ORIGINAL RESEARCH

Effects of community water fluoridation on child dental caries in remote Northern Territory, Australia: a difference-in-difference analysis

AUTHORS

#Ramakrishna Chondur[1] MPH, Health Economist * (iD) [https://orcid.org/0000-0002-4870-4459]

#Kate J Raymond[2] MHL, Chief Dental Officer (iD) [https://orcid.org/0000-0002-6694-5862]

Yuejen Zhao[1] PhD, Principal Health Economist

Ross Bailie[3] FAFPHM, Director, University Centre for Rural Health

Paul Burgess[1] FAFPHM, Director, Health Statistics and Informatics

#Contributed equally

CORRESPONDENCE

*Mr Ramakrishna Chondur ramakrishna.chondur@nt.gov.au

AFFILIATIONS

[1] Health Statistics and Informatics, Northern Territory Department of Health, Casuarina, NT, Australia

[2] Commissioning and System Improvement, Northern Territory Department of Health, Casuarina, NT, Australia

[3] Sydney School of Public Health, Faculty of Medicine and Health, The University of Sydney, Sydney, NSW, Australia

ABSTRACT:

Introduction: Community water fluoridation (CWF) is a cost-effective intervention to reduce dental caries at population level. This Australian study used a difference-in-difference (DiD) analysis to measure dental caries in children exposed to CWF in the Northern Territory (NT), Australia.

Methods: Oral health data obtained from the NT Department of Health contained 64 399 person-year observations from 2008 to 2020, totalling 24 546 children aged 1–17 years. Drinking water quality data for fluoride levels, held by the Power and Water Corporation, were obtained for 50 remote communities and linked to the oral health dataset. The DiD analysis used a treatment group and two control groups to compare the effects of CWF on dental caries outcomes in children, measured using the decayed, missing and filled teeth (dmft/DMFT) index. The treatment group consisted of records from children residing in five remote NT communities that implemented CWF in 2014. The control 1 group included records of children residing in communities with naturally occurring fluoride in drinking water supplies at levels at or above the Department of Health policy threshold of 0.5 mg/L. The control 2 group included records of children residing in communities with naturally occurring fluoride in drinking water supplies below the level recommended by the Department of Health policy (<0.5 mg/L). The data were grouped into time periods prior to the inception of CWF in five remote communities in 2014 (pre-intervention) and after 2014 (post-intervention).

Results: Our results demonstrated that dental caries was significantly decreased for children in the treatment group following the implementation of CWF at a greater magnitude than both control groups for the same time period. Overall, children assigned to the treatment group exhibited a decline in the number of teeth affected by caries by an average of 0.28 (*p*=0.001). Notably, children of ages 7–10 years and 11–17 years experienced significantly greater post-intervention declines in average dmft/DMFT, by 0.32 (*p*=0.051) and 0.40 (*p*=0.012) fewer affected teeth respectively.

Conclusion: While dental caries disproportionately impacts Aboriginal children in remote and very remote NT, it is clear that CWF produces population-level reductions in overall dental caries for these populations. Additionally, our study demonstrates the application of the DiD method in a public health policy evaluation. Our findings suggest that the longstanding policy position of the NT Department of Health on CWF has supported improvements in oral health among child populations that experience high levels of dental caries in remote NT communities.

Keywords:

Aboriginal, Australia, dental caries, fluoridation, Northern Territory, oral health.

FULL ARTICLE:

Introduction

Dental caries is one of the most prevalent and preventable diseases among Australian children[1,2]. Untreated dental caries causes pain, distress, illness and is a leading cause of preventable hospitalisation[2]. Children in the Northern Territory (NT) experience a higher prevalence of dental caries than children who live in other parts of Australia[2,3]. Aboriginal children residing in remote and very remote areas are disproportionately impacted by dental caries compared with their non-Aboriginal counterparts[4]. Of the NT Aboriginal children who received public dental services in 2022, 87% of children aged 11 years had experienced dental caries, and children aged 7 years experienced dental caries in 5.3 teeth on average[4].

Community water fluoridation (CWF) is a widely recommended public health intervention to reduce dental caries[5]. CWF provides protective benefits through systemic administration of fluoride during amelogenesis in utero and during childhood, and through topical effects by increasing concentrations of fluoride in saliva to inhibit enamel demineralisation, promote remineralisation and inhibit bacterial action[6-8]. CWF is the addition of fluoride to drinking water supplies at levels known to benefit dental health[5]. Duration of CWF exposure is inversely associated with caries experience[6,7]. In Australia, CWF began in the 1950s and has made a significant contribution to improve oral health[5]. Rates of population access to fluoridated drinking water vary across Australia, with the NT having a higher proportion of the population without access to fluoridated drinking water (22%) than the national average (11%)[3,5]. While many communities in the southern region of NT access groundwater with naturally occurring fluoride at therapeutically beneficial levels, seven locations in the NT have implemented CWF: Darwin, the remote township of Katherine and five very remote communities (Angurugu, Maningrida, Umbakumba, Wadeye and Wurrumiyanga) among 205 remote communities[9,10]. For the five very remote communities to have implemented water fluoridation in 2013–14, all projects were community-initiated, facilitated by government community development grants.

Unlike other Australian states and territories, water fluoridation in the NT is not underpinned by legislation. The National Health and Medical Research Council (NHMRC) identified optimal levels of fluoride in drinking water for protective oral health benefits of 0.6–1.1 mg/L[5]. A longstanding NT policy on water fluoridation, introduced by the NT Department of Health in 2010[11], used population cost–benefit analysis to recommend that communities should be considered for prioritisation of CWF where the local population is greater than 600 people and natural levels of fluoride in drinking water supplies are less than 0.5 mg/L[12]. An updated cost–benefit study of CWF in remote NT communities, carried out in 2023, indicates that the population threshold in favour of cost-effective implementation of CWF is communities of 300 people or more[13]. While the cost–benefit study demonstrated clear economic benefits in broadening CWF in NT, it did not seek to examine causal inferences between CWF implementation and child dental caries, nor to understand how CWF may impact the trajectory of dental caries experience with age for children in remote NT communities. A deeper understanding of how CWF may impact dental caries in remote NT children throughout the course of childhood is essential to underpin life-course approaches to future government policymaking, investment and program design.

The present study aimed to understand the long-term impacts of CWF on children living in remote and very remote communities of the NT. In doing so, this study sought to demonstrate the use of a difference-in-difference (DiD) analysis as a means of policy evaluation, to quantify the impacts of a longstanding NT Health CWF policy, by measuring dental caries experience in NT children aged 1–17 years living in remote and very remote locations between 2008 and 2020.

Methods

To inform the DiD analysis, a systematic approach was used for collection and sampling of secondary data. As the NT Government is the major longstanding provider of oral health services to most remote communities of NT, service data were the most comprehensive data source available. These data were collected at the point of service by dental practitioners, based on clinical examination. Each record also contained information about individuals' demographic attributes, residential location, Indigenous status, age and dental caries experience.

The sampling strategy is outlined in Figure 1. For a total of 91 sites across the NT, consisting of 19 urban centres, and 72 remote and very remote Aboriginal communities, data for drinking water quality data collections for 2008–2020 were held by the Power and Water Corporation. Drinking water quality data from 75 localities were matched to the 50 remote community populations included in the study[14]. Data were cleansed of duplicate entries. Communities with fewer than 100 total observations were excluded to improve data quality and prevent inadvertent identification of individuals. To minimise confounding of results, individuals' demographic information was screened for a change in location partway through the study period, and these records were removed from the dataset. The oral health data sample captured all children aged 1–17 years who had received dental care in remote and very remote locations of the NT from 2008 to 2020. For each unique patient record, dental caries severity was measured and reported using the decayed, missing and filled teeth index (dmft (primary teeth)/DMFT (permanent teeth)), which is a standard epidemiological measure of dental caries experience[15]. A dmft/DMFT score was collected per individual, per year (termed 'person-year observation') for all children in the sample.

Dental caries experience data were matched with water quality data. Tables 1 and 2 show the distribution of the study population in 50 remote and very remote communities. Of the total 64 399 person-year observations from 24 546 children, 73.6% (47 429)

observations related to communities with fluoride levels at or above 0.5 mg/L, including 13 941 observations relating to the one remote community (Katherine) and five very remote communities with CWF (Angurugu, Maningrida, Umbakumba, Wadeye and Wurrumiyanga) and 33 488 observations relating to 12 communities with naturally occurring fluoride in drinking water supplies at therapeutically beneficial levels at or above 0.5 mg/L. The remaining 16 970 observations related to 32 communities with fluoride levels in drinking water less than 0.5 mg/L. Aboriginal children made up a higher proportion (63.2%) of the study population than non-Aboriginal children (36.8%).

The study used a quasi-experimental design. The DiD analysis is suited to evaluating population health impacts of historical interventions in non-randomised populations[16,17]. As CWF was implemented in remote communities throughout 2013–14, data were grouped into time periods prior to and including 2014 (pre-intervention) and after 2014 (post-intervention), factoring in a 12-month lag period for effects of ongoing fluoride exposure to be observed[6,13]. The treatment group comprised data from the remote communities that received the CWF intervention. To account for possible effects of naturally occurring fluoride in community water supplies, two control groups were used. Control group 1 included all data for communities that had naturally occurring fluoride in drinking water supplies at levels at or above the NT Department of Health policy threshold of 0.5 mg/L. The control 2 group comprised all data for communities that had naturally occurring fluoride in drinking water supplies below the level recommended by the Department of Health policy (<0.5 mg/L) (see Table 1).

Figure 2 presents the conceptual framework of the analysis, comparing the outcome (dmft/DMFT) for the pre–post time-point differences for the treatment and control groups, thus quantifying the differences between these groups that could be attributed to the effect of the CWF intervention. Analysis was conducted using statistical analysis software STATA v17 (StataCorp; https://www.stata.com)[18].

Table 1: Number of communities, children, observations and fluoride levels for treatment and control groups, by pre- and post-intervention periods

Study group	Communities (n)	Pre-intervention (prior to CWF, before 2014)			Post-intervention (after CWF, in 2014)		
		Children (n)	Records (n)	Fluoride (mg/L)	Children (n)	Records (n)	Fluoride (mg/L)
Treated[†]	6	2849	6349	0.36	3124	7592	0.54
Control 1[¶]	12	6046	16 939	0.82	5721	16 549	0.86
Control 2[§]	32	3276	7785	0.16	3530	9185	0.16

[†] Communities supplied with fluoridated water.
[¶] Communities supplied with water containing naturally occurring fluoride level ≥0.5 mg/L (control 1).
[§] Communities supplied with drinking water containing fluoride level <0.5 mg/L (control 2).
CWF, community water fluoridation.

Table 2: Key demographic characteristics by treatment and control groups, Northern Territory 2008–2020

| Characteristic	Communities with optimal fluoride level (≥0.5 mg/L)				Communities without optimal fluoride level (<0.5 mg/L)	
	Treatment[†] (CWF) (*n*=6)		Control 1[¶] (non-CWF) (*n*=12)		Control 2[§] (non-CWF) (*n*=32)	
Person-year records	13 941	21.6	33 488	52.0	16 970	26.4
Age group (years)						
1–6	5239	8.1	11 541	17.9	6303	9.8
7–10	4440	6.9	11 291	17.5	5296	8.2
11–17	4262	6.6	10 656	16.6	5371	8.3
Indigenous status						
Aboriginal	9779	15.2	14 995	23.3	15 941	24.8
Non-Aboriginal	4162	6.5	18 493	28.7	1029	1.6
Remoteness area[‡]						
Remote	8049	12.5	26 723	41.5	1157	1.8
Very remote	5892	9.1	6765	10.5	15 813	24.6

[†] Communities supplied with fluoridated water.
[¶] Communities supplied with water containing naturally occurring fluoride level ≥0.5 mg/L.
[§] Communities supplied with drinking water containing fluoride level <0.5 mg/L.
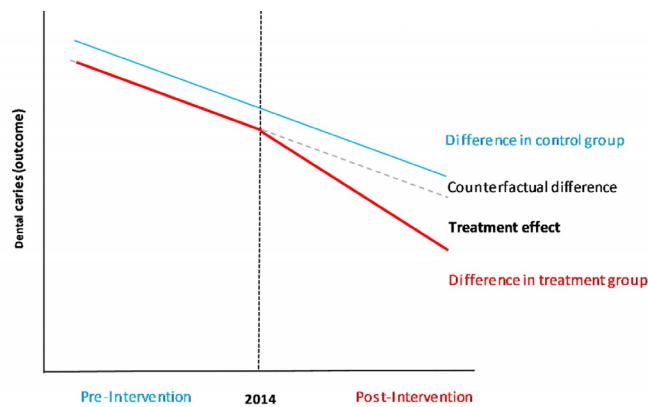[‡] Remote areas comprise eight communities, including Alice Springs and Katherine. The remaining 42 communities are in very remote areas (ref. 14).
CWF, community water fluoridation.
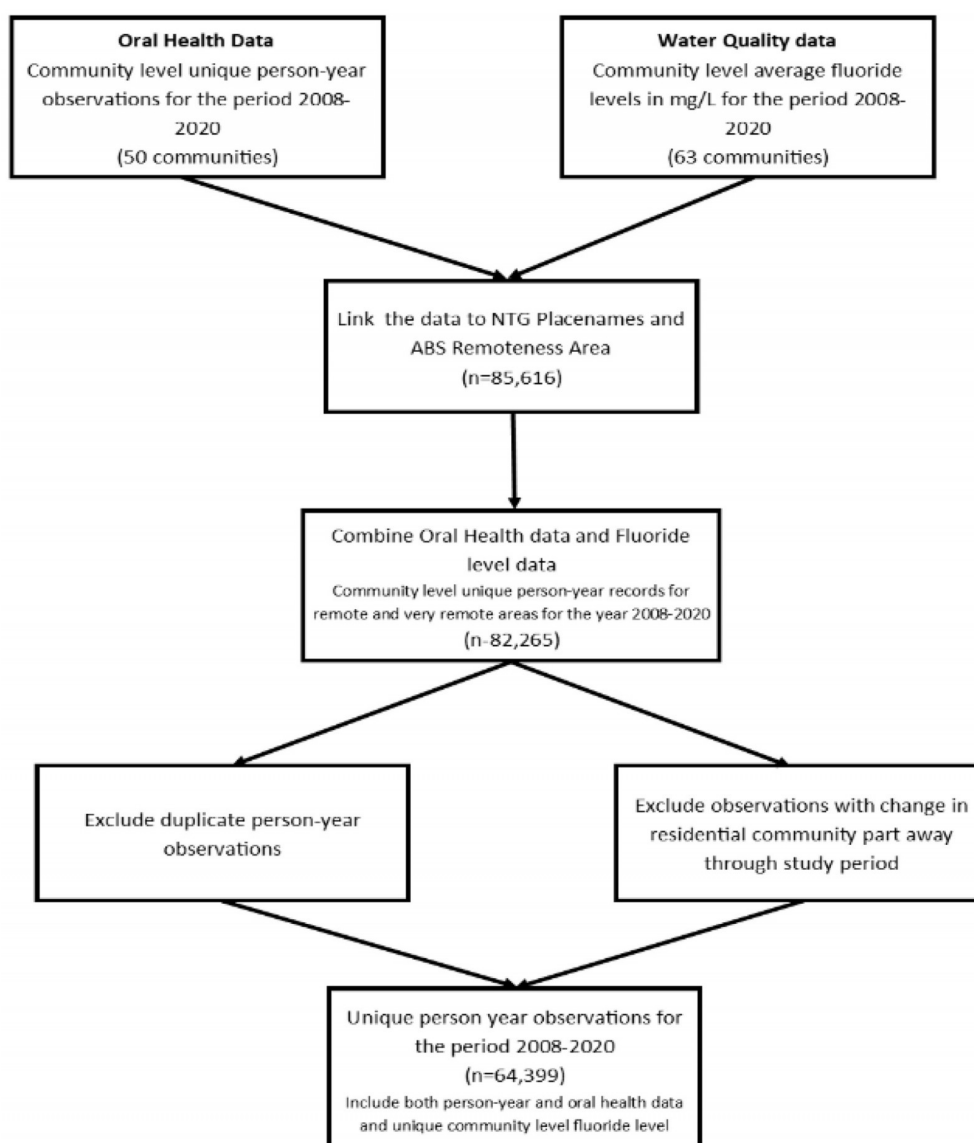
ABS, Australian Bureau of Statistics. NTG, Northern Territory Government.

Figure 1: Data sampling strategy.

† Treatment effect = difference in treatment group – difference in control group.

Figure 2: Difference-in-difference analysis conceptual framework for community water fluoridation.†

Ethics approval

Data were collected and utilised in accordance with the Human Research Ethics Committee of the Northern Territory Department of Health and Menzies School of Health Research ethics approval 2021-3988.

Results

For the total data collection period, from 1 January 2008 to 31 December 2020, the overall prevalence of dental caries in children aged 1–17 years was 62.1%. Aboriginal children experienced dental caries at a rate 1.7 times greater than non-Aboriginal children. The analysis found that 48.3% of children aged 1–6 years, 29.7% of children aged 7–10 years and 70.5% of children aged 11–17 years experienced dental caries in the primary, mixed and permanent dentitions respectively. Aboriginal children were also more likely than non-Aboriginal children to experience dental caries across all age groups, which was found to be statistically significant ($p<0.01$) for all age groups, except children aged 1 year. Figure 3 presents average dmft/DMFT for each of the treatment and control groups, before and after the CWF implementation period. While each of the treatment and control groups experienced general declines in dmft/DMFT over the entire study period, the magnitude of decrease was greatest for the treatment group.

Table 3 summarises results for each of the control and treatment groups and provides further demographic breakdown. Observed decreases in dmft/DMFT between the pre- and post-intervention periods were tested with a high level of statistical significance ($p<0.01$). The control 1 group had a generally lower average dmft/DMFT across all age groups in both the pre- and post-intervention periods, when compared to the treatment and control 2 groups. The average dmft/DMFT for the treatment group decreased to a greater extent than both control groups between the pre- and post-intervention periods. Children in the treatment group aged 7–10 years and 11–17 years experienced the greatest decreases in dmft/DMFT between the pre- and post-intervention periods. The control 2 group experienced the lowest magnitude of decrease in dmft/DMFT across all ages, except for children aged 1–6 years. Declines in dmft/DMFT were greater for non-Aboriginal children compared to Aboriginal children across all treatment and control groups.

Table 4 presents the results of the DiD analysis. Overall, the observed decline in the post-intervention period for the treatment group, compared with both control groups was 0.28 affected teeth (dmft/DMFT). In comparing the average dmft/DMFT for the treatment group and control 1 group, the post-intervention decline in the number of teeth affected by caries across all ages was on average 0.13 dmft/DMFT greater for the treatment group than the control 1 group. A greater post-intervention decline, of 0.30 dmft/DMFT, was observed for the treatment group when compared to the control 2 group. These results were tested with high statistical significance ($p<0.01$), summarised in Table 4. Notably, children of ages 7–10 years and 11–17 years in the treatment group experienced significantly greater post-intervention declines in average dmft/DMFT, by 0.32 and 0.40 fewer affected teeth respectively, when compared to the control 2 group ($p<0.01$). Children aged 1–6 years in the treatment group experienced statistically significant ($p<0.01$) post-intervention declines of 0.43 dmft/DMFT relative to the control 1 group, and 0.52 dmft/DMFT relative to the combined control groups.

Table 3: Dental caries (dmft/DMFT) for children aged 1–17 years, reported by age group, for treatment, control 1 and control 2 groups before and after community water fluoridation intervention, Northern Territory, 2008–2020

Characteristic	Treatment[†] (CWF) (mean±SD)		Control 1[¶] (non-CWF) (mean±SD)		Control 2[§] (non-CWF) (mean±SD)	
	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
Age group (years)						
1–6	3.55±0.08	2.99±0.07	2.15±0.05	2.03±0.05	4.72±0.07	4.31±0.06
7–10	4.31±0.08	3.92±0.08	3.20±0.05	2.80±0.05	5.20±0.07	5.12±0.07
11–17	3.69±0.09	3.32±0.07	2.49±0.05	1.93±0.05	4.14±0.07	4.16±0.07
Indigenous status						
Aboriginal	4.65±0.05	4.12±0.05	3.49±0.04	3.28±0.04	4.85±0.04	4.68±0.04
Non-Aboriginal	2.17±0.08	1.44±0.08	1.85±0.04	1.47±0.04	2.36±0.16	1.69±0.15
Remoteness area[‡]						
Remote	3.11±0.06	2.58±0.06	2.54±0.03	2.15±0.03	3.88±0.15	3.14±0.15
Very remote	4.98±0.07	4.36±0.06	2.91±0.06	2.63±0.06	4.76±0.04	4.59±0.04

[†] Communities supplied with fluoridated water.
[¶] Communities supplied with water containing naturally occurring fluoride level ≥0.5 mg/L.
[§] Communities supplied with drinking water containing fluoride level <0.5 mg/L.
[‡] Remote areas comprise eight communities, including Alice Springs and Katherine. The remaining 42 communities are in very remote areas (ref. 14).
CWF, community water fluoridation. SD, standard deviation.

Table 4: Difference-in-difference analysis of dental caries (dmft/DMFT) for children aged 1–17 years, reported by age group, for treatment, control 1 and control 2 groups, Northern Territory, 2008–2020

| Characteristic	Pre-intervention			Post-intervention			DiD	p-value
	Control	Treatment[†]	Difference	Control	Treatment[†]	Difference		
DiD[¶] between treatment (CWF) and control 1[§] groups								
Total records	2.61	3.86	1.25	2.25	3.37	1.12	−0.13	0.066*
Age group (years)								
1–6	2.15	3.55	1.40	2.03	2.99	0.97	−0.43	0.000***
7–10	3.20	4.31	1.11	2.80	3.92	1.12	0.01	0.926
11–17	2.49	3.69	1.21	1.93	3.32	1.40	0.19	0.089*
DiD between treatment (CWF) and control 2[‡] groups								
Total records	4.70	3.86	−0.84	4.50	3.37	−1.14	−0.30	0.002***
Age group (years)								
1–6	4.72	3.55	−1.17	4.31	2.99	−1.32	−0.14	0.383
7–10	5.20	4.31	−0.89	5.12	3.92	−1.21	−0.32	0.051*
11–17	4.14	3.69	−0.45	4.17	3.22	−0.84	−0.40	0.012**
DiD between treatment (CWF) and non-fluoridated (control 1 and control 2) groups								
Total records	3.27	3.89	0.59	3.05	3.37	0.31	−0.28	0.000***
Age group (years)								
1–6	2.96	3.54	0.59	2.93	2.99	0.07	−0.52	0.000***
7–10	3.82	4.31	0.50	4.57	3.92	0.35	−0.15	0.254
11–17	3.03	3.69	0.67	2.67	3.32	0.63	−0.04	0.722

*$p<0.1$, **$p<0.05$, ***$p<0.01$
[†] Communities supplied with fluoridated water.
[¶] Aboriginal demographic status variable was included as covariant in DiD analysis.
[§] Communities supplied with water containing naturally occurring fluoride level ≥0.5 mg/L.
[‡] Communities supplied with drinking water containing fluoride level <0.5 mg/L.
CWF, community water fluoridation. DiD, difference-in-differences.
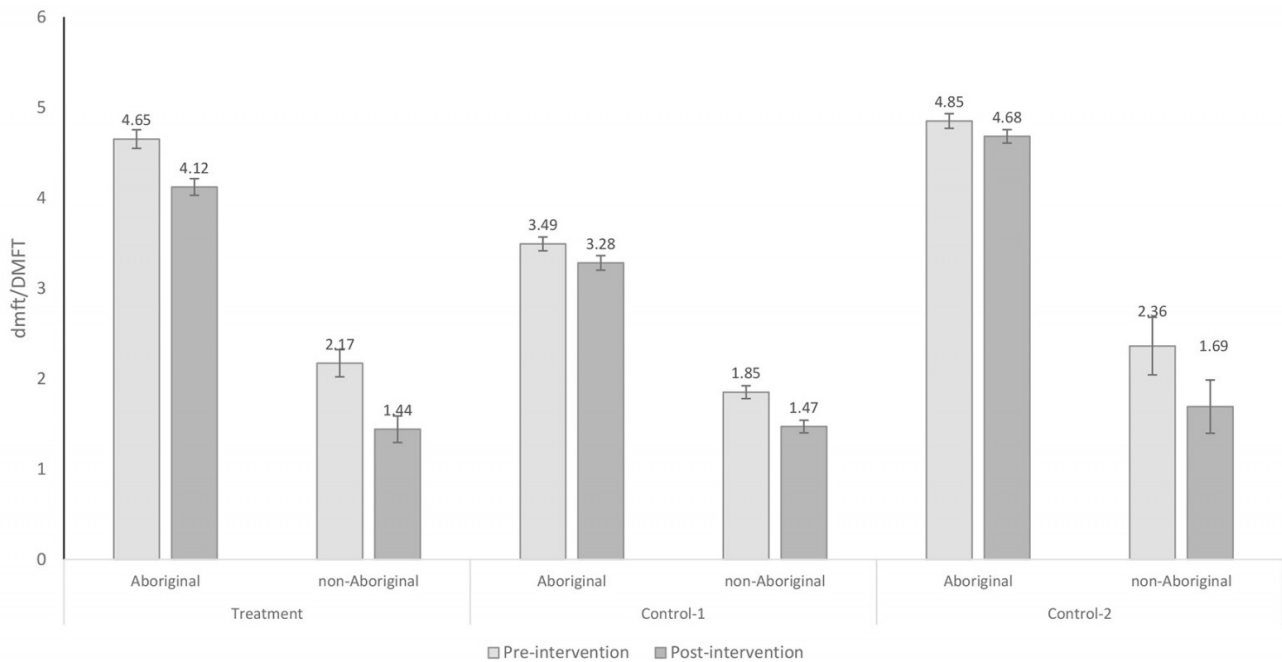
CWF, community water fluoridation. Control 1, communities supplied with water containing naturally occurring fluoride level ≥0.5 mg/L. Control 2, communities supplied with drinking water containing fluoride level <0.5 mg/L. dmft/DMFT, decayed, missing, filled teeth for primary teeth/permanent teeth. 'Treatment', communities supplied with fluoridated water. Pre-intervention, prior to CWF (before 2014). Post-intervention, after CWF implementation (after 2014).

Figure 3: Dental caries experience (dmft/DMFT) at 95% confidence interval for treatment and control groups, for pre-intervention and post-intervention periods.

Discussion

Children of all ages in remote and very remote areas of NT are affected by dental caries at levels much higher than previously reported by national studies of child oral health[1,4]. It is clear that Aboriginal children residing in remote and very remote communities of the NT experience dental caries at levels well above their non-Aboriginal counterparts. Our study not only documented caries experience of remote NT child populations not previously included in sampling conducted by national studies[1-3], but also demonstrates the effectiveness of CWF in reducing high levels of dental caries among child populations in remote and very remote NT, consistent with previous studies of water fluoridation in the remote NT[19]. Our study also identified overall decreases in rates of dental caries among the total NT child population over the study period, consistent with other analyses that have reported general improvements in child dental caries in NT and Australia over similar time periods[20,21]. Other factors, such as efforts to address social determinants of health, health promotion and better management of chronic conditions, may be having a degree of impact, as recent research on life expectancy of Aboriginal people in the NT has demonstrated general improvements over the past decade[22]. However, overall declines in the severity of child dental caries, measured by dmft/DMFT score, confirmed that populations that received CWF exhibit lower rates of dental caries.

Our study provides insight into the relationship between dental caries among the remote and very remote child populations of NT and levels of fluoride in drinking water. Regardless of CWF or naturally occurring fluoride sources, a clear inverse association exists between the number of teeth affected by dental caries in children and fluoride level in remote community drinking water supplies, consistent with data-linkage studies of other populations[23]. We did not seek to predictively model a dose–response relationship curve; however, our approach to hypothesis

testing yielded an important finding. Children in NT communities with long-term naturally occurring fluoride in water supplies at levels at or above 0.5 mg/L experienced dental caries in fewer teeth on average, with a high degree of statistical significance. This finding supports evidence linking long-term duration of exposure to fluoride with better oral health outcomes[6,7,23] and emphasises the importance of a life-course approach to preventive initiatives.

The DiD approach is emerging as a promising method in quasi-experimental analysis and public health policy evaluation[24,25]. Our study demonstrates the usefulness of the DiD method in policy evaluation by adopting a 'natural experiment' design, to assign individuals from similar communities to control and treatment groups depending on the CWF intervention received. The approach is useful in public health settings where stringent, randomised methods of testing population responses to a policy intervention may not be practicable. There are known limitations to the DiD method in health policy evaluation; the validity of results relies on equal background trends being established in control and treatment groups, so that all groups are subject to similar conditions and yield similar health outcomes over time, thus enabling observed changes in outcomes to be attributed to the policy intervention or treatment[24]. Based on our observations, parallel trends in caries experience (dmft/DMFT) were noted for the control 2 and treatment groups prior to CWF implementation. The control 1 group, exposed to naturally occurring fluoride in water supplies throughout the entire study period, had a lower baseline dmft/DMFT, but also experienced a gradual decrease in dmft/DMFT over time.

We accounted for confounders arising from variations in naturally occurring fluoride in water supplies by separating control groups into low levels of naturally occurring fluoride (<0.5 mg/L) and therapeutically beneficial levels of fluoride (≥0.5 mg/L). Our study utilised data collected over an extended period, thereby limiting

the confounding potential of brief periods of changes in levels of services or situational community factors that may skew results over short periods of measurement. The extensive dataset related to children who accessed public oral health services within the study period. Of the current 27 000 Aboriginal children in the NT aged 0–18 years, 20 397 (75%) have accessed public dental services between 2012 and 2022[4]. Thus, we believe our dataset to be reflective of the majority of Aboriginal children in the NT. The remaining proportion of Aboriginal children not captured by the dataset (25%) may be reflective of children not accessing any dental care, or accessing dental care through other programs, administered through the private sector or small number of non-government and community-controlled programs. As our study used oral health data pertaining to children who had contact with a single public oral health program, any changes associated with overall program service levels would also have affected each of the control and test groups similarly.

Our study did not examine exposure to preventive effects of fluoride from other sources. Two longstanding government programs underpin the use of concentrated fluoride varnish in NT children: the Healthy Under 5 Kids Partnering Families Program (HU5K-PF) for children aged 18 months to 5 years[26] and the NT Remote Aboriginal Investment Oral Health Program (NTRAI-OHP) for remote Aboriginal children of all ages[4]. These programs are implemented at similar levels across remote and very remote NT communities, but have been limited in their overall continuity of fluoride varnishing at therapeutically indicated intervals[27]. Given the limited coverage of these oral health preventive programs over extended periods, it is unlikely that the use of fluoride varnish was a significant confounder in our analysis.

Our study did not account for dietary and behavioural confounders such as high consumption of sugar-sweetened beverages, which is known to be widespread in remote and very remote communities of the NT[28,29]. It is known that dietary and behavioural risk factors for oral disease, as well as access to culturally safe services, may disproportionately impact the oral health of Aboriginal people compared to non-Aboriginal people[2]. The treatment and control groups utilised by our study had different proportions of Aboriginal and non-Aboriginal people, which could have potentially confounded the analysis of the study data. Moreover, the treatment and control groups varied in overall population number and age structure. Due to the natural experiment approach to the study, it was not possible to control demographic composition between each of the control and treatment groups. However, the proportion of Aboriginal and non-Aboriginal people in each of the control and treatment groups remained relatively stable over the study period, as did population number and age structure, which is suited to the DiD focus on relative differences in population outcomes over time using a parallel trends assumption[24,25].

Previous studies of CWF effectiveness have postulated that individuals in warmer climates are likely to consume larger amounts of water, and on this basis a suitable concentration of fluoride in drinking water may be at the lower end of the optimal range[30]. To be effective, CWF also requires drinking water to be safe and palatable for consumption. We did not account for differential rates of water consumption, which we assume to be generally similar across NT communities. Any inferences made from our analysis would be contingent upon drinking water consumption continuing at current rates. Our study also did not consider possible dose–response differences in dental caries within the optimally fluoridated range. Numerous NT remote communities have naturally occurring fluoride in water supplies at varying levels within the NHMRC-defined optimal range[5,9,10]. Further studies could assess the dose–response impact of higher levels of water fluoridation on dental caries severity over extended periods.

Our findings suggest that the longstanding policy position of the NT Department of Health, recommending CWF in remote and very remote communities with levels of naturally occurring fluoride in water at levels below 0.5 mg/L[11], has supported improvements in oral health among child populations that experience high levels of dental caries. A case for extending CWF to other remote and very remote communities of NT, with lower levels of naturally occurring fluoride in drinking water (<0.5 mg/L), could be progressed on the basis of clear, predictable and cost-effective population health benefits. A recent cost–benefit analysis of CWF implementation in NT suggests that the economic return on investment can be as high as 16:1 for the NT's largest remote communities, with a payback period as short as 2.2 years[13]. There are also clear synergies arising from co-investment by government in universal prevention offered by CWF in addition to targeted, settings-based preventive programs such as fluoride varnish programs, which have been tested in the NT child population. A previous study of dental caries in remote NT children[31] estimated that the combined effects of a fluoride varnish program and CWF of 1 mg/L could produce an average reduction of 7.8 carious tooth surfaces per child. As critical health workforce shortages in remote and very remote Australia continue, cost-effective, universal health interventions that operate external to health service settings, such as CWF, will offer sustainable and predictable investment for governments to improve population health outcomes, reduce health inequity and reduce health system pressures.

Conclusion

Observed decreases in dental caries among children in remote and very remote NT communities demonstrate promising improvements in population oral health. However, rates of child dental caries, especially for Aboriginal children in remote and very remote NT, are still some of the highest in the country and affect these populations disproportionately compared to their counterparts in major cities. Children who receive adequate levels of fluoride in drinking water, irrespective of natural or CWF sources, experience dental caries in fewer teeth on average compared to children without access to fluoridated water. Overall rates of reduction in dental caries have been accelerated for NT remote child populations following the introduction of CWF.

This study adds to the sizeable body of evidence of clear benefits of extended CWF in areas where fluoride levels in drinking water are below optimal levels. CWF does not replace the need for complementary preventive programs and oral health promotion; rather, investment in CWF is likely to increase the impacts of other preventive efforts. Moreover, CWF is a cost-effective and sustainable health intervention that is not dependent upon a health workforce currently facing critical shortages, making it a sound investment in population health. Future CWF policy advancements in NT should focus on implementation, by working with communities to broaden the reach of CWF into remote and very remote areas where indicated. To assist prioritisation, future studies could consider regional trends in dental caries for NT

children, relative to fluoridation levels.

REFERENCES:

1 Australian Research Centre for Population Oral Health. Oral health of Australian Indigenous children compared to non-Indigenous children enrolled in school dental services. *Australian Dental Journal* 2014; **59(3):** 395-400. DOI link, PMid:25040876

2 Australian Institute of Health and Welfare. *Oral health and dental care in Australia.* 2023. Available: web link (Accessed 22 December 2023).

3 Australian Institute of Health and Welfare. *National Oral Health Plan 2015-2024: performance monitoring report: in brief.* 2020. Available: web link (Accessed 22 December 2023).

4 Australian Institute of Health and Welfare. *Oral health outreach services for Aboriginal and Torres Strait Islander children in the Northern Territory: July 2012 to December 2022.* Canberra: Australian Institute of Health and Welfare, 2023.

5 National Health and Medical Research Council. *Information paper - water fluoridation: dental and other human health outcomes.* Canberra. National Health and Medical Research Council, 2017.

6 Cho HJ, Jin BH, Park DY, Jung SH, Lee HS, Paik DI, et al. Systemic effect of water fluoridation on dental caries prevalence. *Community Dentistry and Oral Epidemiology* 2014; **42(4):** 341-348. DOI link, PMid:24428350

7 Jack B, Ayson M, Lewis S, Irving A, Agresta B, Ko H, et al. *Health effects of water fluoridation: evidence evaluation report.* Canberra: National Health and Medical Research Council, 2016.

8 Beltran ED, Burt BA. The pre- and posteruptive effects of fluoride in the caries decline. *Journal of Public Health Dentistry* 1988; **48(4):** 233-240. DOI link, PMid:3054080

9 Power and Water Corporation. *Annual drinking water quality report 2020.* 2021. Available: web link (Accessed 18 November 2023).

10 Power and Water Corporation. *Indigenous Essential Services annual report 2012.* 2012. Available: web link (Accessed 16 November 2023).

11 Northern Territory Government. *Position statement - the use of fluorides in the Northern Territory, Novermber 2010.* 2010. Available: web link (Accessed 26 August 2023).

12 Gray N, Beirne K, Zhao Y, Guthridge S. *Water fluoridation in remote Indigenous communities in the Northern Territory: a cost-benefit analysis.* [Internal report]. Darwin: Department of Health and Families, 2008.

13 Zhao Y, Raymond K, Chondur R, Sharp W, Gadd E, Bailie R, et al. Costs and benefits of community water fluoridation in remote Aboriginal communities of the Northern Territory. *Australian Journal of Rural Health* 2023; **31(5):** 1017-1026. DOI link, PMid:37706591

14 Australian Bureau of Statistics. *The Australian Statistical Geography Standard (ASGS) digital boundaries.* 2020. Available: web link (Accessed 1 August 2023).

15 World Health Organization. *Oral health surveys: basic methods.* 5th edn Geneva: WHO, 2013.

16 Rajeev D. *The porous dialectic: experimental and non-experimental methods in development economics. WIDER Working Paper 11/2013.* Finland: UNU-WIDER, 2013.

17 Basu S, Meghani A, Siddiqi A. Evaluating the health impact of large-scale public policy changes: classical and novel approaches. *Annual Review of Public Health* 2017; **38:** 351-370. DOI link, PMid:28384086

18 Villa JM. Simplifying the estimation of difference in differences treatment effects with Stata. *The Stata Journal* 2016; **16(1):** 52-71. DOI link

19 Bailie RS, Stevens M, Armfield JM, Ehsani JP, Beneforti M, Spencer J. Association of natural fluoride in community water supplies with dental health of children in remote Indigenous communities – implications for policy. *Australian and New Zealand Journal of Public Health* 2009; **33(3):** 205-211. DOI link, PMid:19630837

20 Australian Institute of Health Welfare. *Australia's children.* Canberra: AIHW, 2022.

21 Do LG, Spencer AJ. *Oral health of Australian children: the National Child Oral Health Study 2012-14.* 2016. Available: web link (Accessed 25 August 2024).

22 Zhao Y, Li SQ, Wilson T, Burgess CP. Improved life expectancy for Indigenous and non-Indigenous people in the Northern Territory, 1999-2018: overall and by underlying cause of death. *Medical Journal of Australia* 2022; **217(1):** 30-35. DOI link, PMid:35644458

23 Kirkeskov L, Kristiansen E, Bøggild H, Von Platen-Hallermund F, Sckerl H, Carlsen A, et al. The association between fluoride in drinking water and dental caries in Danish children. Linking data from health registers, environmental registers and administrative registers. *Community Dentistry and Oral Epidemiology* 2010; **38(3):** 206-212. DOI link, PMid:20156234

24 Angrist JD, Pischke J-S. *Mostly harmless econometrics: An empiricist's companion.* New Jersey: Princeton University Press, 2009.

25 Dimick JB, Ryan AM. Methods for evaluating changes in health care policy: the difference-in-differences approach. *JAMA* 2014; **312(22):** 2401-2402. DOI link, PMid:25490331

26 Skinner J, Dimitropoulos Y, Sohn W, Holden A, Rambaldini B, Spallek H, et al (Eds). Child fluoride varnish programs implementation: a consensus workshop and actions to increase scale-up in Australia. *Healthcare* 2021; **9(8):** 1029. DOI link, PMid:34442166

27 Skinner J, Dimitropoulos Y, Rambaldini B, Calma T, Raymond K, Ummer-Christian R, et al. Costing the scale-up of a national primary school-based fluoride varnish program for Aboriginal children using dental assistants in Australia. *International Journal of Environmental Research and Public Health* 2020; **17(23):** 8774. DOI link, PMid:33255962

28 Brimblecombe JK, Ferguson MM, Liberato SC, O'Dea K. Characteristics of the community-level diet of Aboriginal people in remote northern Australia. *Medical Journal of Australia* 2013; **198(7):** 380-384. DOI link, PMid:23581959

29 Lee AJ, O'Dea K, Mathews JD. Apparent dietary intake in remote Aboriginal communities. *Australian Journal of Public Health* 1994; **18(2):** 190-197. DOI link, PMid:7948337

30 World Health Organization. *Preventing disease through healthy*

environments: inadequate or excess fluoride: a major public health concern. Geneva: World Health Organization. **2019.**

31 Slade GD, Bailie RS, Roberts-Thomson K, Leach AJ, Raye I, Endean C, et al. Effect of health promotion and fluoride varnish on dental caries among Australian Aboriginal children: results from a community-randomized controlled trial. *Community Dentistry and Oral Epidemiology* 2011; **39(1):** 29-43. DOI link, PMid:20707872