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Measuring the gaps in drinking water quality and policy across regional and remote Australia

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Drinking water quality remains a persistent challenge across regional and remote Australia. We reviewed public reporting by 177 utilities and conducted a national assessment of reported exceedances against the health-based and aesthetic guideline values of the Australian Drinking Water Guidelines (ADWG). Four definitions of a basic level of drinking water quality were tested to quantify service gaps across regional and remote areas of each subnational jurisdiction in 2018–2019. At least 25,245 people across 99 locations with populations <1000 reportedly accessed water services that did not comply with health-based guideline values. Including larger towns and water systems, the estimated service gap rises to at least 194,572 people across more than 115 locations. Considering health parameters and the ADWG definition of 'good' aesthetic characteristics, the reported service gap rises further to at least 627,736 people across 408 locations. Forty percent of all locations with recorded health exceedances were remote Indigenous communities. Monitoring and reporting gaps indicate that the actual incidence of non-compliance with the guideline values of the ADWG could be much higher than our estimates. Our results quantified the divergence in the assessment of water quality outcomes between Sustainable Development Goal Target 6.1 and the ADWG, demonstrated disparities between service levels in capital cities and the rest of Australia, and highlighted the need for place-based solutions. The methods and dataset provide a 'proof-of-concept' for an Australian national drinking water quality database to guide government investments in water services.

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INTRODUCTION

The United Nations 2021 Sustainable Development Report indicates that Australia has achieved Sustainable Development Goal (SDG) Target 6.1[1]. Notwithstanding high service standards in large cities and the resolution of several recurring boil water alerts in recent years (e.g.[2,3]), 'universal and equitable access to safe and affordable drinking water for all' does not yet exist across Australia[4–6]. Poor drinking water quality and access remain barriers to improved health and economic outcomes in many Australian regional and remote communities[7–9].

Australia's gaps in drinking water quality are not unique among high-income countries that are reportedly close to or already achieving SDG Target 6.1. For example, deficiencies in safe water access have resulted in the following: at least US$15 billion legislated to replace lead pipes and control water contamination in the United States[10]; C$7.6 billion in actual and planned spending to end 162 long-term boil water advisories and improve water and wastewater systems in First Nations communities in Canada[11]; and NZ$3.6 billion to upgrade New Zealand's water networks and overhaul policy and regulatory frameworks[12].

Major public investments in Australia's drinking water infrastructure have been identified as a national policy priority[13–15]. In the context of that reform agenda, the Productivity Commission (PC) – the Australian federal government's independent advisory agency on economic, social, and environmental reform – recommended that subsidies to water suppliers in high-cost locations should be designed to ensure affordable access to a 'basic level of service' that, at a minimum, includes safe and reliable drinking water[6]. This 2021 PC recommendation is supported by organisations representing Indigenous peoples[16], health and community service providers[17,18], water utilities[19], and local governments[20].

The Australian Drinking Water Guidelines (ADWG) provide the national framework for describing, managing, and monitoring drinking water quality[21]. Although they are not mandatory national standards, ADWG health-based and aesthetic guideline values for microbial, physical, and chemical characteristics provide a basis for state and territory government water quality regulations (e.g.[22,23]), industry norms for external reporting (e.g.[24]), and federal government water policy (e.g.[25,26]). The ADWG specify that guideline values should inform short- and long-term monitoring of service improvements, with the key performance measure being no detection of E. coli in the distribution system. Health-based guideline values for chemical parameters are conservatively estimated and most, but not all, relate to life-time exposure. Aesthetic guideline values for physical characteristics ensure "good quality water – that is, water that is aesthetically pleasing and safe, and that can be used without detriment to fixtures and fittings"[21]. Notably, the focus of the ADWG on *good* aesthetic quality represents a higher standard than the guidelines of the World Health Organisation which emphasise *acceptable* quality[27]; in practice, this is reflected in Australian guideline values being *lower* than most other countries for some key aesthetic parameters, including hardness, sodium, and total dissolved solids[28].

Section 3.10.2 of the ADWG state that water suppliers should produce an annual public report summarising performance against numerical guideline values to support evaluation of service improvements and "ensure that drinking water quality management is open and transparent"[21]. In terms of monitoring, the ADWG highlight that "it is neither physically nor economically feasible to test for all drinking water quality parameters equally"[21]. Instead, monitoring should focus on key health-based and aesthetic characteristics, including potential contaminants identified in water system and hazard analysis. In practice, state and

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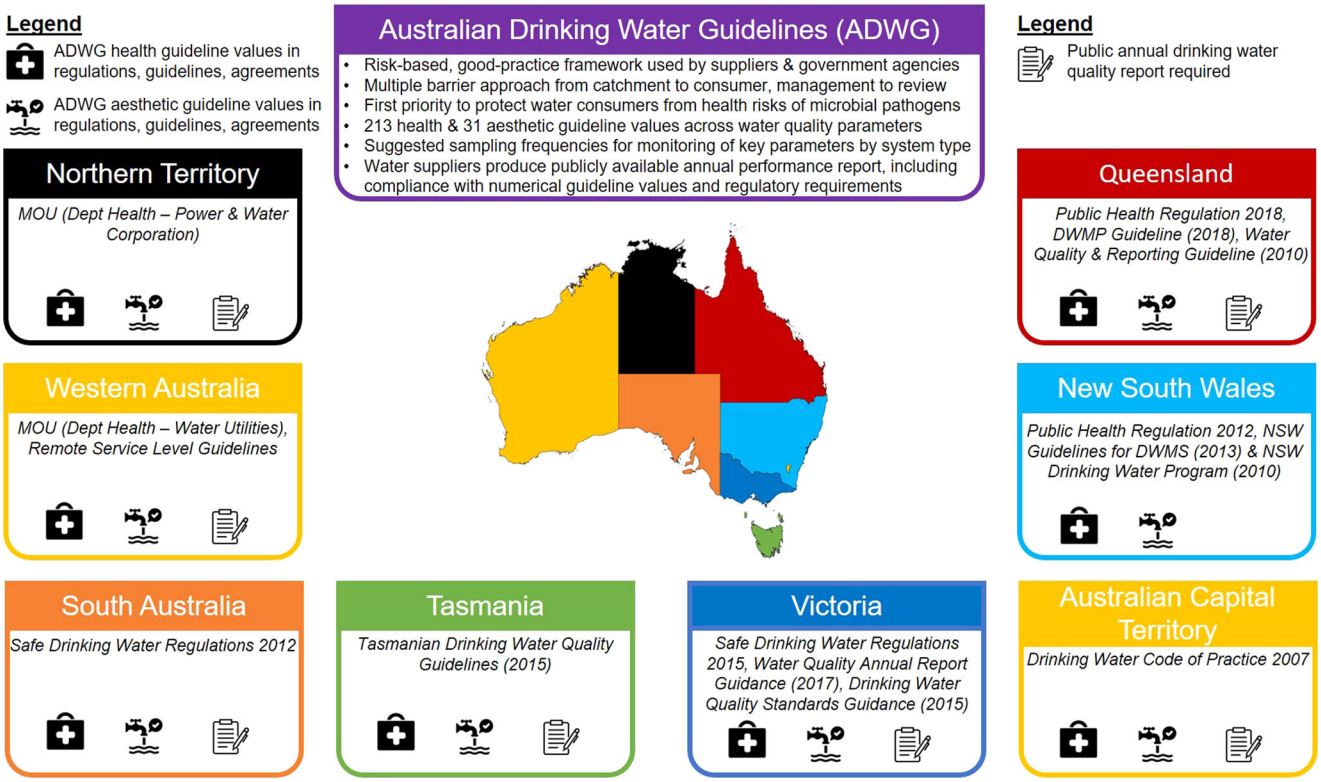

Fig. 1 Overview of monitoring and reporting under the Australian Drinking Water Guidelines and state/territory regulatory frameworks. Text in italics indicates regulatory documents referencing ADWG guideline values. Whether meeting health-based guideline values is mandatory varies across jurisdictions, parameters, and by the type of water supplier. Aesthetic guideline values are typically incorporated as non-mandatory objectives and/or reporting requirements only, except for turbidity in Victoria. Minimum standards for tested parameters and sampling frequencies may be specified across all suppliers in a jurisdiction or determined through tailored monitoring plans. New South Wales is the only jurisdiction where public annual reports are not a formal requirement; for other jurisdictions, non-public annual reporting to regulators only is typically required for water carters and very small suppliers. Icons downloaded from the Noun Project (https://thenounproject.com/) using a NounPro for EDU Subscription.

Table 1. Drinking water quality summary statistics in Australia's Urban National Performance Report, 2018–19.

Indicator	Results summary
'Percentage of population where microbiological compliance was achieved'	100% for 83 water suppliers; 98.9% and 99% for 2 water suppliers
'Number of zones where chemical compliance was achieved'	All zones in 68 water suppliers; average of 88.8% of zones across 17 water suppliers where non-compliances occurred
'Water quality guidelines'	79/85 water suppliers confirmed that either Australian Drinking Water Guidelines or state/territory regulatory guidelines in use
'Risk-based water management plan externally assessed'	55 water suppliers answered 'Yes'; 30 suppliers answered either 'No', 'Not applicable', and/or indicated the date of next external audit required by regulation
'Number of water quality complaints per 1,000 properties'	Average across 78 reporting water suppliers = 2.1; median = 1.4; maximum = 14.4

Source data from the Urban National Performance Report[30].

territory regulations or regulatory bodies specify guideline values which water suppliers must report against and any specific requirements or exemptions relevant to particular water systems (e.g.[29]). Figure 1 summarises the role of guideline values in the ADWG and the adoption of annual reporting across jurisdictional regulatory frameworks.

Despite widespread monitoring and reporting against ADWG health-based and aesthetic guideline values, data collation at the national level is incomplete. The Urban National Performance Report (NPR)[30] – the annual review used to report against SDG Target 6.1 – encompasses the 85 utilities and other suppliers of drinking water that serve more than 10,000 connections. The most recent figure from Australia's SDG reporting – 98% of the population using 'safely managed drinking water services' in 2017[31] – does not cover people accessing water from smaller utilities and suppliers nor private supplies. Approximately two million people, or 8% of Australia's population, are thereby unrepresented in national statistics for drinking water access. Five of the 166 Urban NPR indicators directly concern drinking water quality (see Table 1 for an overview and 2018–2019 values).

At the sub-national level, there is a wealth of detailed annual reporting against ADWG health-based and aesthetic guideline values in the service areas of major utilities and all capital cities except Sydney (see[32–37]). Outside these areas, public reporting can be fragmented, as in the case of Australia's most populous state (New South Wales) where regional drinking water quality data is recorded in a centralised government database that is not publicly accessible (see[38]), utilities are not required to publish annual reports, and the most comprehensive data are summary statistics for each local water utility on health-based microbial and chemical ADWG compliance[39]. Monitoring and reporting gaps are prevalent in very remote areas across Australia. For example, a 2021 audit found that the Western Australian government agency supplying remote water services did not conduct any routine drinking water quality testing in 51 small Indigenous communities[40].

Greater transparency and public accountability could support more effective delivery of government programs. In 2020, the Audit Office of New South Wales found that the responsible government department had not effectively supported regional town water infrastructure planning since at least 2014, lacked an evidence-based approach to investment decisions, and "lack of internal procedures, records and data mean that the department cannot demonstrate it has effectively engaged, guided or supported [local water utility planning]"[41]. Unsafe and insecure access to water services in remote Indigenous communities remain a widely recognised national policy issue (e.g.[6,14,40]) despite government inquiries[42–45], academic research[7,46–51], and media reporting[52–57] across decades. Many factors can contribute to this complex policy challenge. High operating costs, harsh environmental conditions, remoteness, and barriers to collaborative management (see[49] for a review) are amplified by the historical and ongoing prevalence of Indigenous water injustice in Australian water policy[9,58–62]. In terms of guiding policy to improve water services in remote locations, the establishment of quantitative community service indicators is a significant recent reform of the national initiative to address disparities in life outcomes between Indigenous and non-Indigenous people[63]. Federal government agencies have also highlighted the need for better monitoring and reporting to guide public investments in expanding access to safe and reliable drinking water services[6,14].

This paper assesses the publicly available data, highlights key data gaps, and quantifies the populations and locations where reported drinking water quality did not meet basic levels of service defined in relation to the ADWG. First, we outline four possible approaches to defining basic levels of drinking water quality in the Australia context. Second, we construct a national dataset of exceedances against ADWG health-based and aesthetic guideline values from reporting data across 177 utilities for the financial year 2018–19. Third, we match water quality, population, and location data to estimate the number of people and locations by state or territory jurisdiction where basic levels of service were not met at least once. Fourth, we examine the data to identify key health and aesthetic exceedances, contrast outcomes between capital cities and remote Indigenous communities, and highlight the data gaps. We conclude with a summary of the study's limitations and the steps toward establishing a publicly accessible national drinking water quality database for Australia.

RESULTS

Definitions of a basic level of drinking water quality

We provide four alternative definitions of a basic level of drinking water quality with reference to the ADWG and SDG Target 6.1 indicators:

1. *'Sustainable Development Goal (SDG) 6.1'* – Water quality results do not exceed ADWG health-based guideline values and any associated state/territory annual compliance standards across all reported samples of the fecal contamination (E. coli) and 2 priority chemical (arsenic, fluoride) parameters specified by the WHO/UNICEF JMP for SDG Target 6.1 monitoring (excluding false positives);
2. *'ADWG Health' - Compliance with all ADWG health-based guideline values* – Water quality results do not exceed ADWG health-based guideline values and any associated state/territory compliance targets for all reported samples across the microbial contamination performance measure (E. coli), 212 chemical parameters, and radiological quality (excluding false positives);
3. *'ADWG Good' - Compliance with all ADWG health-based guideline values and the ADWG aesthetic guideline values for physical characteristics beyond which the quality of the water might no longer be regarded as 'good' – ADWG Health* definition plus the mean annual results for 6 physical characteristics (true colour, turbidity, hardness, total dissolved solids (TDS), pH, dissolved oxygen) across reported samples do not exceed aesthetic guideline values;
4. *'Metropolitan' - Compliance with all ADWG health-based and aesthetic guideline values – ADWG Good* definition plus the mean annual results for 25 chemical parameters (e.g. chlorine, sodium, iron, manganese, chloride) across reported samples do not exceed the higher of: (i) the corresponding ADWG aesthetic guideline value, or (ii) the highest mean value reported for the capital city of the corresponding state/territory jurisdiction.

The *SDG 6.1* definition supports assessment of how Australia-wide reporting of access to 'safely managed water services' under the Sustainable Development Goals might change if available data from smaller water suppliers were included in national reporting. The *ADWG Health* definition provides insights into the number of people and locations where public investments may be required to ensure a basic level of drinking water quality focused only on health parameters. Note that the inclusion of jurisdictional compliance targets integrates existing approaches to a 'basic level of service' (e.g. E. coli. annual compliance of 99.8% in South Australia, 98% in Tasmania and Queensland).

The *ADWG Good* definition reflects the ADWG definition of 'good' water quality and the emphasis in the guidelines on water suppliers meeting consumer expectations. In practice, accounting for aesthetic considerations in defining basic service levels is necessary because: (i) unpalatable water affects consumer risk perceptions, potentially leading to indirect health impacts from accessing unsafe alternative sources of hydration[48,64,65], including sugary drinks[66,67]; (ii) buying bottled or trucked water due to distrust of water services[68,69] is a financial burden for low-income households inconsistent with affordable access; and (iii) high levels of hardness and TDS may affect water infrastructure integrity, operational costs, and safety[70]. Note that the ADWG definition of 'good' water also includes 'taste and odour' which is specified as "not offensive to most people"[21]. This characteristic does not have an assigned numerical value as non-compliance can have numerous causes, including the presence of micro-organisms in raw water.

The *Metropolitan* definition provides a benchmark for assessing the gap in drinking water quality between regional/remote areas and capital cities – where most of Australia's population lives and non-compliance with aesthetic guideline values rarely occurs. Given that any reported monitoring against all guideline values is incorporated into this definition, it provides an upper bound for a basic level of drinking water quality that reflects the breadth of criteria defined by the ADWG.

Table 2. Population and number of locations in regional and remote Australia reported to lack access to the 'SDG 6.1' definition of a basic level of drinking water quality.

State/territory jurisdiction	Locations with <1000 population	Locations with 1000–10,000 population	Locations with >10,000 population	All locations
Northern Territory	950 [4]	0	0	**950** [4]
Queensland	2,835 [8]	0	0	**2835** [8]
South Australia	3082 [8]	9623 [2]	15,265 [1]	**27,970** [11]
Tasmania	0	0	0	0
Victoria	640 [1]	8350 [1]	0	**8990** [2]
Western Australia	424 [10]	0	0	**424** [10]
TOTAL	**7931** [31]	**17,973** [3]	**15,265** [1]	**41,169** [35]
New South Wales	?	?	?	?

Number of locations are indicated in square brackets. Totals are highlighted in bold and do not include New South Wales. Source data and calcuations are available from the supplementary dataset[111].

Table 3. Population and number of locations in regional and remote Australia reported to lack access to the 'ADWG Health' definition of a basic level of drinking water quality.

State/territory jurisdiction	Locations with <1000 population	Locations with 1000–10,000 population	Locations with >10,000 population	All locations
Northern Territory	4444 [13]	0	0	**4444** [13]
Queensland	7044 [24]	10,515 [5]	100,185 [4]	**117,744** [33]
South Australia	7710 [25]	14,928 [5]	15,265 [1]	**37,903** [31]
Tasmania	836 [2]	0	0	**836** [2]
Victoria	740 [2]	8,350 [1]	0	**9.090** [3]
Western Australia	4,471 [33]	0	0	**4471** [33]
TOTAL	**25,245** [99]	**33,793** [11]	**115,450** [5]	**174,488** [115]
New South Wales	?	?	?	**20,084** [?]

Number of locations are indicated in square brackets. Totals are highlighted in bold and do not include New South Wales. Source data and calcuations are available from the supplementary dataset[111].

Service gaps by population, location, and jurisdiction

Tables 2–5 provide a breakdown of the exposed population and number of locations where public reporting indicates that basic levels of drinking water quality were not met at least once during the 12-month reporting period. Overall, we estimated that at least 194,572 people across regional and remote areas of Australia accessed water supply systems that did not meet the *ADWG Health* level of service in 2018–2019. The detailed analysis that follows does not include New South Wales due to limited data availability for that jurisdiction (see Methods section for further details).

Excluding New South Wales, we estimated that at least 174,488 people in 115 locations were exposed to non-compliance with the *ADWG Health* benchmark. Incorporating aesthetic parameters, these estimates increased to at least 627,736 people in 408 locations (*ADWG Good*) or at least 1.4 million people in 819 locations (*Metropolitan*). By contrast, only an estimated 41,169 people in 35 locations where data were available did not have access to water services meeting the *SDG 6.1* definition. For context, these population estimates equate to at least 0.7% (*SDG 6.1*), 3.1% (*ADWG Health*), 11.1% (*ADWG Good*), and 25.0%

Table 4. Population and number of locations in regional and remote Australia reported to lack access to the 'ADWG Good' definition of a basic level of drinking water quality.

State/territory jurisdiction	Locations with <1000 population	Locations with 1000–10,000 population	Locations with >10,000 population	All locations
Northern Territory	18,258	14,721	23,726	**56,705**
	[61]	[8]	[1]	[70]
Queensland	16,816	34,554	225,739	**277,109**
	[56]	[12]	[6]	[74]
South	35,730	71,966	45,958	**153,654**
Australia	[110]	[26]	[3]	[139]
Tasmania	836	0	0	**836**
	[2]			[2]
Victoria	6148	21,460	0	**27,608**
	[16]	[4]		[20]
Western Australia	20,032	20,016	71,776	**111,824**
	[90]	[10]	[3]	[103]
TOTAL	**97,820**	**162,717**	**367,119**	**627,736**
	[335]	[60]	[13]	[408]
New South Wales	?	?	?	?

Number of locations are indicated in square brackets. Totals are highlighted in bold and do not include New South Wales. Source data and calcuations are available from the supplementary dataset[111].

Table 5. Population and number of locations in regional and remote Australia reported to lack access to the 'Metropolitan' definition of a basic level of drinking water quality.

State/territory jurisdiction	Locations with <1000 population	Locations with 1000–10,000 population	Locations with >10,000 population	All locations
Northern Territory	22,545	21,024	23,726	**67,295**
	[72]	[9]	[1]	[82]
Queensland	20,671	94,296	471,625	**586,592**
	[73]	[29]	[10]	[112]
South	72,142	126,985	110,899	**310,026**
Australia	[328]	[48]	[7]	[383]
Tasmania	9046	32,933	11,040	**53,019**
	[26]	[9]	[1]	[36]
Victoria	23,406	109,957	138,494	**271,857**
	[57]	[34]	[7]	[98]
Western Australia	20,833	22,697	71,776	**115,306**
	[93]	[12]	[3]	[108]
TOTAL	**168,643**	**407,892**	**827,560**	**1,404,095**
	[649]	[141]	[29]	[819]
New South Wales	?	?	?	?

Number of locations are indicated in square brackets. Totals are highlighted in bold and do not include New South Wales. Source data and calcuations are available from the supplementary dataset[111].

(*Metropolitan*) of the approximately 5.7 million people living outside capital cities in 2018–19.

We reported the number of locations alongside population estimates and partitioned the results by location size because one exceedance in larger water systems can strongly influence total population estimates. For example, exceedances for trihalomethanes and chlorine in two regional Queensland centres (populations of 52,073 and 22,206) were the primary source of the total population estimates for the *ADWG Health* definition. Similarly, 99.6% annual E. coli compliance across 8 towns within a regional water supply system dominated the results for the *SDG 6.1* level of service in South Australia and overall. The removal of that single exceedance from the sample would reduce the Australia-wide exposed population for the *SDG 6.1* definition from 41,169 to 13,324, but not the corresponding estimate for the *ADWG Health* benchmark because only 72.8% of samples from that system complied with the guideline value for trihalomethanes in 2018–19.

We highlight that 33 health exceedances were not included in the assessments of service level coverage where either the water

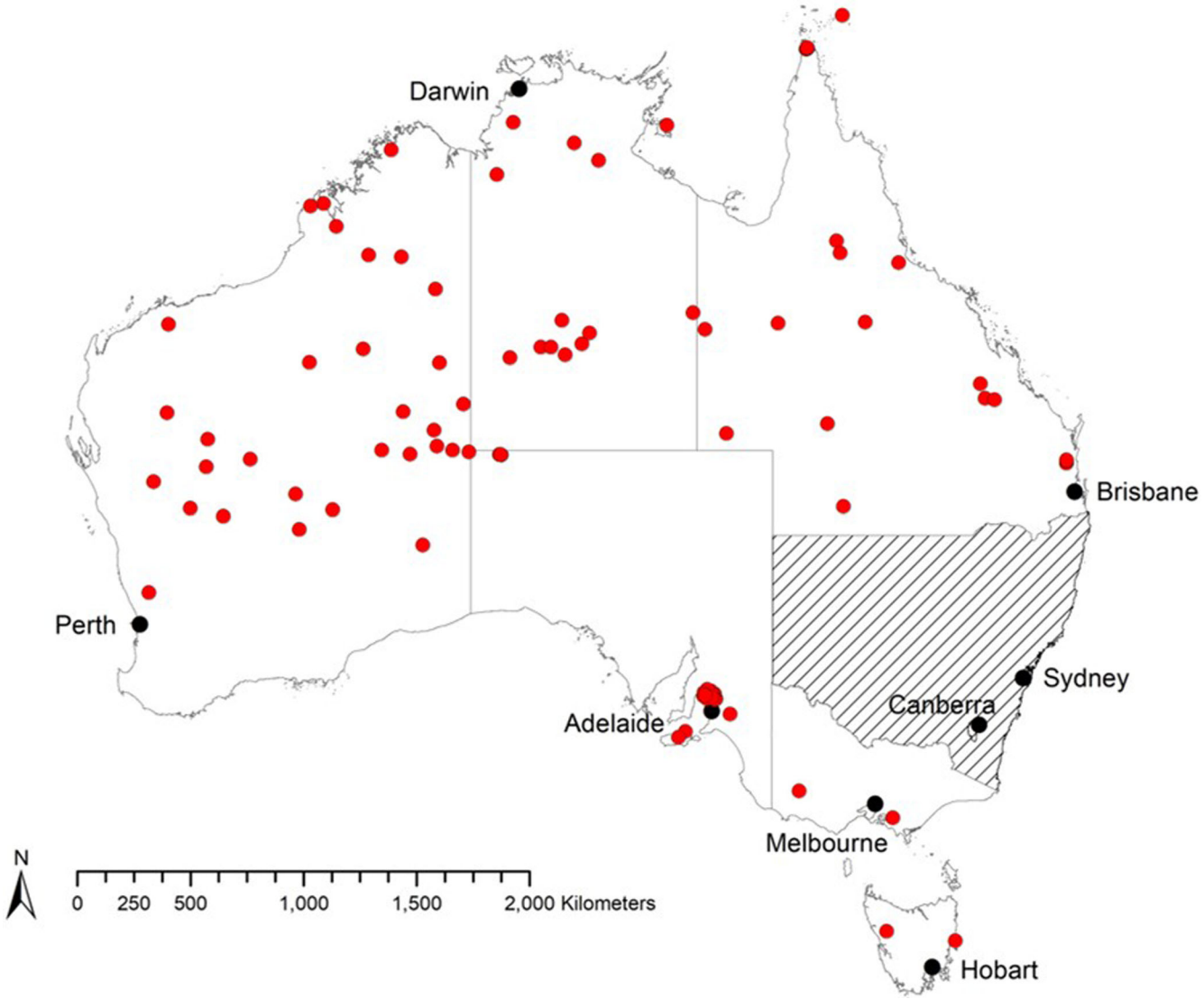

Fig. 2 Locations in regional and remote Australia where at least one exceedance against health-based guideline values of the Australian Drinking Water Guidelines occurred in 2018–2019. New South Wales shaded due to lack of information on location, parameter, and exact values associated with reported exceedances. Locations not shown where a single exceedance was reported as a false positive or total exceedances did not lead to non-compliance with annual jurisdictional compliance targets.

supplier demonstrated that the sample was a false positive, jurisdictional compliance targets were not breached across the annual reporting period, or the cause may have been a data entry error. The very high population estimates for lack of access to the *Metropolitan* benchmark was because of the prevalence of chlorine samples exceeding odour thresholds. Removing that parameter from the latter definition would reduce the exposed population to 634,879 people across 422 locations.

Notably, 99 of the 115 locations where residents accessed a water system reportedly not achieving the *ADWG Health* benchmark were smaller towns and settlements with less than 1,000 people (Fig. 2), and 62 of these are classified as 'Remote' or 'Very Remote' by the Australian Bureau of Statistics (ABS) Remoteness Area classification[71]. Across jurisdictions, the estimated populations where basic levels of drinking water quality were reportedly not achieved varied markedly according to different definitions (Fig. 3). Overall, the most common exceedances against health-based guideline values were for trihalomethanes, nitrate, E. coli, and fluoride (Fig. 4). Aside from chlorine and pH, the most common aesthetic exceedances involved hardness, sodium, and TDS; Fig. 5 shows the range in reported exceedances for those three parameters.

Geographic gaps

We identified 4 health exceedances across water systems serving approximately 10.2 million people in Australian state and territory capital cities in 2018–19 (not including Sydney). This estimate does not include 7 E. coli exceedances that did not result in non-compliance with an annual jurisdictional target. A total of 18 aesthetic exceedances were identified, including 16 for chlorine and 2 for TDS.

The high service levels observed in capital cities contrast with outcomes in those remote Indigenous communities where drinking water quality was monitored and reported. Table 6 presents a summary of reported health and aesthetic exceedances across those communities. For the *ADWG Health* definition, the 48 exposed communities comprised 40% of all locations across Australia where that benchmark was reportedly not achieved.

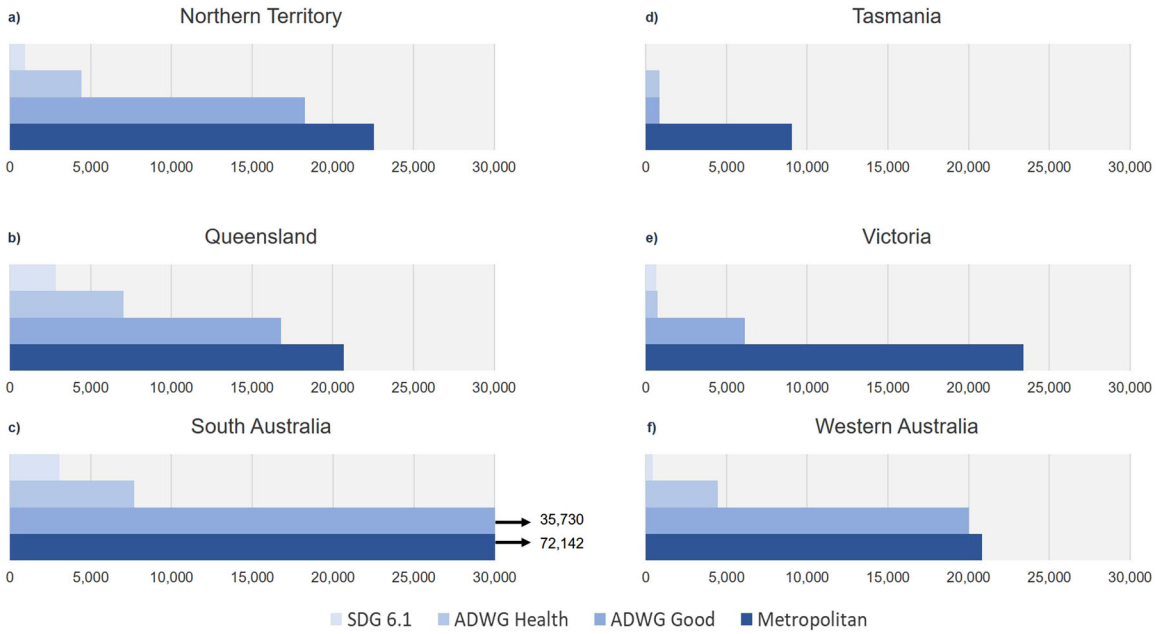

Fig. 3 Estimated populations of Australian state/territory jurisdictions where water quality service level definitions were not achieved in 2018–2019 (towns and settlements <1000 people). a Northern Territory. **b** Queensland. **c** South Australia. **d** Tasmania. **e** Victoria. **f** Western Australia. Source data are provided as a Source Data file.

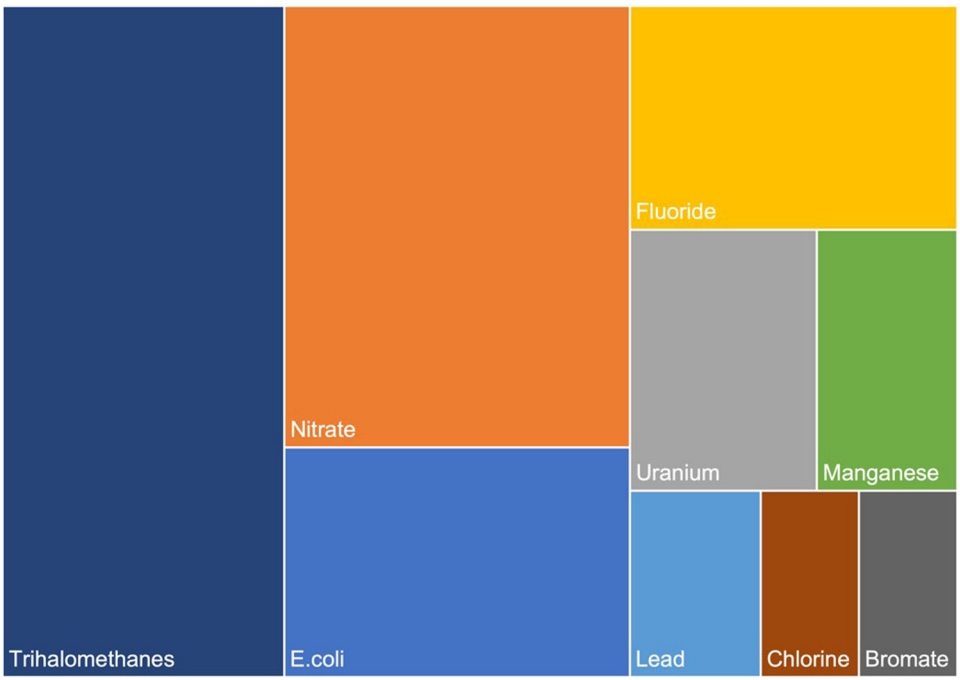

Fig. 4 National composition of exceedances against ADWG health-based guideline values by parameter. Size of coloured rectangles represents the percentage of exceedances associated with the corresponding parameter. Total of 105 exceedances included. Multiple exceedances in the same location against the same health parameter considered to be a single exceedance. Exceedances reported as false positives or not leading to non-compliance with annual jurisdictional compliance targets are not included. 99.1% compliance with Trihalomethanes target across 17 towns in SA Water Barossa system considered to be a single exceedance for this diagram. Single exceedances for Antimony, Barium, Dichloro-acetic and Trichloro-acetic Acid, PFHxS/PFOS not displayed. Source data are provided as a Source Data file.

Monitoring and reporting gaps

The dataset underlying our analyses was compiled from a review of publicly available sources. Table 7 provides an overview of the substantial monitoring and/or reporting gaps identified. These gaps mean that all estimates of populations, locations, and proportions are likely to be a lower bound for each definition. A major gap in terms of population coverage is New South Wales where, unlike the rest of Australia, production of annual drinking water quality reports is not a regulatory requirement for any water

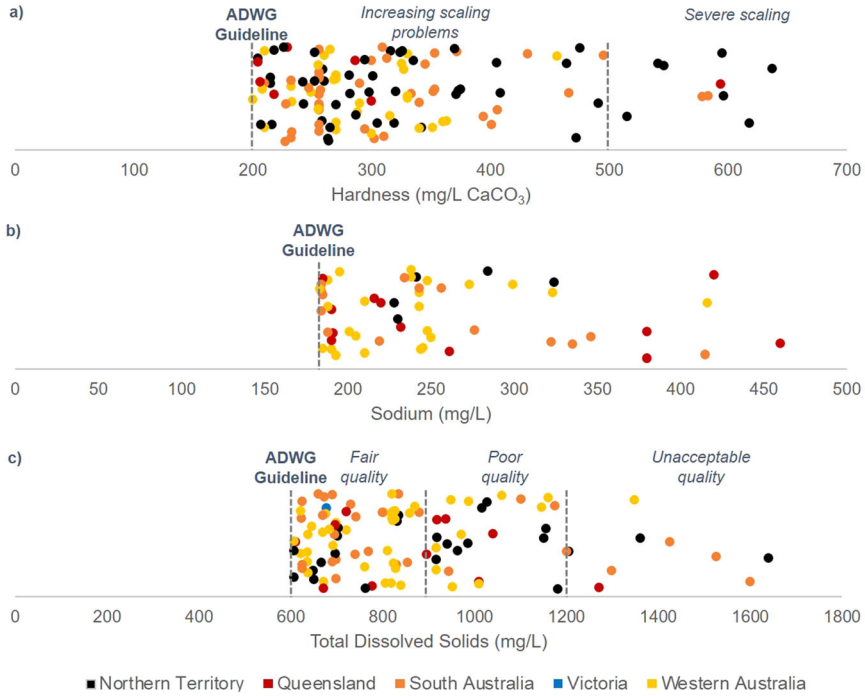

Fig. 5 Mean values of key aesthetic characteristics in regional and remote locations of Australia where aesthetic guideline values of the ADWG were reportedly not achieved in 2018–19. a Hardness. **b** Sodium. **c** Total dissolved solids. Note: No public data available for water systems supplied by the Tasmanian government-owned water utility and New South Wales local water utilities. Source data are provided as a Source Data file.

suppliers. In this jurisdiction, our review found only 18 of 81 local water utilities provided sufficient data to assess compliance against health-based and aesthetic guideline values of the ADWG. Approximately 1.2 million people are served by the remaining 63 local water utilities. Across the 68 water utilities in Queensland, we identified 24 where monitoring and reporting issues, such as no testing of chemical parameters, may have contributed to the lack of reported exceedances. Our review did not identify a public data source in any jurisdiction or nationally for drinking water quality from private supplies or water carting.

DISCUSSION

Our work provides three main contributions and related implications. First, we demonstrated methods to define and apply basic levels of service for drinking water quality. In practice, our definitions provide starting points for determining which specific parameters and target values would be applied in each jurisdiction. Further, the recording of noncompliance with quantitative benchmarks to prioritise locations for subsidies could be extended to reliability, affordability, and other components of basic levels of service. Section 3.8.1 of the ADWG emphasises that customers should play a central role in determining service levels[21]. In supporting a Productivity Commission recommendation on improving monitoring and reporting in remote Indigenous communities, the Northern Land Council highlighted "the need for individual communities to be actively involved in determining their required level of service and hence requirements for water service provision"[16]. Extending this approach to basic levels of service may require governments to conduct state- and territory-wide participatory processes for customers to determine and revise benchmarks. Such processes may draw on a growing body of research and practice on the recognition, representation, and realisation of Indigenous values, knowledge, and rights in Australian water policy (e.g.[59,62,72–78]). In the context of drinking water services in remote Indigenous communities, empirical research has informed strategies and actions to enable collaborative governance with external actors, including conducting local water baseline assessments, culturally-informed and long-term engagement, developing local employment opportunities, working with community champions, and delivering education and capacity-building programs in local languages[49,79].

Second, our analysis provides an improved understanding of drinking water quality in regional and remote Australia compared to national reporting under the Urban NPR. We demonstrated that there are substantial differences across drinking water quality service levels. In terms of SDG Target 6.1, we showed that this definition represents a minimal approach relative to the ADWG, albeit one that has not yet been achieved. In terms of SDG reporting and the Australian Government's next Voluntary National Review, we highlighted the existing opportunities to expand coverage beyond large water utilities and use existing public data to represent the Australia-wide drinking water quality situation more accurately. Proposed public investments to improve monitoring and reporting in remote areas would further address the inconsistency between real-world water quality outcomes and national-level statistics[14].

Third, we showed that exceedances beyond ADWG guideline values are most prevalent in small and remote towns and settlements, and especially remote communities. Thus, policy initiatives seeking to improve drinking water services may need to carefully consider and adapt to cultural and geographic contexts[3], and incorporate training, improvements to source water quality, and other non-capital investments[80]. In Australia, full-cost recovery from customers is the guiding principle determining the financial management of water utilities[81]. Many local water utilities that supply regional Queensland and New South Wales have small customer bases and incur high operating costs. Regional and remote locations typically exhibit higher incidence of socio-economic disadvantage. Consequently, programs to ensure basic levels of service need to account for costs, the ability to pay, and other place-specific constraints on delivering

Table 6. Number of remote Indigenous communities reported to lack access to definitions of a basic level of drinking water quality.

State/territory jurisdiction	Number of remote Indigenous communities where basic levels of drinking water quality not achieved				Health parameter exceedances (number of communities)	Aesthetic parameter exceedances excluding chlorine (number of communities)
	SDG 6.1	ADWG Health	ADWG Good	Metropolitan		
Northern Territory	4	12	60	65	Uranium (4), Manganese (3), Fluoride (3), E. coli (1), Antimony (1), Barium (1)	Hardness (39), TDS (19), pH (17), Chloride (7), Manganese (7), Iron (5), Silica (5), Sodium (5), Turbidity (3), True Colour (1)
Queensland	2	6	6	6	Trihalomethanes (4), E. coli (2)	Turbidity (1), Iron (1), True Colour (1)
South Australia	3	3	11	13	Fluoride (3)	Hardness (9), TDS (7), Chloride (2), Iron (1), Turbidity (1)
Western Australia	10	27*	27*	27*	Nitrate (19), E. coli (10), Uranium (4)	Insufficient data
TOTAL	**19**	**48**	**104**	**111**	Nitrate (19), E. coli (13), Uranium (8), Manganese (3), Fluoride (6), Trihalomethanes (4), Antimony (1), Barium (1),	Hardness (48), TDS (26), Chloride (9), Manganese (8), Iron (7), Silica (5), Sodium (7), Turbidity (5), True Colour (2)
New South Wales	?	?	?	?	Insufficient data	Insufficient data

*No publicly available data for aesthetic indicators in remote communities serviced by the Western Australian Department of Communities and data on health parameters with ADWG guideline values available for only E. coli, nitrate, and uranium. Numbers in bold indicate totals across Northern Territory, Queensland, South Australia, and Western Australia. Source data are provided as a Source Data file.

improved drinking water services. Further, some communities currently lack water service provision altogether. For communities where water quality is not monitored, water quality issues may be 'invisible' and these data gaps should be prioritised for resolution.

We contend that a national drinking water quality database is a pre-requisite to defining and measuring basic levels of service within each Australian state and territory jurisdiction. A multi-stakeholder co-design process would be required to establish and maintain the database, including decision-making processes and data practices consistent with Indigenous Data Sovereignty and Governance where applicable (see[82,83]). A publicly accessible database could: inform participatory processes to define service levels; support the identification of priority locations for government subsidies and other investments; provide a focal point for engagement between utilities and consumers; monitor outcomes over time; enable better understanding of the determinants of service improvements; and build trust between consumers, suppliers, and policy-makers. Figure 6 highlights government agency programs and processes at federal and sub-national levels that could be informed by the database. Given the broad scope of policy applications, and the important role of accessible open data in promoting accountability of public organisations[84], an independent statutory body at the federal level may be an appropriate data custodian.

The ADWG are subject to a rolling bi-annual review and updated regularly. As new evidence is generated on the potential health risks of chemical contaminants (e.g.[85]), and new programs developed to address specific water quality issues (e.g.[86]), a national database would support targeted policy responses as guideline values are updated. Moreover, the collation of historical data could support epidemiological research on exposure to water contaminants and the incidence of chronic and acute health conditions.

Our compilation of ADWG exceedances is a 'proof-of-concept' for an Australian national drinking water quality database. A key practical requirement would be to mandate Australia-wide standardised or minimum reporting conventions within jurisdictional regulations, including summary statistics for water quality parameters (e.g. minimum, maximum, 95th percentile, and average values), number of samples collected, and number of exceedances. Subnational regulatory reforms for standardised monitoring and reporting, including compulsory public reporting for local water utilities in New South Wales, could be initiated through the proposed renewal of the Intergovernmental Agreement on a National Water Initiative[6]. The value of a national drinking water quality database would be enhanced by the inclusion of indicators for water-borne disease outbreaks; key risks associated with source water quality, such as cyanobacterial blooms and bushfires; and the other aspects of basic levels of service, such as affordability and reliability, determined by state and territory jurisdictions. Furthermore, the integration of source water quality monitoring results would improve the transparency of government agencies' performance against the objectives of water resource management frameworks, such as the Murray-Darling Basin Plan[26].

Insights on the design and potential uses of a national drinking water quality database for Australia could be gained from: (i) the Safe Drinking Water Information System in the United States[87], (ii) public information on short-term and long-term drinking water advisories provided by Indigenous Services Canada[88,89], and (iii) the former Drinking Water Online database of the New Zealand government[90].

Our analysis showed that national reporting on SDG 6.1 and water utility performance in Australia obscures inequities in water access: metropolitan versus regional and remote; Indigenous versus non-Indigenous communities; monitored versus unmonitored water supplies. Official reporting of high-income countries close to or already achieving SDG Target 6.1 perpetuates a myth of

Table 7. Summary of key data gaps in 2018/19 for public reporting of drinking water quality in Australian states/territories.

Jurisdiction	Key data gaps
Western Australia	• No drinking water quality monitoring for 51 small remote Indigenous communities serviced by the Department of Communities. Many of these communities do not have access to any water treatment[40].
	• Compliance data only available from a secondary source across 4 health parameters for the 80 remote communities where testing occurred in 2018–20[40].
Northern Territory	• Lack of drinking water regulation & monitoring for remote Indigenous communities not served by state-owned water suppliers[60], including approximately 500 homelands/outstations with an estimated total population of 10,000 people.
South Australia	• Lack of testing and/or reporting for small and remote communities not serviced by the state-owned water corporation[18].
Queensland	• Lack of publicly available data, including 2018–19 reporting not obtainable for 22 of 68 utilities and no annual public reporting obtainable for 3 councils.
	• Limited monitoring and reporting for 24 local council water utilities, e.g. sampling frequencies that do not comply with ADWG or regulatory requirements, limited parameters tested, inconsistencies, and/or summary statistics not reported.
	• Queensland government regulations do not require water utilities to provide comprehensive quantitative data analysis and reporting by parameter.
Tasmania	Lack of testing and/or reporting for the 22% of the population not served by the state-owned water utility.
New South Wales	• Public reporting of water quality testing by local water utilities is voluntary and the NSW Health Drinking Water Monitoring Database is not publicly accessible[38].
	• Water quality testing publicly reported by only 25 of 81 local water utilities providing potable water services; reporting format varies greatly across these 25 utilities, e.g. monthly reports, online databases, multi-year reports, and posting laboratory results without analysis. Analysis across the four basic levels of drinking water quality only possible for 18 utilities.
	• The New South Wales government's Local Water Utility Performance Monitoring dashboard provides aggregate results across the 81 local water utilities for 2018–19 on the percentage of the served population in zones with microbial and chemical compliance; no data on ADWG aesthetic compliance is reported.
	• Lack of public reporting for 62 communities in the Aboriginal Communities Water and Sewage Program.
All states & territories	• Lack of monitoring and/or public reporting for private water supplies, water carters, and small water suppliers.

Further information on data gaps in Queensland and New South Wales local water utilities can be found within the supporting dataset[111].

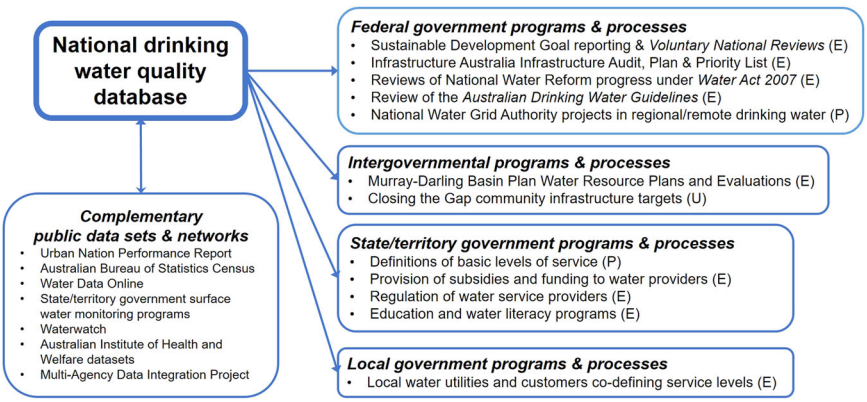

Fig. 6 Information flows from a national drinking water quality database to government water programs and processes in Australia. (E) Existing programs and processes, (P) Proposed programs and processes, (U) Under development programs and processes.

universal, clean, affordable, trustworthy, and uniformly governed water access[91]. The reality in reportedly high-performing countries, including Canada[92,93] and the United States[94–96], is that water access is uneven and many challenges remain[97,98]. Race, income, housing, geography, and utility size correspond to gaps in water access and drinking water quality[94,95,97,99]. Societal power imbalances, colonial practices of the state, and fragmented governance can (re)produce unsafe, unacceptable, and untrusted water services in Indigenous communities[93,100,101]. The geographic and monitoring/reporting gaps described in this paper reflect the structural barriers to sustainable improvements in water services[49,97].

Here, we show that the inequities in high-income countries become more visible when locally-contextualised benchmarks are used (e.g. 'ADWG Good'). Notwithstanding the benefits of the SDGs to galvanise global action, there are inherent difficulties in using standardised global indicators to measure progress toward the goal of 'universal and equitable access to safe and affordable drinking water for all'[102–105]. Supplementing country reporting against SDG 6.1 with benchmarks relevant to local policy, such as the definitions of a 'basic level of drinking water quality' for Australia proposed in this paper, can improve awareness of who has affordable access to good quality water, who does not, the structural factors involved, and increase accountability of governments and broader society for the gaps.

Our results are subject to multiple limitations. First, our dataset provides a snapshot of a single year and does not provide insights into service performance across time. Since 2018–19, investments

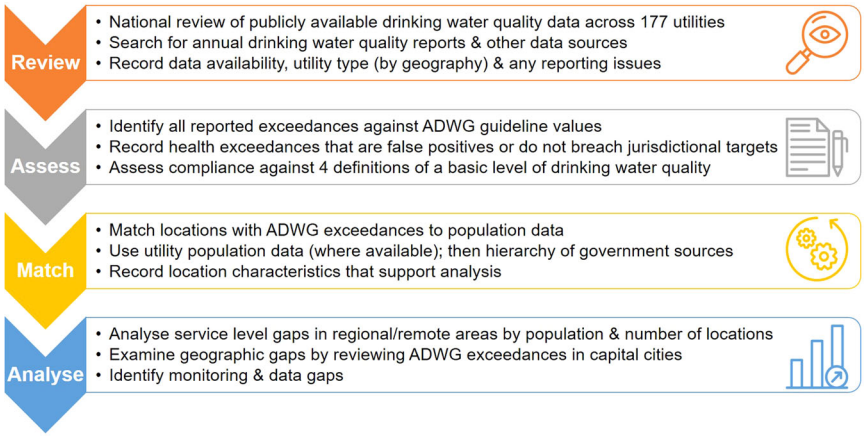

Fig. 7 Methodology to construct dataset of ADWG exceedances and estimate populations and locations lacking access to basic levels of service. Icons downloaded from the Noun Project (https://thenounproject.com/) using a using a NounPro for EDU Subscription.

have improved water quality in some locations where ADWG health exceedances occurred (e.g.[106]), and new exceedances have emerged in others (e.g.[107]). Second, our population estimates are less reliable for those locations where utilities do not provide data on the serviced population. Third, our analyses did not account for: contaminants subject to a jurisdictional requirement that have no ADWG health-based guideline value, such as the Naegleria fowleri amoeba in Western Australia[40]; breaches of operational guidelines, such as free residual chlorine in the reticulation network falling below 0.2 mg/L; boil water notices or drinking water advisories (e.g.[108]); and locations that experienced severe disruptions, taste and odour issues, or other causes of poor quality services not reflected in water quality reporting (e.g.[57]). Fourth, our analyses did not distinguish between prolonged versus occasional non-compliance with water quality guidelines. This is due to a lack of standardised reporting conventions across jurisdictions. Fifth, the analyses did not account for variable incidence and frequency of testing parameters; the absence of monitoring or reporting for a contaminant does *not* mean it is not present. Sixth, many small remote Indigenous communities in Australia are not provided with water services by external suppliers and, consequently, limited or no water monitoring occurs. These communities exposed to (arguably) the highest risk of unsafe drinking water are also those least represented in water quality reporting

Finally, we focused on the outcome-based drinking water indicators provided by ADWG health-based and aesthetic guideline values. Improved water quality monitoring and reporting is necessary but not sufficient: outcome-based indicators need to be combined with structural and process indicators[104]; data are not always used effectively[109]; test results provide snapshots of water quality at points in time and an incomplete picture of all potential hazards[105]; and governance challenges for remote water supply systems require a portfolio of solutions[97].

METHODS

National review of publicly available drinking water quality data

Our research focused on publicly available drinking water quality data to ensure that the methods and results are transparent, replicable and adaptable by policy-makers, and consistent with Section 3.10.2 of the ADWG and Principles 5, 9, 10 and 12 of the OECD Principles on Water Governance[110]. We identified 177 drinking water suppliers from the Urban NPR and state/territory government agency websites. This sample predominantly includes large state-owned water corporations and small local water utilities that are subject to public health regulation and, in all jurisdictions except New South Wales, annual public reporting requirements. We searched each supplier's website to obtain annual drinking water quality reports for the financial year 2018–2019. We also searched the websites and archives of government agencies and regulators for other drinking water quality information. Where these methods did not yield results for a specific water supplier, we also used relevant search terms in the Google search engine (e.g. 'Cloncurry drinking water management plan 2019').

For Queensland and New South Wales, we used the Wayback Machine internet archive (https://archive.org/web/) to search for 2018–19 reports that were not available on the current version of council webpages. In New South Wales, we obtained 25 local water utility reports, documents, or webpages providing water quality information. However, only 18 provided sufficient data to support our analysis. Hence, we relied on aggregated ADWG health-based compliance data for New South Wales[39] which does not provide information by town, water system, nor health parameter, and does not report against aesthetic parameters. For each of the 177 utilities across Australia, we recorded: data availability; year if not 2018–19 (see further below); classified each utility as either 'Capital City', 'Regional/Remote', or 'Mixed'; and whether there were issues with limited sampling or reporting that could affect the analysis.

Our review yielded annual drinking water quality reports and data for regional and remote locations from (i) the annual reports of 22 state/territory government-owned water utilities; (ii) 4 local government or mining company-owned small water utilities in Western Australia; (iii) annual drinking water management plans of 65 local council-owned utilities in Queensland, (iv) a Western Australian Auditor-General audit of service provision in 143 remote Indigenous communities by the Western Australian Department of Communities, and (v) summary information on health compliance for microbial and chemical parameters for 81 New South Wales local water utilities. For each supplier, we collated drinking water quality data for the smallest geographic unit available, e.g. each water supply zone, which was then defined as a 'location' in the analysis. All data points relate to samples from the reticulation network. We also reviewed annual drinking water reports of 12 water utilities serving customers across 7 Australian capital cities. The Australian Capital Territory was not included in the analysis of regional and remote areas because its population is almost entirely located within the capital city of Canberra. The data on remote and regional locations excludes all locations in outer metropolitan areas classified as 'Major Cities' under the ABS Remoteness Area structure[71]. The 'References' tab in the supporting dataset[111] provides links to all data sources.

All data is for the financial year 1st July 2018 to 30th June 2019, except for 22 Queensland local utilities where we used data from 2017–2018 or the most recent year available and[40] which reports water sampling conducted across the 2019 and 2020 calendar years. The year from 2018–2019 was chosen for analysis because it was the most recent year available, except for 2019–2020 when major bushfires across Australia affected source water quality and interrupted monitoring activities in many locations. Figure 7 provides a summary of the methods. All data are provided in the supporting dataset[111].

Recording and assessment of ADWG exceedances

We recorded average, maximum, 95th percentile values and/or number and percentage of exceedances for all locations where a drinking water quality parameter was reported to not comply with ADWG health-based and aesthetic guideline values. Note that a single exceedance triggers non-compliance with ADWG health-based guideline values and we followed ADWG rounding conventions. Non-compliance with aesthetic guideline values relates to the average annual value of testing results. Evidence and references for 33 health exceedances that were reported as false positives, may have been caused by data entry errors, or did not breach annual compliance targets are provided under 'Health Comment' in the jurisdictional worksheets in the supporting dataset[111].

Matching ADWG exceedances to population and location data

We used the following hierarchy to estimate and source population data: (i) data provided by the water utility; (ii) population data from the ABS 2016 Census on the corresponding Urban Centre and Locality (UCL), State Suburb (SSC), or Indigenous Locations (ILOCs) (in that order of availability); and (iii) population data for remote communities from government organisations.

Population data values and sources for each location are provided in the supporting dataset[111]. Note that UCL statistical areas correspond to densely populated urban areas and, for smaller regional or remote settlements, only those with populations greater than 200. Consequently, UCL data may have underestimated the population in a given location exposed to exceedances because water supply systems may extend beyond the UCL boundary. Conversely, SSC and ILOC statistical areas in regional and remote locations include non-urban households that may not be connected to the water supply system. Hence, SSC and ILOC data potentially overestimated the exposed population for towns with less than 200 residents. For South Australia, Tasmania, and Queensland, drinking water quality data in some locations were reported for systems encompassing multiple towns. In these cases, it was assumed that system-wide ADWG exceedances applied to all towns within the system. We were unable to source population data for 4 locations.

We classified all regional/remote locations according to the ABS Remote Area structure. Remote Indigenous communities were identified in the dataset as those communities serviced by the Remote Areas Essential Services Program (Western Australia), Indigenous Essential Services (Northern Territory), classified as remote Aboriginal communities served by South Australia Water Corporation, or locations within Queensland Aboriginal Shire Councils or Torres Strait Island Regional Council classified as 'Remote' or 'Very Remote'.

DATA AVAILABILITY

The dataset generated and analysed in this study is available through Open Science Framework[111]. The source data for figures and tables are provided with this paper.

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AUTHOR CONTRIBUTIONS

P.R.W. and R.Q.G. conceived and designed the work. P.R.W., A.M., K.T. and E.R. acquired, analysed and/or interpreted data. P.R.W. drafted the work, with substantial revisions by A.M., K.T., E.R., and R.Q.G.

COMPETING INTERESTS

The authors declare no competing interests.

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