Check for updates

Journal of Dental Research
1–10
© The Author(s) 2026

Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/00220345261491339
journals.sagepub.com/home/jdr

Effectiveness of Community Water Fluoridation in Queensland: A Population-Based Causal Analysis Following the 2008 Policy Change

L.G. Do[1], A. John Spencer[2], K. Roberts-Thomson[2], R. Lalloo[1], J. Broadbent[3], M. Foley[1], H. Whelton[4], T. Le[1], M. Herzig[5], C.T. Sexton[1], E. Gielis[5], B. Appleyard[5], H.S. Schuch[1], and D.H. Ha[1]

Abstract

Water fluoridation (WF) is an important preventive program against dental caries. Recent Cochrane reviews reported only limited new scientific evidence of WF. This research aimed to provide contemporary evidence on the causal relationship between WF and oral health. A causal framework was used to ensure methodological rigour in repeated cross-sectional, population-based studies of randomly selected 5 to 14 y old children in Queensland, thereby enabling controlled difference-in-differences (DiD) analyses. The primary exposure was access to WF, defined as newly fluoridated (New-WF; areas that became fluoridated since 2010), never fluoridated (No-WF), or long-term fluoridated areas (Long-WF). The outcomes were dental caries experience (decayed, missing, or filled tooth surfaces) and prevalence in the primary and permanent dentition, collected by dental examiners who were uniformly trained and calibrated during both phases. The DiD estimands were the differences in changes in outcomes between New-WF and the control (No-WF), estimated from multivariable regression models. Data of 5,407 children during 2010–2012 and 7,718 children during 2022–2024 were collected. Variations in key confounders (area and individual socioeconomic factors) were controlled for using inverse probability of treatment weights. Dental caries among children in New-WF had consistently declined relative to the control groups. In the primary dentition, the New-WF children had a 1.40-fold (95% confidence interval [CI]: 1.08 to 1.80) reduction in caries experience and a 1.28-fold (1.00 to 1.67) reduction in caries prevalence, equivalent to 1.1 fewer affected tooth surfaces and a 10.8% lower prevalence. In the permanent dentition, reductions were smaller: a 1.32-fold (0.95 to 1.84) reduction in caries experience and a 1.04-fold (0.81 to 1.33) reduction in prevalence. These findings show that WF is effective in preventing dental caries in children when disease levels are low and other preventive programs are available. This controlled DiD study provides robust contemporary scientific evidence of the effects of WF on dental caries, strengthening WF as a public health policy.

Keywords: fluoride use, child dental caries, population programs, causal inference approach, observational study, Australia

Introduction

Dental caries is highly prevalent, costly to treat, and has a significant negative impact on quality of life. Fluoride exposure, particularly through fluoridation of community water supplies, has long been considered a cornerstone of its prevention (Centers for Disease Control and Prevention 2001; National Health and Medical Research Council [NHMRC] 2017; Pollick 2018). Dental caries is disproportionately concentrated in people of lower socioeconomic backgrounds, creating unfair and unjust inequalities (Do et al 2018).

Water fluoridation (WF), a public health program, should be informed by scientific evidence; however, randomised controlled trials (RCTs) are not practical or feasible (Do et al 2025). Much of the existing evidence on WF effectiveness largely predates the widespread availability of fluoride toothpaste and other preventive measures, raising questions about its relevance to current populations (McDonagh et al 2000; Iheozor-Ejiofor et al 2015). Recent systematic reviews (NHMRC 2017; Iheozor-Ejiofor et al 2024) have also raised methodological limitations of the existing evidence. Together,

[1]School of Dentistry, Faculty of Health, Medicine and Behavioural Sciences, The University of Queensland, Australia
[2]Adelaide Dental School, The University of Adelaide, Australia
[3]Faculty of Dentistry, University of Otago, Dunedin, New Zealand
[4]College of Medicine and Health, University College Cork, Cork, Ireland
[5]Queensland Health, Brisbane, Australia

A supplemental appendix to this article is available online.

Corresponding Author:
L.G. Do, School of Dentistry, Faculty of Health, Medicine and Behavioural Sciences, The University of Queensland, 7th floor, Herston, Queensland 4006, Australia.
Email: l.do@uq.edu.au

these timeliness and methodological issues, which are conceptually distinct but have often been conflated in public debate, have contributed to renewed political and public challenges to WF programs. More recently, debate over the potential effects of fluoride on neurodevelopment (Taylor et al 2025) has been a primary driver of renewed public and political challenges to fluoridation programs, notwithstanding substantial methodological critiques of this evidence (Do et al 2025; Levy 2025).

Observational research can contribute evidence of the causal relationship in population programs through the application of causal inference methods (Hernán and Robins 2020; Hernán 2021; Listl et al 2022). The controlled difference-in-differences (DiD) approach is a best practice for evaluating the effectiveness of public health programs when RCTs are not feasible, not ethical and/or when the interventions are at the population level, as is the case with WF (Sofer et al 2016; Wing et al 2018) and satisfies the requirements for health policy evaluation (Stuart et al 2014; Marino et al 2025; Bilinski et al 2026). While the DiD approach is well established in health services and economics research, its application to evaluating oral health policies, including WF, remains rare. This study demonstrates its feasibility in this field.

Historically, Queensland was the only Australian state with low WF coverage (<5%). In 2008, the state government mandated WF of public water supplies, and the rollout commenced during 2010–2012. However, in 2012, the new state government removed the mandate, handing decisional and financial responsibility to local governments. Hence, some areas did not proceed with WF or ceased it. The WF coverage stabilised to about 70% (NHMRC 2017; Sexton et al 2024). Taking advantage of that unique opportunity, we conducted a population-based Queensland Child Oral Health Study with 5,407 children during 2010–2012 to establish the "before" phase of the evaluation (Do and Spencer 2015). We completed the "after" phase in 2022–2024, using the same methods to establish a population-based before-and-after study to evaluate the effectiveness of WF.

This article reports the findings of that before-and-after study and aims to provide new, high-level scientific evidence on the causal relationship between WF and dental caries to inform policymakers on the effectiveness of WF as a public health policy.

Methods

The study was approved by the Children's Health Queensland Ethics Committee. The children's parents provided written informed consent. The STROBE Guidelines for reporting cross-sectional research were followed (Vandenbroucke et al 2007).

Study Design

Both the before (2010–2012) and after (2022–2024) phases were conducted using similar study designs, questionnaires, and examination protocols and were led by the same investigators (Do and Spencer 2015; Do et al 2026). They allowed for evaluating changes in child oral health status in areas that implemented and remained fluoridated (New-WF) relative to children in the negative control, nonfluoridated areas (No-WF) and the existing positive control area, long-term fluoridated (Long-WF). No-WF included areas that were never fluoridated and areas that implemented but ceased WF after up to 3 y. This design enabled the application of the controlled DiD method.

Zone-level fluoridation status was determined from Queensland water plants, which report fluoride levels in public water at each phase. Children's residence was matched to relevant water supply boundaries to define their fluoridation status. This is distinct from the individual lifetime-exposure measure described below under per-protocol (PP) analyses, which additionally accounts for residential mobility and household water source.

The study population was Queensland children aged 5 to 14 y. The sampling frame was similar in both phases, using a multistaged, stratified random sample selection procedure to obtain representative samples of the target population at each time (Do and Spencer 2016; Do et al 2026). Schools were first stratified by region, then sorted by a composite index of school socioeconomic status and selected with probability proportional to enrolment size. The second stage selected a cluster of children from each age within each school. Data were weighted to adjust for selection probabilities, and further post hoc adjustments were made to ensure that sample-based estimates closely reflected the 2011 and 2021 Census-based parameters.

Data Collection

The primary outcome was dental caries, assessed using both the prevalence and experience measures across primary and permanent dentition. The methods for assessing dental caries were based on the US 3rd NHANES (National Institute of Dental and Craniofacial Research 2002) and Australia's National Child Oral Health Study (Do and Spencer 2016). Data were collected through standardised oral epidemiological examinations by trained and calibrated dental examiners. Two senior trainers (L.G.D. and D.H.H.) conducted training at both times. All examiners were tested in the field against the senior trainers to estimate interexaminer reliability. Refresher training sessions were conducted every 6 mo or when an examiner had a more than 2-mo break from the fieldwork.

The counts of decayed, missing, or filled primary (dmfs) and permanent (DMFS) tooth surfaces were used as indicators of cumulative caries experience. Dental caries prevalence was also used as an outcome. Dental caries in the primary dentition was measured among children aged 5 to 10 y and in the permanent dentition among children aged 8 to 14 y. These age ranges were selected to prevent potential misclassification due to the low number of primary teeth among children aged 10+ y and of permanent teeth among children <8 y.

A parental questionnaire was used to collect data on socioeconomic factors, dental health behaviours and practices and patterns of dental visits. Household income and parental education were parent reported and categorised into low/medium/

high at each phase; parental country of birth and child Indigenous identity were parent reported and dichotomised.

Defining the Causal Framework

Our causal question was, "What was the effect of the expansion of WF on the population-level indicators of dental caries in Queensland children residing in the New-WF areas, relative to what would have happened without the expansion?" A causal directed acyclic graph was developed to guide the evaluation (Appendix Fig 1).

Fluoridation status was assigned at the level of the local government areas. A higher proportion of regional areas remained nonfluoridated. Hence, socioeconomic factors were associated with fluoridation status through their correlation with area-level residence and are also established individual-level determinants of dental caries. We therefore treated them as confounders.

The causal models were generated as multivariable regression models for the primary indicators of dental caries. The causal estimand was defined as the average treatment effect among the treated (Lechner 2011). That was the difference in the overtime changes in dental caries indicators between New-WF and No-WF. The regression model used to calculate DiD estimands is presented below. The regression coefficient for the interaction β_3 is the DiD causal estimand.

$$Y = \beta_0 + \beta_1 Time + \beta_2 Fluoridation + \beta_3 \left(Time * Fluoridation\right) + \beta_n Covariates + e$$

Causal Assumptions

In plain terms, dental caries could change over this period for reasons unrelated to WF. A simple before-and-after comparison in New-WF areas alone would therefore not be able to estimate the causal effects of WF (Bilinski et al 2026). The controlled DiD design addresses this by subtracting the change observed in comparable No-WF over the same period, isolating the additional change attributable to WF. This estimate can be interpreted as the causal effect of WF when the 4 assumptions below hold (Lechner 2011; Caniglia and Murray 2020).

Assumption 1: Consistency: The observed exposure of interest is equal to the counterfactual exposure of interest. In practice, WF is a well-defined, objectively measurable program (fluoridated vs not), so there is little ambiguity about the exposure.

Assumption 2: Positivity: All individuals or subgroups can receive all levels of exposure. In practice, no child or subgroup was structurally barred from ever having access to fluoridated water.

Assumption 3: Exchangeability and parallel trends: Any unmeasured determinants of the outcome are either time invariant or group invariant. The parallel trends assumption posits that trends in outcomes between exposed and control groups were similar prior to the intervention and would have continued to evolve similarly if the program had not been implemented (Dimick and Ryan 2014). Determinants of dental caries within the same age group are well defined and do not vary over time or across locations. In practice, we checked this by confirming that age-specific caries trends were near parallel between zones before fluoridation began (Appendix Fig 5) and by statistically balancing known determinants using the inverse probability of treatment weight (IPTW) (Fig 1A, B).

Assumption 4: Exchangeability and strict exogeneity: The implementation of exposure was not related to the baseline level of the outcome. In practice, fluoridation was rolled out by government mandate, not local caries rates. Any areas with public water supplies were eligible.

Balancing the Determinants

Key socioeconomic determinants of dental caries may vary across locations due to differences in population profiles. Hence, we conducted a statistical balance of the determinants by estimating IPTW (Hernán and Robins 2006; Nandi et al 2012; Hernán 2021), which was applied in our research (Ha et al 2025). We estimated IPTW separately for each phase to balance the distribution of household income, parental education, parents' country of birth, and Indigenous identity. The estimated IPTW was combined with the sample weights to balance the determinants and used in the models.

Intention-to-Treat and Per-Protocol Analyses

Our primary analysis compared zones with and without WF, regardless of population movements and drinking water consumption, analogous to the intention-to-treat (ITT) analysis. Such an approach is important for maintaining objectivity; however, it cannot fully assess the effectiveness of population programs (Smith et al 2021). Individuals could move between locations with different levels of exposure, choose different sources of drinking water, or install a water filter that removes fluoride. These so-called 'spillover effects' (Dimick and Ryan 2014) need to be accounted for. We collected data on residential movements of the samples, water sources, and use of water filters. If filters capable of removing fluoride were used, water was considered not fluoridated. We then estimated the percentage of lifetime exposure to WF to determine their actual exposure as 1 of 3 groups: 0%, >0% and <100%, and 100% lifetime exposure (Do and Spencer 2015; Spencer et al 2018). The distribution of the 3 groups was described by time and zone in the Results. We conducted an additional PP analysis by including only those with 0% exposure in nonfluoridated areas and those with 100% exposure in fluoridated areas.

Causal Models

We generated multivariable regression models for the primary indicators of dental caries. As the sample was selected using a

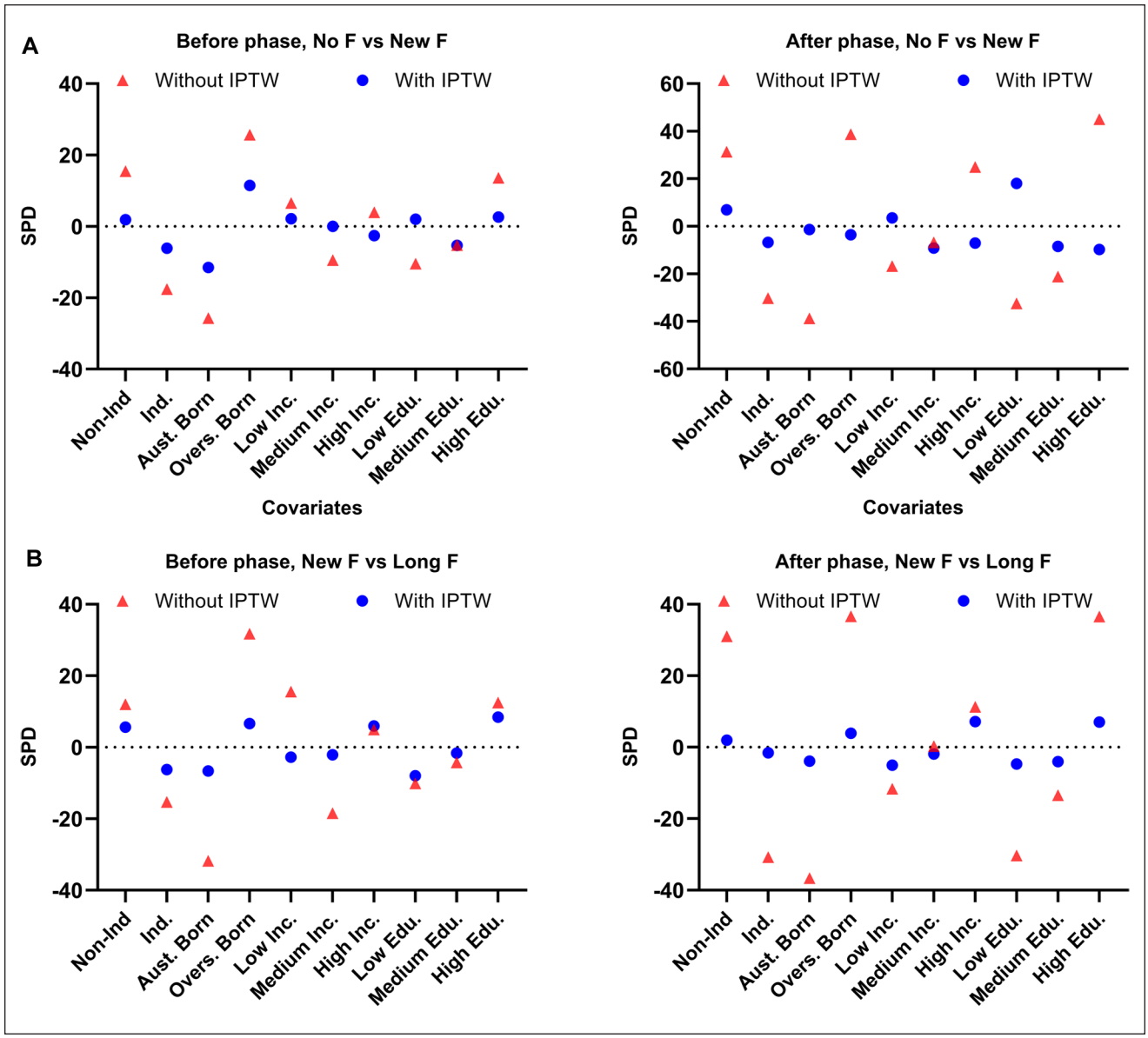


Figure 1. Standardised proportional differences (SPDs) with and without inverse probability of treatment weights (IPTW). (**A**) Never fluoridated (No-WF) versus newly fluoridated (New-WF). (**B**) New-WF versus long-term fluoridated (Long-WF).

stratified cluster sampling frame, SAS-callable SUDAAN LOGLINK procedures were used, employing the Taylor linearisation method, assuming a stratified-with-replacement design. The prevalence was analysed using log-binomial regression, and the experience was analysed using negative binomial regression for count data. The models applied the combined weights of the sample weight and the estimated IPTW. The models also adjusted for age, sex, and the key socioeconomic determinants of dental caries used to estimate IPTW, yielding doubly robust estimates and their variance estimates. Estimates of the outcomes were generated as predictive marginals of the models.

Confirmatory Analysis

For confirmatory analyses, we used the positive control (Long-WF), which had already received fluoridation during the before phase. Dental caries levels were lower than those in nonfluoridated areas (Do and Spencer 2015). Due to differences in exposure levels at the before phase, the outcome indicators of Long-WF during the after phase may not be true counterfactuals of New-WF. However, it helps confirm the causal effect if the magnitude of changes in New-WF relative to No-WF and Long-WF are comparable, and the direction of New-WF changes is toward the levels observed in Long-WF.

Table 1. Characteristics of the Samples by Time and Exposure Status.

	Children Aged 5 to 10 y, W% (95% CI)					
	No-WF Zone		New-WF Zone		Long-WF Zone	
	Before, *n* = 725	After, *n* = 1,655	Before, *n* = 1,607	After, *n* = 2,965	Before, *n* = 1,140	After, *n* = 1,064
Sex						
Male	52.7 (45.6–59.9)	47.2 (42.9–51.6)	51.9 (48.8–55)	48.4 (44.4–52.5)	49.0 (45.7–52.3)	54.2 (46.2–62.1)
Female	47.2 (40.0–54.3)	52.7 (48.3–57.0)	48 (44.9–51.1)	51.5 (47.4–55.5)	50.9 (47.6–54.2)	45.7 (37.8–53.7)
Indigenous identity[a]						
Non-Indigenous	80.5 (73.6–87.5)	81.9 (75.1–88.7)	93.4 (91.4–95.5)	94.3 (92.4–96.2)	88.3 (86–90.6)	80.2 (71.0–89.4)
Indigenous	17.6 (11.1–24.0)	18.0 (11.2–24.8)	5.6 (3.7–7.5)	5.6 (3.7–7.5)	9.3 (7.2–11.4)	19.7 (10.5–28.9)
Household income						
Low	35.2 (23.8–46.6)	40.9 (33.7–48.1)	32.2 (27.2–37.2)	26.2 (20.5–31.9)	30.4 (27.1–33.7)	43.7 (32.2–55.2)
Medium	39.9 (34.3–45.4)	42.3 (38.0–46.5)	39.6 (35.9–43.3)	40.0 (36.0–43.9)	45.7 (42.4–49)	35.9 (29.2–42.7)
High	24.8 (16.5–33.0)	16.6 (11.8–21.5)	28.1 (23.7–32.4)	33.7 (26.4–41.0)	23.7 (20.6–26.9)	20.2 (12.8–27.6)
Parental education						
Low	36.1 (28.2–44.0)	39.9 (34.2–45.6)	30.1 (25.6–34.5)	20.1 (15.2–25.0)	37.8 (34.4–41.2)	42.4 (33.7–51.0)
Medium	29.7 (23.9–35.5)	31.4 (27.7–35.0)	23.3 (20.4–26.2)	17.1 (13.9–20.3)	22.7 (19.8–25.5)	28.7 (22.6–34.7)
High	34.1 (26.4–41.7)	28.6 (22.8–34.4)	46.5 (41.6–51.4)	62.6 (55.4–69.8)	39.4 (36.2–42.6)	28.8 (21.1–36.5)
	Children Aged 8 to 14 y, W% (95% CI)					
	No-WF Zone		New-WF Zone		Long-WF Zone	
	Before, *n* = 874	After, *n* = 1,433	Before, *n* = 1,767	After, *n* = 2,603	Before, *n* = 1,113	After, *n* = 843
Sex						
Male	48.4 (43.2–53.5)	51.7 (46.2–57.1)	52.5 (49.3–55.7)	53.1 (50.3–55.9)	47.8 (43.4–52.3)	53.3 (48.2–58.5)
Female	51.5 (46.4–56.7)	48.2 (42.8–53.7)	47.4 (44.2–50.6)	46.8 (44.0–49.6)	52.1 (47.6–56.5)	46.6 (41.4–51.7)
Indigenous identity[a]						
Non-Indigenous	84.0 (74.8–93.2)	82.5 (76.3–88.8)	92.7 (91.1–94.3)	94.5 (92.7–96.3)	88.2 (85.8–90.7)	77.0 (70.7–83.3)
Indigenous	13.0 (5.0–21.1)	15.7 (10.1–21.3)	4.4 (3.1–5.7)	4.8 (3.1–6.6)	8.8 (6.6–11.0)	20.4 (13.5–27.4)
Household income						
Low	37.8 (28.7–47.0)	36.7 (30.5–42.9)	33.1 (29.1–37.0)	28.7 (21.3–36.1)	26.7 (23.1–30.2)	33.7 (24.4–43.0)
Medium	35.6 (31.1–40.1)	43.4 (36.9–49.9)	40.2 (37.2–43.3)	38.6 (35.0–42.2)	48.3 (43.6–53.1)	40.5 (31.0–50.0)
High	26.5 (18.5–34.4)	19.8 (14.3–25.3)	26.6 (22.9–30.2)	32.5 (24.4–40.6)	24.9 (21.2–28.6)	25.7 (10.0–41.3)
Parental education						
Low	40.1 (32.3–47.8)	34.2 (27.2–41.2)	32.3 (28.7–35.9)	20.8 (15.4–26.2)	35.1 (31.1–39.1)	39.7 (29.2–50.2)
Medium	25.2 (20.6–29.7)	30.5 (24.0–37.1)	22.0 (19.4–24.6)	16.9 (13.9–19.9)	26.3 (22.6–30.0)	29.5 (19.9–39.1)
High	34.6 (27.6–41.7)	35.1 (26.3–43.9)	45.6 (41.7–49.5)	62.1 (54.6–69.6)	38.4 (33.5–43.4)	30.6 (11.7–49.6)

95% CI, 95% confidence interval; Long-WF, long-term fluoridated; New-WF, newly fluoridated (areas that became fluoridated since 2010); No-WF, never fluoridated; W%, weighted percent.
[a]A few children did not report their Indigenous identity.

Sensitivity Analysis

Toothbrushing, fluoride applications, sugar consumption, and dental visits can be associated with dental caries. Those factors were not confounders in our analysis, as they were not expected to be associated with the exposure, but they could be covariates of the outcomes. The application of IPTW and the socioeconomic factors in the models closed the pathways through those covariates. Nevertheless, we conducted a sensitivity analysis with those covariates in the models. The findings are presented in the Appendix.

Results

Among the children, 3,472 and 5,684 of those aged 5 to 10 y and 3,754 and 4,879 of those aged 8 to 14 y were included in the before and after phases, respectively (Table 1). Children aged 8 to 10 y were included in both analyses because of their mixed dentition. The sex distribution was consistent across groups. The proportion of Indigenous children was consistent over time in the No-WF and New-WF groups but was higher in the after phase in Long-WF, with similar patterns across both age groups. The distributions by income and parental education remained relatively stable, except for an increase in the high-education group in the New-WF zone.

The distribution of the children by percentage of lifetime exposure to fluoridated water changed dramatically in New-WF, as expected (Table 2). There were some small changes in No-WF and Long-WF.

The standardised proportional differences (SPD) for the key socioeconomic factors, not weighted by IPTW, were large between the No-WF and New-WF groups (Fig 1A). When

Table 2. Distribution of the Samples by Time, Zone and Actual Percentage of Lifetime Exposure to Fluoridated Water.

	Children Aged 5 to 10 y, W% (95% CI)					
	No-WF Zone		New-WF Zone		Long-WF Zone	
	Before, *n* = 725	After, *n* = 1,655	Before, *n* = 1,607	After, *n* = 2,965	Before, *n* = 1,140	After, *n* = 1,064
Lifetime exposure						
0%	81.5 (72.5–90.5)	74.9 (70.8–79.0)	83.6 (78.8–88.5)	1.2 (0.0–2.8)	3.1 (1.6–4.6)	1.9 (0.0–5.4)
>0% to <100%	14.7 (10.0–19.4)	22.9 (18.8–26.9)	14.0 (11.8–16.3)	15.9 (13.6–18.1)	29.9 (26.9–32.9)	16.6 (12.7–20.6)
100%	3.8 (0.0–10.6)	2.2 (0.0–4.8)	2.3 (0.0–5.8)	82.9 (79.9–85.9)	67.0 (63.9–70.2)	81.5 (76.6–86.3)
	Children Aged 8 to 14 y, W% (95% CI)					
	No-WF Zone		New-WF Zone		Long-WF Zone	
	Before, *n* = 874	After, *n* = 1,433	Before, *n* = 1,767	After, *n* = 2,603	Before, *n* = 1,113	After, *n* = 843
Lifetime exposure						
0%	80.1 (73.3–87.0)	74.8 (69.0–80.6)	81.4 (78.0–84.8)	1.5 (0.1–2.9)	2.6 (1.3–3.9)	2.1 (0.0–5.3)
>0% to <100%	17.5 (13.1–21.9)	21.3 (15.9–26.8)	16.9 (14.8–19.1)	21.5 (18.5–24.5)	35.8 (31.8–39.8)	21.3 (17.4–25.2)
100%	2.4 (0.0–6.5)	3.9 (1.5–6.3)	1.6 (0.0–4.4)	77.0 (73.5–80.5)	61.5 (57.4–65.7)	76.6 (69.9–83.2)

95% CI, 95% confidence interval; Long-WF, long-term fluoridated; New-WF, newly fluoridated (areas that became fluoridated since 2010); No-WF, never fluoridated; W%, weighted percent.

weighted by IPTW, those SPDs were within acceptable ranges (<10%). Most SPDs were close to 0. Similarly, the SPDs without IPTW between New-WF and Long-WF were significant (Fig 1B). Those SPDs were within the acceptable ranges when weighted with IPTW.

The parallel trends of the experience and prevalence of dental caries were illustrated as age-specific estimates for the before phase (Appendix Fig 5). Overall, the age-specific trends in dental caries were well defined. In the before phase, when the No-WF and New-WF groups had no exposure to WF, their age-specific trends were nearly parallel. These trends were observed for both primary and permanent dentitions.

The dental caries experience and prevalence in the 3 exposure groups were assessed for the before and after phases (Figs 2 and 3). The causal estimands (absolute and relative DiD estimates between No-WF and New-WF) using the main ITT analysis and the additional PP analysis are shown below the figures.

Primary Dentition

At the before phase, the mean dmfs scores in the No-WF and New-WF groups were comparable and markedly larger than the dmfs score in the Long-WF group (Fig 2). The indicator in No-WF declined slightly, while that in New-WF declined at a markedly greater rate. The mean dmfs score of children in New-WF in the after phase became comparable to that of children in Long-WF. The absolute DiD estimates indicate that those children in New-WF had 1.1 (0.0 to 2.1) fewer tooth surfaces with dental caries in the ITT analysis and 1.7 (0.5 to 2.9) surfaces in the PP analysis in the after phase than in the before phase than those in No-WF. The respective relative DiD estimates were 1.40 (1.08 to 1.80) and 1.67 (1.26 to 2.22), indicating greater reductions in New-WF than in No-WF.

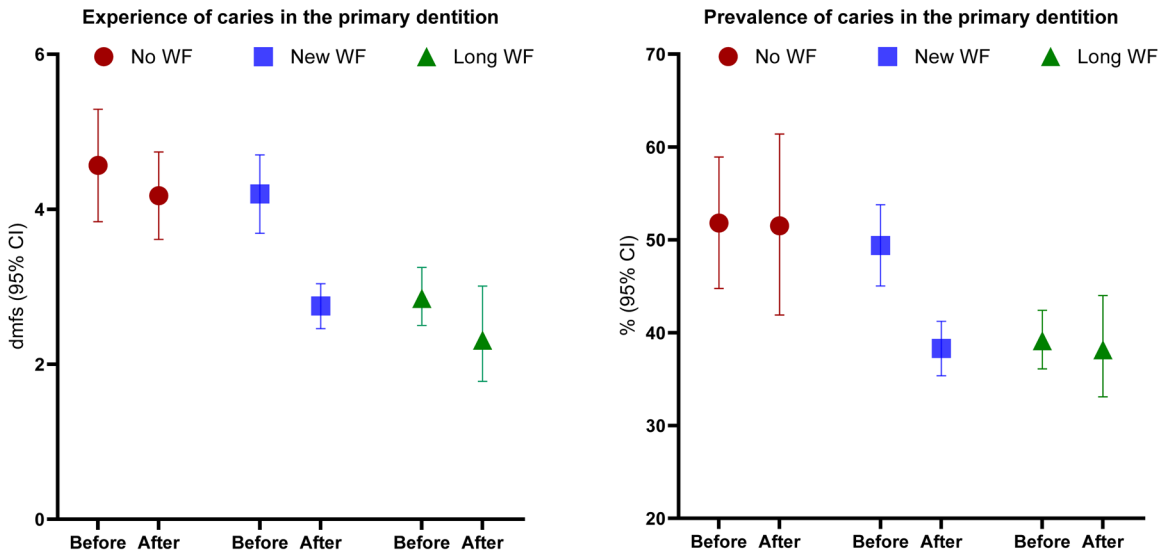
Similarly, No-WF and New-WF had comparable prevalence of dental caries in the primary dentition (Fig 2). While the prevalence remained unchanged in No-WF, there was a significant decline in New-WF, bringing it to a level comparable to Long-WF. The absolute DiD estimate was 10.8% (0.4 to 24.2) in the ITT analysis and 17.1% (1.2 to 32.5) in the PP analysis. The corresponding relative DiD estimates were 1.28 (1.00 to 1.67) and 1.42 (1.09 to 1.84), respectively.

The confirmatory analysis comparing New-WF with Long-WF demonstrated that the primary outcomes of New-WF had moved toward those of Long-WF (Figs 2 and 3). The absolute and relative changes in the primary outcomes were highly comparable with the causal estimands between New-WF and No-WF.

Permanent Dentition

At the before phase, indicators of dental caries in the permanent dentition were comparable between No-WF and New-WF (Fig 3). There were declines in dental caries experience and prevalence in both No-WF and New-WF, but these remained higher than in Long-WF. The absolute DiD estimate for the prevalence was small: 1% in the ITT analysis and 3% in the PP analysis. The causal difference in the experience of dental caries in the permanent dentition was more marked. The absolute DiD estimate was 0.3 DMFS in the ITT analysis and 0.5 DMFS in the PP analysis. The relative DiD estimates for dental caries experience in permanent dentition were 1.32 and 1.42, respectively. The confirmatory analysis also indicated that the primary outcomes of New-WF moved toward those of Long-WF. The magnitudes of the changes were comparable to the causal estimands between New-WF and No-WF.

The sensitivity analysis, which included covariates of dental caries (dental visits, sugar consumption, fluoride applications,



INTENTION-TO-TREAT ANALYSIS:

Average Treatment effect in the Treated (ATT): New WF vs No WF

Experience of dental caries (dmfs)		Prevalence of dental caries (%)	
DiD	**ATT (95%CI)**	**DiD**	**ATT (95%CI)**
Absolute:	**1.1** (0.0–2.1)	**Absolute:**	**10.8%** (0.4 – 24.2)
Relative:	**1.40** (1.08–1.80)	**Relative:**	**1.28** (1.00 –1.67)

PER-PROTOCOL ANALYSIS:

Average Treatment effect in the Treated (ATT): New WF vs No WF

Experience of dental caries (dmfs)		Prevalence of dental caries (%)	
DiD	**ATT (95%CI)**	**DiD**	**ATT (95%CI)**
Absolute:	**1.7** (0.5–2.9)	**Absolute:**	**17.1%** (1.2 –32.5)
Relative:	**1.67** (1.26–2.22)	**Relative:**	**1.42** (1.09 –1.84)

CONFIRMATORY ANALYSIS:

Average Treatment effect in the Treated (ATT): New WF vs Long WF

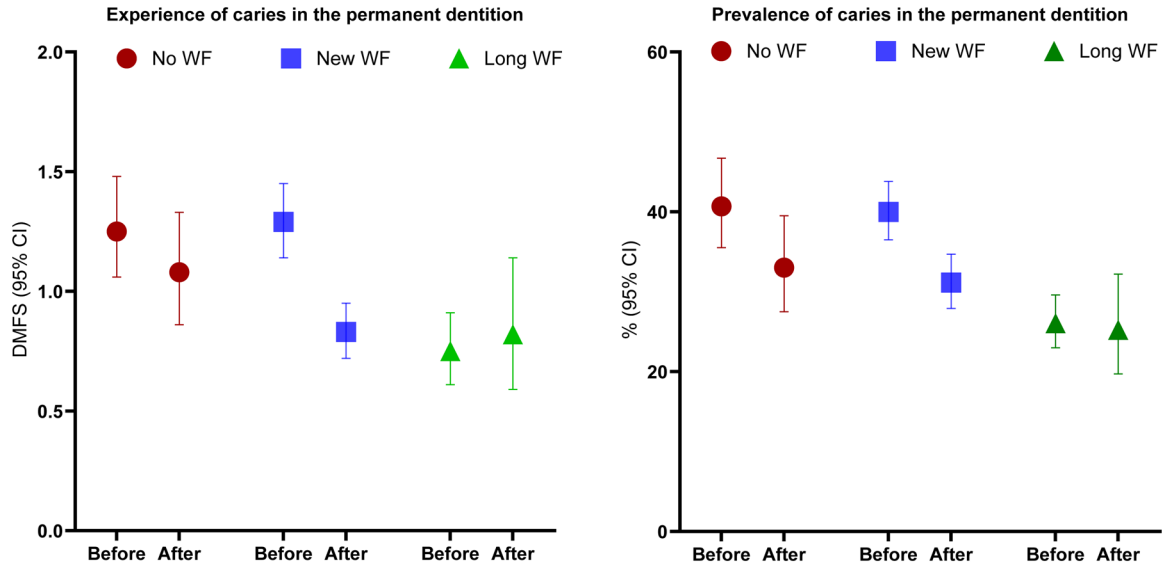
Experience of dental caries (dmfs)		Prevalence of dental caries (%)	
DiD	**ATT (95%CI)**	**DiD**	**ATT (95%CI)**
Absolute:	**0.8** (-0.1–1.7)	**Absolute:**	**10.6** (3.3–17.9)
Relative:	**1.24** (0.90–1.71)	**Relative:**	**1.28** (1.06–1.54)

Figure 2. Before-and-after changes in the experience and prevalence of dental caries in the primary dentition in the 3 zones by water fluoridation status. ATT, average treatment effect in the treated; CI, confidence interval; DiD, difference-in-differences; Long WF, long-term fluoridated; New WF, newly fluoridated (areas that became fluoridated since 2010); No WF, never fluoridated.

and toothbrushing), showed that the directions and magnitude of the changes in the primary outcomes were similar to those in the primary analysis (Appendix Figs 6 and 7). These analyses demonstrated that the observed changes in the primary outcomes were not affected by changes in those covariates.

Discussion

This population-based controlled DiD analysis investigated the causal effect of expanding WF on dental caries. In answering the causal research question, the study provided evidence of a



INTENTION-TO-TREAT ANALYSIS:

Average Treatment effect in the Treated (ATT): New WF vs No WF

Experience of dental caries (DMFS)		Prevalence of dental caries (%)	
DiD	**ATT (95%CI)**	**DiD**	**ATT (95%CI)**
Absolute:	**0.3** (-0.1–0.6)	**Absolute:**	**1.0%** (-8.3–7.2)
Relative:	**1.32** (0.95–1.84)	**Relative:**	**1.04** (0.81–1.33)

PER-PROTOCOL ANALYSIS:

Average Treatment effect in the Treated (ATT): New WF vs No WF

Experience of dental caries (DMFS)		Prevalence of dental caries (%)	
DiD	**ATT (95%CI)**	**DiD**	**ATT (95%CI)**
Absolute:	**0.5** (0.0–0.9)	**Absolute:**	**3.0%** (-6.7–12.8)
Relative:	**1.42** (1.00–2.06)	**Relative:**	**1.11** (0.84–1.47)

CONFIRMATORY ANALYSIS:

Average Treatment effect in the Treated (ATT): New WF vs Long WF

Experience of dental caries (DMFS)		Prevalence of dental caries (%)	
DiD	**ATT (95%CI)**	**DiD**	**ATT (95%CI)**
Absolute:	**0.6** (0.2–1.0)	**Absolute:**	**6.3%** (-1.5–14.1)
Relative:	**1.75** (1.15–2.67)	**Relative:**	**1.19** (0.89–1.61)

Figure 3. Before-and-after changes in the experience and prevalence of dental caries in the permanent dentition in the 3 zones by water fluoridation status. ATT, average treatment effect in the treated; CI, confidence interval; DiD, difference-in-differences; DMFS, decayed, missing, or filled permanent teeth; Long WF, long-term fluoridated; New WF, newly fluoridated (areas that became fluoridated since 2010); No WF, never fluoridated.

causal relationship between the expansion of WF and a significant reduction in the prevalence and experience of dental caries in the primary dentition. There was also a small reduction in the indicators of dental caries in permanent dentition.

The study findings are important, given the current paucity of contemporary high-quality scientific evidence on the effectiveness of WF (Iheozor-Ejiofor et al 2024). There are also uncertainties regarding the magnitude of the effect when the

population level of dental caries is low and other fluoride sources are available. Those issues affect the expansion and maintenance of this important population preventive program (Do et al 2025).

Caries levels in this population are low to moderate by international standards, comparable to recent estimates from other high-income countries where WF was evaluated (Goodwin et al 2024). Other preventive measures available to Queensland children included near-universal access to fluoride toothpaste, dental services providing regular checkups and, where clinically indicated, fissure sealants and topical fluoride applications, regardless of WF status. Those preventive measures are considered important for oral health in Nordic countries, which do not have WF (Nyvad and Fejerskov 2026). Our finding that WF conferred benefit even in this context of low disease burden and multiple coexisting preventive measures speaks to the continued value of WF as a population-level program. Importantly, WF passively delivers a constant low level of fluoride to all individuals through a physiological act of drinking, regardless of socioeconomic status or physical ability. Hence, WF can reduce socioeconomic inequality in oral health (Matsuo et al 2020; Matsuyama et al 2025).

The study was designed and conducted to satisfy the requirements of the causal inference approach using observational data, combining careful study design with appropriate statistical adjustment (Hernán and Robins 2006; Hernán 2021). Accordingly, the study employed a controlled DiD design with concurrent control groups, and the overall study design and analytical approaches were structured to satisfy the key assumptions of the DiD framework (Lechner 2011; Dimick and Ryan 2014; Wing et al 2018).

The observed effects of WF on caries were large and consistent across both experience and prevalence in the primary dentition, while it had smaller effects on the permanent dentition. A large proportion of the children in our study did not spend their entire lives in fluoridated areas. Some local areas commenced fluoridation but later discontinued it, which was considered as No-WF in our analysis, potentially resulting in lower observed DiD estimates.

The study's findings were consistent with the current body of knowledge. It has been widely accepted that WF is effective (NHMRC 2017; Iheozor-Ejiofor et al 2024). Its removal from public water supplies might lead to a costly worsening of child oral health (Choi and Simon 2025). A recent cohort study reported that WF reduced dental caries, with a larger effect size in the primary than in the permanent dentition (Goodwin et al 2024).

The study has a significant strength in having both a negative control and a positive control. The former enabled the controlled DiD analysis to calculate the causal estimands of fluoridation expansion. The latter enabled additional confirmatory analysis to further examine the causal effect. A potential limitation of the study was that the dental examiners were not blind to the location and, therefore, the possibility of exposure to fluoridated water at that location. However, the examiners had no knowledge of the children's main source of water. Our additional analysis of lifetime exposure to WF showed that nonblinding did not affect the overall findings. We regularly conducted quality-control procedures to ensure consistency in dental examinations. The reliability of dental examinations against the senior trainers was excellent. Our clinical assessment did not use radiographs, which may have led to an underestimation of proximal caries (Newman et al 2009). This potential measurement issue is consistent across New-WF and No-WF zones in our study. Such a limitation would lead to an underestimation of WF's preventive effect, as it is more effective on smooth tooth surfaces. Fissure sealants on permanent molars, where present, can further obscure caries-related surface changes. Both phenomena could contribute to the smaller effect observed in the permanent dentition, independent of any true difference in the effect of WF by dentition.

Conclusion

This research has provided contemporary scientific evidence of the effects of WF on dental caries. Implementation, maintenance and expansion of WF as a public health program continue to improve population oral health in contemporary society.

Author Contributions

L.G. Do, contributed to conception and design, data acquisition, analysis, and interpretation, drafted and critically revised the manuscript; A. John Spencer, contributed to conception and design, data acquisition, critically revised the manuscript; K. Roberts-Thomson, contributed to conception, data acquisition, critically revised the manuscript; R. Lalloo, J. Broadbent, M. Foley, H. Whelton, T. Le, M. Herzig, E. Gielis, B. Appleyard, contributed to acquisition, critically revised the manuscript; C.T. Sexton, contributed to analysis, critically revised the manuscript; H. Schuch, contributed to interpretation, critically revised the manuscript; D.H. Ha, contributed to conception and design, data acquisition and interpretation, critically revised the manuscript. All authors gave their final approval and agree to be accountable for all aspects of the work.

Acknowledgments

All members of the research team and dental teams are gratefully acknowledged. Participating schools, children and their parents are gratefully acknowledged. Dr Ben Stute, Queensland Chief Dental Officer, and Professor Pauline Ford of The University of Queensland are acknowledged for their contribution to the project's funding and conduct.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship and/or publication of this article: The study was funded by the National Health and Medical Research Council Ideas grant APP1181029 and supported by The University of Queensland, Queensland Health and Queensland Education.

Role of the Funder/Sponsor

The funder had no role in the design or conduct of the study; collection, management, analysis or interpretation of the data; preparation, review or approval of the manuscript; or decision to submit the manuscript for publication.

ORCID iDs

L.G. Do https://orcid.org/0000-0003-3684-9949
R. Lalloo https://orcid.org/0000-0001-5822-1269
J. Broadbent https://orcid.org/0000-0002-8905-398X
H. Whelton https://orcid.org/0000-0002-0881-360X
D.H. Ha https://orcid.org/0009-0005-9472-7650

Data-Sharing Statement

Deidentified data used in this study are stored in The University of Queensland's Research Data Management (UQRDM) system (cloud.rdm.uq.edu.au). Deidentified data can be requested from the corresponding author, subject to execution of a data use agreement and approval from the Children's Health Queensland Ethics Committee, consistent with the terms of the original ethics approval. SAS codes used for the study are available from the corresponding author.

References

Bilinski A, Feng S, Hatfield LA. 2026. Estimating intervention effects with difference-in-differences. JAMA. 336(6):508–509. https://doi.org/10.1001/jama.2026.12551

Caniglia EC, Murray EJ. 2020. Difference-in-difference in the time of cholera: a gentle introduction for epidemiologists. Curr Epidemiol Rep. 7(4):203–211. https://doi.org/10.1007/s40471-020-00245-2

Centers for Disease Control and Prevention. 2001. Recommendations for using fluoride to prevent and control dental caries in the United States. MMWR Recomm Rep. 50(RR-14):1–42.

Choi SE, Simon L. 2025. Projected outcomes of removing fluoride from US public water systems. JAMA Health Forum. 6(5):e251166. https://doi.org/10.1001/jamahealthforum.2025.1166

Dimick JB, Ryan AM. 2014. Methods for evaluating changes in health care policy: the difference-in-differences approach. JAMA. 312(22):2401–2402. https://doi.org/10.1001/jama.2014.16153

Do LG, Schuch HS, Ha DH. 2026. Queensland child oral health—successes, challenges, and future directions. Pressbooks. https://doi.org/10.14264/b75032d

Do LG et al. 2018. Race- and income-related inequalities in oral health in Australian children by fluoridation status. JDR Clin Translat Res. 3(2):170–179. https://doi.org/10.1177/2380084417751350

Do LG, Ha DH, Spencer AJ, Rugg-Gunn A. 2026. Controversies and public health implications of community water fluoridation. J Dent Res. 105(5):561–569. https://doi.org/10.1177/00220345251394295

Do LG, Spencer AJ. 2015. Contemporary multilevel analysis of the effectiveness of water fluoridation in Australia. Aust N Z J Public Health. 39(1):44–50. https://doi.org/10.1111/1753-6405.12299

Do LG, Spencer AJ. 2016. Oral health of Australian children. The National Child Oral Health Study 2012-14. Adelaide University Press. https://doi.org/10.20851/ncohs

Goodwin M et al. 2024. The CATFISH study: an evaluation of a water fluoridation program in Cumbria, UK. Community Dent Oral Epidemiol. 52(4):590–600. https://doi.org/10.1111/cdoe.12967

Ha DH et al. 2026. Effect of early life income and sugars intake on child oral health: marginal structural modelling using a birth cohort study. Caries Res. 60(1):1–11. https://doi.org/10.1159/000546215

Hernán MA, Robins JM. 2020. Causal inference: what if. Chapman & Hall/CRC.

Hernán MA. 2021. Methods of public health research—strengthening causal inference from observational data. N Engl J Med. 385(15):1345–1348. https://doi.org/10.1056/nejmp2113319

Hernán MA, Robins JM. 2006. Estimating causal effects from epidemiological data. J Epidemiol Community Health. 60(7):578–586. https://doi.org/10.1136/jech.2004.029496

Iheozor-Ejiofor Z et al. 2015. Water fluoridation for the prevention of dental caries. Cochrane Database Syst Rev. 2015(6):CD010856. https://doi.org/10.1002/14651858.cd010856.pub2

Iheozor-Ejiofor Z et al. 2024. Water fluoridation for the prevention of dental caries. Cochrane Database Syst Rev. 10(10):CD010856. https://doi.org/10.1002/14651858.cd010856.pub3

Lechner M. 2011. The estimation of causal effects by difference-in-difference methods. Found Trends® Econom. 4(3):165–224. https://doi.org/10.1561/0800000014

Levy SM. 2025. Caution needed in interpreting the evidence base on fluoride and IQ. JAMA Pediatr. 179(3):231–234. https://doi.org/10.1001/jamapediatrics.2024.5539

Listl S, Matsuyama Y, Jürges H. 2022. Causal inference: onward and upward! J Dent Res. 101(8):877–879. https://doi.org/10.1177/00220345221084283

Marino M, Stuart EA, Galea S. 2025. Methodological rigor in health policy and health services research. JAMA Health Forum. 6(12):e255887. https://doi.org/10.1001/jamahealthforum.2025.5887

Matsuo G, Aida J, Osaka K, Rozier RG. 2020. Effects of community water fluoridation on dental caries disparities in adolescents. Int J Environ Res Public Health. 17(6):2020. https://doi.org/10.3390/ijerph17062020

Matsuyama Y et al. 2025. Water fluoridation as a population strategy reducing oral health inequalities: high-dimensional effect heterogeneity analysis using machine learning. Int J Epidemiol. 54(4):dyaf080. https://doi.org/10.1093/ije/dyaf080

McDonagh MS et al. 2000. Systematic review of water fluoridation. BMJ. 321(7265):855–859. https://doi.org/10.1136/bmj.321.7265.855

Nandi A, Glymour MM, Kawachi I, VanderWeele TJ. 2012. Using marginal structural models to estimate the direct effect of adverse childhood social conditions on onset of heart disease, diabetes, and stroke. Epidemiology. 23(2):223–232. https://doi.org/10.1097/ede.0b013e31824570bd

National Health and Medical Research Council. 2017. Information paper—water fluoridation: dental and other human health outcomes. National Health and Medical Research Council.

National Institute of Dental and Craniofacial Research. 2002. National Health and Nutrition Examination Survey dental examiners procedures manual. US National Center for Health Statistics.

Newman B, Seow WK, Kazoullis S, Ford D, Holcombe T. 2009. Clinical detection of caries in the primary dentition with and without bitewing radiography. Aust Dent J. 54(1):23–30. https://doi.org/10.1111/j.1834-7819.2008.01084.x

Nyvad B, Fejerskov O. 2026. Remarkable decline and sustained low levels of caries in the Nordic populations-explanations and implications for public oral health. Eur J Oral Sci. 134(4):e70114. https://doi.org/10.1111/eos.70114

Pollick H. 2018. The role of fluoride in the prevention of tooth decay. Pediatr Clin North Am. 65(5):923–940. https://doi.org/10.1016/j.pcl.2018.05.014

Sexton CT et al. 2024. Socio-economic status and access to fluoridated water in Queensland: an ecological data linkage study. Med J Aust. 220(2):74–79. https://doi.org/10.5694/mja2.52196

Smith VA, Coffman CJ, Hudgens MG. 2021. Interpreting the results of intention-to-treat, per-protocol, and as-treated analyses of clinical trials. JAMA. 326(5):433–434. https://doi.org/10.1001/jama.2021.2825

Sofer T, Richardson DB, Colicino E, Schwartz J, Tchetgen Tchetgen EJ. 2016. On negative outcome control of unobserved confounding as a generalization of difference-in-differences. Stat Sci. 31(3):348–361. https://doi.org/10.1214/16-sts558

Spencer AJ, Do LG, Ha DH. 2018. Contemporary evidence on the effectiveness of water fluoridation in the prevention of childhood caries. Community Dent Oral Epidemiol. 46(4):407–415. https://doi.org/10.1111/cdoe.12384

Stuart EA et al. 2014. Using propensity scores in difference-in-differences models to estimate the effects of a policy change. Health Serv Outcomes Res Methodol. 14(4):166–182. https://doi.org/10.1007/s10742-014-0123-z

Taylor KW et al. 2025. Fluoride exposure and children's IQ scores: a systematic review and meta-analysis. JAMA Pediatr. 179(3):282–292. https://doi.org/10.1001/jamapediatrics.2024.5542

Vandenbroucke JP et al. 2007. Strengthening the Reporting of Observational Studies in Epidemiology (STROBE): explanation and elaboration. PLoS Med. 4(10):e297. https://doi.org/10.1371/journal.pmed.0040297

Wing C, Simon K, Bello-Gomez RA. 2018. Designing difference in difference studies: best practices for public health policy research. Annu Rev Public Health. 39:453–469. https://doi.org/10.1146/annurev-publhealth-040617-013507