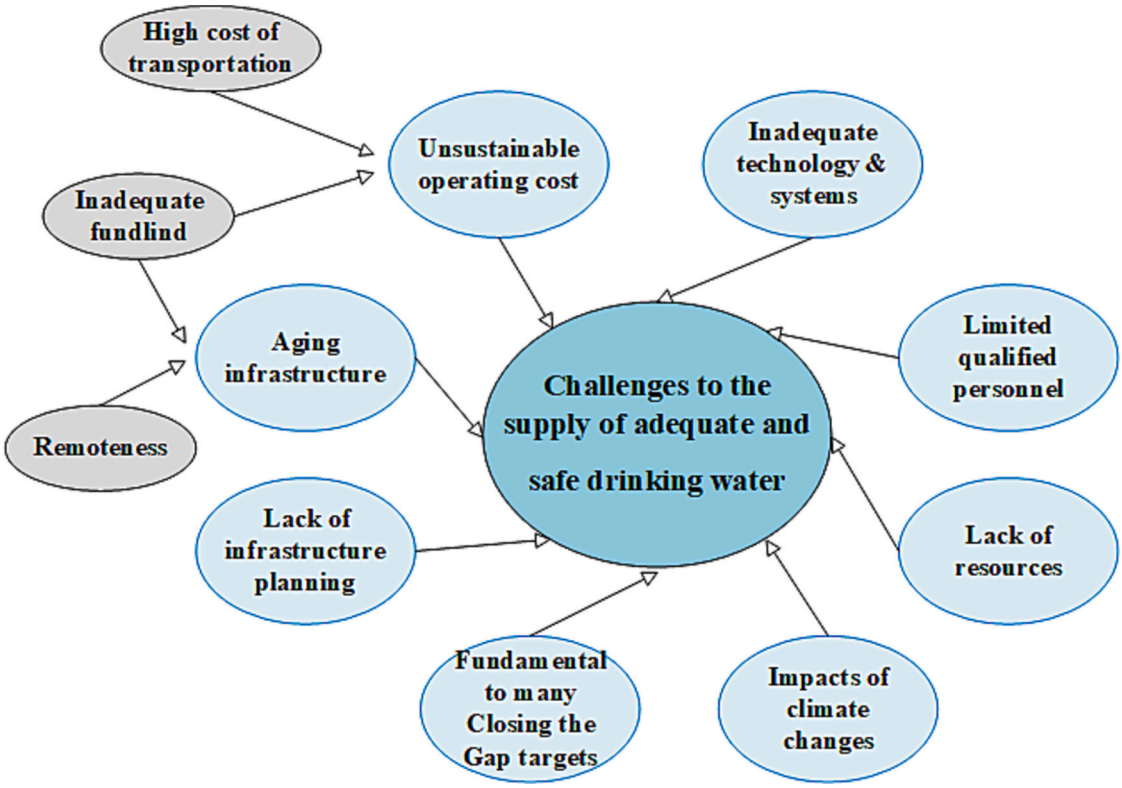

Fig. 4. Challenges to supplying of safe and potable water in remote Australia (Water Services Association of Australia, 2022a).

infrastructure and service provision. Besides, Power and Water has an approved Safe Water Plan that follows the Australian Drinking Water Guidelines and uses a risk-based approach. The plan is a three-year (2019–2022) improvement journey. The plan focuses on four main initiatives, which include understanding customer expectations, ensuring safe water supply schemes, continuously improving the Drinking Water Quality Management System, and ensuring reliable and sustainable operation performance (Power and Water Corporation., 2021).

The National Water Grid Fund collaborates with the Northern Territory Government to allocate $150 million for water infrastructure projects in First Nations communities, ensuring equitable access to safe water (National Water Grid, 2023a). The selection process prioritizes projects with the highest net benefit and encourages collaborative efforts. Alignment with National Water Initiative Principles and proactive engagement with First Nations are key factors, ensuring consistency and robust outcomes in decision-making (National Water Grid, 2023b).

Addressing sporadic elevated concentrations of manganese and iron in Georgetown's water supply in Queensland, a treatment facility was established between March and May of 2015 (Etheridge Shire Council., 2022). Subsequent data from Georgetown's water treatment process demonstrates the efficacy of the advanced filtration system in diminishing turbidity, as well as iron and manganese levels. While these contaminants are inherently present in the untreated water source, their effects and concentrations have been exacerbated by the scarcity of precipitation (Rajapakse et al., 2017).

The office of Auditor General Western Australia published the Delivering Essential Services to Remote Aboriginal Communities –Follow-up report with the changes made since 2015. In total, 37 communities under the Remote Aboriginal and Torres Strait Islander Environmental Health Program (RAESP) have been equipped with new water treatment assets. Out of these, 28 communities had chlorine systems installed while 10 others received ultra-violet disinfection units. In Cosmo Newberry, Jameson, Jigalong, and Tjuntjuntjara, reverse osmosis systems were installed to ensure a clean water supply. Moreover, the existing water assets in three communities were improved by upgrading a part of the asset. To ensure water safety, the Department implemented water safety management plans in 2016 which are now operational in 34 communities. These plans include bore management which involves blending water from different sources to achieve the desired volume while ensuring that the chemical levels of nitrates and uranium remain within safe limits (Office of the Auditor General Western Australia, 2021).

Furthermore, regulatory bodies oversee essential services across different Australian states. The Economic Regulation Authority safeguards consumer interests in Western Australia for water, electricity, gas, and rail (Economic Regulation Authority, 2023). The Queensland Competition Authority handles monopoly infrastructure pricing in Queensland (Queensland Competition Authority, 2023). The Essential Services Commission of SA regulates water retail pricing in South Australia (Essential Services Commission of SA, 2023). In Northern Territory, the Utilities Commission ensures fair pricing, reliability, and quality (Utilities Commission Northern Territory, 2023). Similarly, the Essential Services Commission focuses on long-term consumer interests in essential services in Victoria (Essential Services Commission, 2023). IPART ensures fair pricing for safe and reliable services in NSW (IPART NSW, 2023). These authorities play a crucial role in establishing water prices and licensing, enforcing regulations, and overseeing water supply and sewerage service sectors while advocating for the welfare of water consumers.

In a broader context, the Productivity Commission evaluates advancements aligned with the National Water Initiative (NWI), offering recommendations and direction to address challenges related to costs, quantity, and quality in regional and remote regions (Productivity Commission, 2021b).

7. Discussion

Access to clean and safe water is essential for maintaining human health, but Indigenous communities worldwide face significant challenges due to poverty, limited access to services, and compromised water quality. In the United States, Indigenous populations face water-related challenges caused by social factors such as poverty, Indigenous identity, low education, and advanced age. Canada's Indigenous communities also face issues ranging from declining water quality to regulatory obstacles and inadequate assistance, with boil water advisories persisting for decades. Similarly, Indigenous communities in New Zealand face various water-related issues. Although there are remediation measures established in each and every community, the current methods of addressing water security in First Nations communities faces challenges related to governance, decision-making, and financial sustainability. Also, limited community participation, neglect of cultural aspects, and a focus on technical solutions hinder progress. Similarly, it is important to prioritize research on Indigenous preferences and promote co-design through pilot projects and knowledge sharing.

The provision of safe and reliable drinking water in remote and indigenous communities in Australia is a complex and ongoing challenge. Aboriginal settlements, which have replaced traditional nomadic lifestyles, are often located in remote areas and rely on groundwater accessed through boreholes. However, this groundwater is susceptible to both microbial and chemical contamination. Microbial risks arise from the lack of infrastructure maintenance and poor hygiene practices, leading to waterborne illnesses. Chemical contamination, including high levels of uranium, arsenic, fluoride, nitrate, manganese, iron, and microbial contaminants, exceeds the thresholds set by the Australian Drinking Water Guidelines (ADWG). Prolonged exposure to these substances can have severe health consequences. Climate change further exacerbates the situation by causing saltwater intrusion, concentrated pollutants in water sources, droughts, and reduced groundwater recharge. This leads to altered water quality, increased salinity levels, and the potential for algal blooms, impacting both the direct and indirect health of communities.

A comprehensive analysis of drinking water quality in Queensland reveals concerning trends, with many rural and remote councils exceeding recommended limits for various parameters. High conductivity, hardness, turbidity, fluoride content, iron, and manganese levels pose significant challenges to water quality. Addressing these issues requires further investigation into the sources of contamination and the implementation of appropriate treatment measures. Similar challenges exist in other regions, such as New South Wales and Western Australia, where contaminants like hardness, fluoride, turbidity, and total dissolved solids (TDS) remain a concern. Inadequate water supplies in rural communities can lead to the consumption of sugar-sweetened beverages, contributing to adverse health effects, particularly among Indigenous populations. In Western Australia, nitrate and uranium contamination in groundwater is prevalent, while the quality of drinking water in certain regional towns consistently falls short of ADWG standards. Improved assets and water management plans have shown positive effects, but the challenges of microbial contamination, high nitrates, and uranium levels persist. The Northern Territory also faces issues with manganese, barium, antimony, uranium, and fluoride in drinking water. Changes in aesthetic parameters can also affect people's willingness to consume water, potentially leading to dehydration and related health complications.

To address these issues, it is crucial to sustain the delivery of clean and safe drinking water and adequate sanitation to rural and remote Indigenous communities. This requires coordinated efforts to address biological, chemical, and environmental challenges, including consistent water quality testing, adequate funding, addressing governance structures, using technology fit for purpose, and understanding cultural and historical aspects of the communities. Policy initiatives seeking to improve drinking water services should consider cultural and

geographic contexts and incorporate training, improvements to source water quality, and other non-capital investments. Collaborating with land councils to adopt a strategic, transparent, and risk-based approach to water infrastructure and service provision is also recommended to rectify structural inequalities. Coordinated efforts are necessary to ensure the provision of clean and safe drinking water to remote and Indigenous communities, which is essential to improve health outcomes and promote social equity.

8. Conclusion and future research need

In conclusion, the provision of clean and safe drinking water to remote and Indigenous communities remains a complex and ongoing challenge worldwide. Indigenous populations in various countries, including the United States, Canada, and New Zealand face significant water-related issues, ranging from poor water quality to regulatory obstacles and limited access to services. In Australia, Aboriginal settlements in remote areas rely on groundwater that is susceptible to microbial and chemical contamination, posing risks to community health. Climate change further compounds these challenges by altering water quality and availability.

The analysis of drinking water quality in Queensland and other regions of Australia reveals concerning trends, with many rural and remote councils exceeding recommended limits for various parameters. Addressing these issues requires further investigation, source identification, and the implementation of appropriate treatment measures. The consumption of sugar-sweetened beverages due to inadequate water supplies exacerbates health concerns, particularly among Indigenous populations. Nitrate and uranium contamination, as well as aesthetic parameter changes, further contribute to the complexity of the situation in different regions.

While some recommendations may have global applicability, the overall study highlights the importance of understanding unique challenges within the specific context of indigenous populations. The intricate interplay of cultural practices, isolation, and historical factors shapes water quality issues for indigenous communities, necessitating tailored strategies that consider technical, scientific, and cultural aspects. The study emphasizes the need for solutions that are not only effective but also sensitive to the unique circumstances and perspectives of indigenous groups, ultimately aiming for equitable and sustainable improvements in water quality.

Looking ahead, future researchers must not only sustain the delivery of clean and safe drinking water to rural and remote Indigenous communities but also explore the implementation of innovative water treatment methods to address the identified parameters impacting water quality. By introducing a suitable water treatment method, it is possible to mitigate microbial and chemical contamination, thus improving the overall water quality and safeguarding the health of community members. Future research should focus on identifying and evaluating effective water treatment technologies that are specifically tailored to the needs and challenges of Indigenous communities. These technologies should address some or many of a range of parameters such as microbial risks, high levels of uranium, arsenic, fluoride, nitrate, manganese, iron, and other contaminants that exceed recommended thresholds. Furthermore, research should aim to develop cost-effective and sustainable treatment solutions that can be easily implemented and maintained in remote and resource-limited settings. By integrating innovative water treatment methods into existing water management strategies, Indigenous communities can benefit from improved access to clean and safe drinking water, leading to better health outcomes and enhanced social equity.

CRediT authorship contribution statement

- Conceptualisation (all), Literature review (all), Data collection and analysis (KB, JR), Writing and drafting (KB), Critical revision (JR, CG), Addressing the revisions (KB), Supervision (JR, CG), Finalising the manuscript (all)

Name	Contribution
B. M. J. K. Balasooriya	• Conceptualisation • Literature review • Data collection and analysis • Writing and drafting • Addressing the revisions • Finalising the draft
Jay Rajapakse	• Conceptualisation • Literature review • Data collection and analysis • Critical revision • Supervision
Chaminda Gallage	• Conceptualisation • Literature review • Critical revision • Supervision

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Corrigendum

Corrigendum to "A review of drinking water quality issues in remote and indigenous communities in rich nations with special emphasis on Australia" [Sci. Total Environ. 903 (2023) 1–17/166559]

B.M.J. Kalpana Balasooriya [a], Jay Rajapakse [b,*], Chaminda Gallage [a]

[a] School of Civil and Environmental Engineering, Faculty of Engineering, Queensland University of Technology (QUT), Brisbane, QLD 4001, Australia
[b] School of Civil and Environmental Engineering, Faculty of Engineering, Queensland University of Technology (QUT), 2 George Street, GPO Box 2434, Brisbane, QLD 4001, Australia

The authors regret that the printed version of the above article contained errors due to attributing all of the "South Australia" water quality data to "New South Wales" instead of South Australia. Therefore, drinking water quality data refereeing to "New South Wales (NSW)" should be replaced with "South Australia (SA)". The caption of Section 5.2.2 should read as "South Australia" and in the second line "New South Wales (NSW)" replaced with "South Australia (SA)". The correct and final version follows.

5.2.2. South Australia

Based on the data collected from 18 water supply systems in remote aboriginal communities in South Australia, it is evident that there are still water quality issues despite the presence of treatment measures. The data presented in Table 3 demonstrates that the concentration of certain contaminants, such as hardness, fluoride, turbidity, and total dissolved solids (TDS), continue to be a concern for consumers at the tap. Additionally, it is important to note that there has been an increase in turbidity levels at the consumer tap in recent years 2021–22 (SA Water Corporation, 2020, SA Water Corporation, 2022).

The paragraph two under Section 5.2.2 about New South Wales is correct although it is now not relevant under "South Australia". Therefore, it should be read following paragraph 8 under Section 5.2. The caption of Table 3 should read as "Changes in remote aboriginal community source water quality and consumer tap water quality in South Australia against ADWG (SA Water Corporation, 2020, 2022)."

"New South Wales" under paragraph three of Section 7 should read as "South Australia".

The third bullet point of 'highlights' should read as:

- High levels of hardness, fluoride, turbidity, and TDS in South Australia

In the Abstract and the Graphical Abstract, data referred under NSW should be read under SA. The updated Graphical abstract is as follows.

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* Corresponding author.
E-mail address: jay.rajapakse@qut.edu.au (J. Rajapakse).

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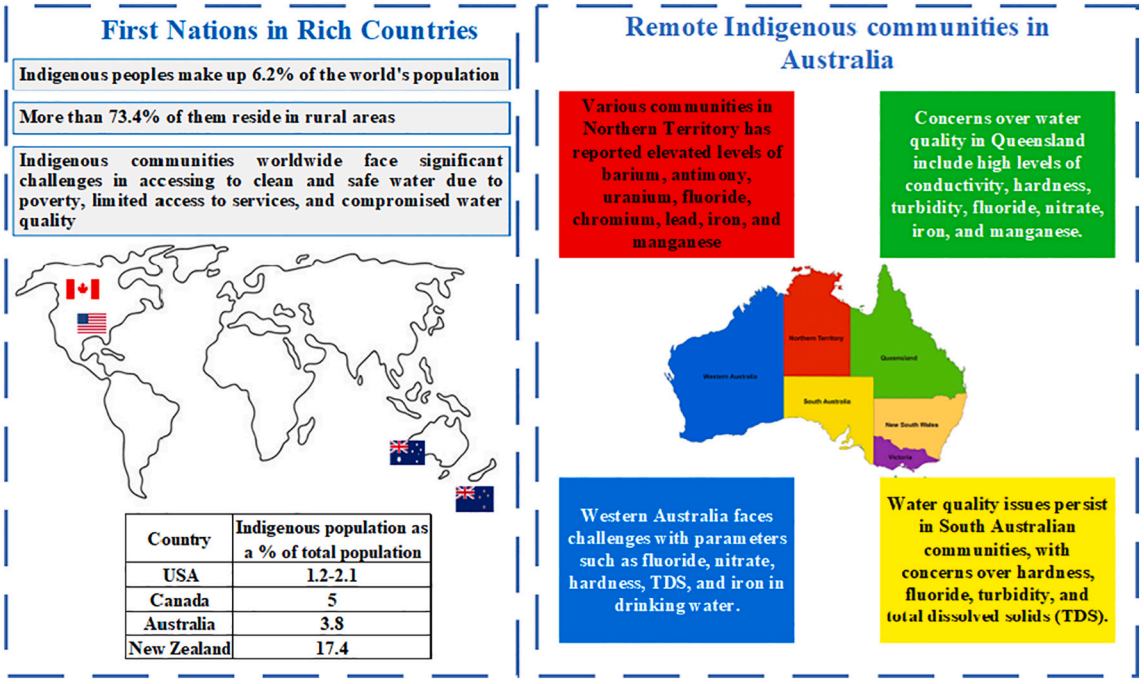

The authors would like to apologise for any inconvenience caused.