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How effective and cost-effective is water fluoridation for adults and adolescents? The LOTUS 10-year retrospective cohort study

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Abstract

Objective: To pragmatically assess the clinical and cost-effectiveness of water fluoridation for preventing dental treatment and improving oral health in a contemporary population of adults and adolescents, using a natural experiment design.

Methods: A 10-year retrospective cohort study (2010–2020) using routinely collected NHS dental treatment claims data. Participants were patients aged 12 years and over, attending NHS primary dental care services in England (17.8 million patients). Using recorded residential locations, individuals exposed to drinking water with an optimal fluoride concentration (≥0.7 mg F/L) were matched to non-exposed individuals using propensity scores. Number of NHS invasive dental treatments, DMFT and missing teeth were compared between groups using negative binomial regression. Total NHS dental treatment costs and cost per invasive dental treatment avoided were calculated.

Results: Matching resulted in an analytical sample of 6.4 million patients. Predicted mean number of invasive NHS dental treatments (restorations 'fillings'/extractions) was 3% lower in the optimally fluoridated group (5.4) than the non-optimally fluoridated group (5.6) (IRR 0.969, 95% CI 0.967, 0.971). Predicted mean DMFT was 2% lower in the optimally fluoridated group (IRR 0.984, 95% CI 0.983, 0.985). There was no difference in the predicted mean number of missing teeth per person (IRR 1.001, 95% CI 0.999, 1.003) and no compelling evidence that water fluoridation reduced social inequalities in dental health. Optimal water fluoridation in England 2010–2020 was estimated to cost £10.30 per person (excludes initial set-up costs). NHS dental treatment costs for optimally fluoridated patients 2010–2020 were 5.5% lower, by £22.26 per person (95% CI -£21.43, −£23.09).

Conclusions: Receipt of optimal water fluoridation 2010–2020 resulted in very small positive health effects which may not be meaningful for individuals. Existing fluoridation programmes in England produced a positive return on investment between 2010 and 2020 due to slightly lower NHS dental care utilization. This return should be evaluated against the projected costs and lifespan of any proposed capital investment in water fluoridation, including new programmes.

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KEYWORDS
adults, dentistry, economics, health inequities, oral health, routinely collected health data, water fluoridation

1 | BACKGROUND

Permanent dentition caries, the most prevalent condition globally, results in extensive negative impacts for both individuals and society.[1] The first studies of initiation of community water fluoridation reported that it reduced the mean number of teeth affected by up to two-thirds.[2,3] Fluoridation of drinking water is therefore justifiably recognized as one of the 20th century's greatest public health achievements.[4] As with any public health intervention, continued monitoring is required as the implementation context evolves over time. In particular, fluoride toothpastes became available in the mid-1970s and are considered to be the key factor in the dramatic decline in the prevalence and severity of dental caries in high income countries since the 1960s.[5] In such countries caries has evolved from a rapidly progressing disease of childhood which results in early tooth loss, to a slowly progressing disease with the greatest burden now experienced by adults.[6]

High-quality reviews of water fluoridation identify a lack of contemporary evidence across age groups, limited evidence which includes adults, and economic analyses which use historic data on the likely impact of fluoridation on caries, combined with modelled, rather than actual costs.[7-10] Furthermore, no systematic review has ever identified sufficient evidence, in terms of volume, quality, and consistency, that water fluoridation reduces social inequalities in dental caries.[10] In 2002, a comprehensive review by the UK Medical Research Council (MRC) made recommendations for further research on water fluoridation.[11] These included; further research on the effects of water fluoridation in adults, how the effects may vary by social class, and economic impacts. In addition, the MRC requested information on health and wellbeing outcomes that matter to patients and the public, beyond the usual caries measures of decayed, missing, or filled teeth.[11]

Conducting research on the effects of water fluoridation in adults involves greater methodological challenges than in children. Notably, recruitment and retention without an obvious public setting such as schools, measurement of exposure over longer-time frames, and capturing the longer-term impacts of recurrent caries, and the restorative cycle.[12] These challenges meant that existing evidence gaps and recommendations for research in adults remained largely unaddressed when planning this study. During initial public involvement activities, patients and the public told us that preventing dental treatment, particularly that involving 'the drill' or 'injection', was a key outcome they would hope to avoid as a result of water fluoridation. Others were not losing teeth to extraction and avoiding dental charges.

The present study has been designed to address some of the priorities for research first articulated by the MRC 20 years ago, in a pragmatic and cost-efficient way, using routinely collected NHS dental claims data.

1.1 | Aim

To pragmatically assess the clinical and cost-effectiveness of water fluoridation for preventing dental treatment and improving oral health in a contemporary population of adults, using a natural experiment design.

Adolescents aged 12 years and over were included in the study cohort because by this age, they are likely to have all of their permanent, adult teeth (except third molars). Furthermore, the NIHR CATFISH study was underway which provides contemporary data on the effects of water fluoridation in children up to the age of 12.[13]

2 | METHODS

The LOTUS study (fLuOridaTion for adUltS) was a retrospective cohort study using routinely collected National Health Service (NHS) dental treatment claims (FP17) data, submitted to the NHS Business Services Authority (NHS BSA), between 22nd November 2010 and 21st October 2020. Data were collected in a range of NHS primary dental care settings, including: general dental practices, community dental services, domiciliary settings, prisons, urgent/out-of-hours and specialized referral-only services.

The primary objective was to evaluate the impact of water fluoridation on NHS invasive dental treatments (restorations and extractions). Secondary objectives were to evaluate the impact on oral health (caries experience [DMFT] and missing teeth), social inequalities in oral health, and to determine cost-effectiveness and return-on-investment.

Approval for NHS BSA to select the cohort and de-identify the data was given by the Health Research Authority Confidentiality Advisory Group (20/CAG/0072) and the study received ethical approval from North East, Tyne & Wear South Research Ethics Committee (20/NE/0144). The study protocol was published in 2021.[12]

Treatment claims for individual courses of treatment from different settings were linked together by NHS BSA to create the longitudinal cohort, using the following selection criteria:

- Claims relating to a unique individual (confirmed by 1: 1 NHS number and NHS BSA ID match)
- 12 years and over on 22nd November 2010
- Valid English postcode at first dental visit

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- Attended at least twice between 22nd November 2010 and 21st October 2020. This was to provide least two data points on location of residence (to assign fluoridation exposure).

Treatment claims relating solely to orthodontic care were excluded, as were patients who had requested the NHS National Data Opt-Out.

The fully anonymised study population dataset was transferred to The University of Manchester in April 2021. Individuals were assigned a personalized water fluoride exposure for 2010–2020 (Mg F/L). This was achieved by combining the Lower Super Output Area(s) (LSOAs) the individual had lived in (LSOAs are census districts containing an average of 1500 people), with LSOA-level annual mean drinking water fluoride concentrations (Mg F/L) for each year between 2010 and 2020.[14,15] LSOA of patient residence in each year was carried backwards or forwards from each course of dental treatment, until a new LSOA was recorded. Simple imputation was used if there were missing LSOA-level data on annual fluoride concentration for some of the years. Patients exposed to an individual grand mean water fluoride concentration of 0.7 mg F/L and above 2010–2020 were assigned to the 'optimally fluoridated' group and patients with a grand mean of less than 0.7 mg F/L were assigned to the 'non-optimally fluoridated' group. The threshold of 0.7 mg F/L was chosen to define optimally fluoridated because previous work had identified widespread dosing below the 1 mg F/L target,[16] and this threshold aligned with binary analyses in English statutory health monitoring reports.[17]

To create comparable groups for analysis, individuals in the optimally fluoridated group were matched to individuals in the non-optimally fluoridated group using propensity scores. Baseline characteristics for matching were selected using subject matter knowledge and theory to include all hypothesised confounders and important outcome predictors. Prior to variable selection, causal assumptions were made explicit using directed acyclic graphs (DAGs) (S1). Baseline characteristics were sourced from data recorded at the patient's first course of dental treatment. They included individual-level (age, sex, patient Index of Multiple Deprivation decile (IMD), ethnicity, and NHS charge exemption status as a proxy for income level), and contextual-level characteristics (patient urban–rural designation, dental practice IMD, dental practice contract type, number of Units of Dental Activity (UDAs) commissioned in patient's local authority). Further detail on these measures is available in S1.

Propensity scores were estimated in R (MatchIt) using logistic regression.[18,19] Distance matching was carried out using three specifications of nearest neighbour matching (one-to-one, variable ratio, and variable ratio with a 0.25 calliper). Due to the very large sample size, propensity score estimation and matching were conducted using the University of Manchester's computationally intensive research platform (The Interactive Computation Shared Facility, aka Incline).

The resulting matched dataset which best met our pre-specified criteria regarding overall sample size, balance on baseline characteristics, and ability to estimate the Average Treatment effect in the Treated group (ATT), was taken forwards for further analysis. Values of absolute standardized mean differences (SMDs) were used in preference to hypothesis tests to determine covariate balance, with SMDs below a threshold of 0.1 standard deviations considered to constitute adequate balance.[20] The effect of optimal water fluoridation on the primary and secondary clinical outcomes was estimated using a generalized linear model (GLM), including matching weights and using cluster robust standard errors. To determine whether there was a differential effect of water fluoridation according to deprivation, we included patient deprivation decile as an interaction term.

Cost effectiveness was assessed as the cost of water fluoridation required to avoid one episode of invasive dental treatment (Incremental Cost-Effectiveness Ratio [ICER]). To avoid double counting benefits (because the primary measure of health effect is number of invasive dental treatments), changes in costs of dental treatment are not included in the ICER. Differences in overall costs to the public sector are reflected in the return on investment (ROI) estimate. Differences in NHS costs by fluoridation group were estimated using a GLM. The time horizon was 2010–2020 and the perspective accounted for the direct costs accrued by relevant public sector bodies (Public Health England [PHE], Local Authorities and NHS).

Operating and capital costs of water fluoridation for England were supplied by PHE for the years 2013–2019. Earlier costs were not available. Annual costs for 2010–2012 were imputed using the mean from 2013 to 2019. NHS dental care utilization and patient charges were contained within the study population dataset and an average Unit of Dental Activity (UDA) price for England, supplied by NHS BSA (under the Freedom of Information Act [2000]) was used to calculate costs to the NHS. The main health economic analysis included all types of NHS dental care, not just invasive treatments. All costs were converted to 2020 prices.[21] We also undertook a sensitivity analysis based on the Scottish fee-per-item system of costing dental treatment, which allowed us to disaggregate invasive dental treatments from other treatments and examine relative differences in costs between groups (S3).

3 | RESULTS

We sourced water fluoride concentration sample data (Mg F/L) and corresponding water supply zone (WSZ) maps covering >99% of the 32, 844 LSOAs in England between 2011 and 2019, with slightly lower data availability for 2010 (97.5%) and 2020 (80.3%) (S2).[14] After simple imputation for the years with missing data, 99.8% of LSOAs in England had an annual water fluoride concentration assigned between 2010 and 20. A map illustrating the coverage of optimal water fluoridation using these data is available in Figure 1.

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TABLE 1 Baseline individual level characteristics of the unmatched and matched cohorts.

Cohort	Unmatched		Matched	
Characteristic	Non-optimally fluoridated	Optimally fluoridated	Non-optimally fluoridated	Optimally fluoridated
Total participants	16 243 711	1 593 891	4 777 710	1 592 570
Male (%)	7 227 473 (44.5)	707 093 (44.4)	2 119 584 (44.4)	706 528 (44.4)
Female (%)	9 016 238 (55.5)	886 798 (55.6)	2 658 126 (55.6)	886 042 (55.6)
Age: Mean (SD)	42.7 (18.1)	43.1 (18.0)	43.5 (18.3)	43.1 (18.0)
Deprivation decile				
IMD Q1 (%) (most deprived)	1 508 826 (9.3)	271 545 (17.0)	813 723 (17.0)	271 241 (17.0)
IMD Q2 (%)	1 549 589 (9.5)	228 849 (14.4)	685 104 (14.3)	228 368 (14.3)
IMD Q3 (%)	1 625 795 (10.0)	164 686 (10.3)	493 686 (10.3)	164 562 (10.3)
IMD Q4 (%)	1 665 910 (10.3)	138 048 (8.7)	413 940 (8.7)	137 980 (8.7)
IMD Q5 (%)	1 669 258 (10.3)	141 958 (8.9)	425 658 (8.9)	141 886 (8.9)
IMD Q6 (%)	1 682 393 (10.4)	130 876 (8.2)	392 451 (8.2)	130 817 (8.2)
IMD Q7 (%)	1 664 049 (10.2)	135 444 (8.5)	406 113 (8.5)	135 371 (8.5)
IMD Q8 (%)	1 663 949 (10.2)	136 154 (8.5)	408 306 (8.6)	136 102 (8.6)
IMD Q9 (%)	1 634 394(10.1)	131 645 (8.3)	394 791 (8.3)	131 597 (8.3)
IMD Q10 (%) (least deprived)	1 579 548 (9.7)	114 686 (7.2)	343 938 (7.2)	114 646 (7.2)
Ethnicity				
White (%)	11 112 050 (68.4)	1 058 370 (66.4)	3068228.4 (64.2)	1 057 826 (66.4)
Mixed/Multiple (%)	170 337 (1.1)	15 792 (1.0)	54712.8 (1.2)	15 762 (1.0)
Asian/Asian British (%)	655 708 (4.0)	109 810 (6.9)	374725.2 (7.8)	109 605 (6.9)
Black/African/Caribbean/ Black British (%)	268 743 (1.7)	29 894 (1.9)	89608.2 (1.9)	29 748 (1.9)
Other ethnic group (%)	214 010 (1.3)	15 763 (1.0)	55264.8 (1.2)	15 744 (1.0)
No information recorded (%)	3 822 863 (23.5)	364 262 (22.9)	1135170.6 (23.8)	363 885 (22.9)
NHS exemption status				
Not exempt (%)	11 884 863 (73.1)	1 095 157 (68.7)	3204184.8 (67.1)	1 094 527 (68.7)
Income related exemption (%)	3 497 084 (21.5)	421 828 (26.5)	1317265.2 (27.6)	421 219 (26.5)
Non-income related exemption (%)	861 764 (5.3)	76 906 (4.8)	256 260 (5.4)	76 824 (4.9)

The study population dataset (full unmatched cohort transferred from NHS BSA) contained records relating to 17 855 239 unique individuals (Figure 2). The cleaned and parsed dataset contained 137 million rows and 63 columns (31.5GB). Propensity score estimation and matching using nearest neighbour methods took, on average, 6 days to complete for each matching specification. The dataset resulting from the nearest neighbour, variable ratio matching specification was taken forwards for analysis, as it resulted in the largest sample size, adequate balance of baseline characteristics according to established guidelines, and retained all participants in the treated group, allowing us to estimate the ATT.[20] Table 1 presents individual level characteristics at baseline, for the unmatched and matched cohorts. Baseline contextual characteristics are available in S2.

After fluoride exposure assignment and propensity score matching the matched (analytical) cohort contained data on 6 370 280 individuals (Figure 2). Due to substantial overdispersion, negative binomial regression models were used for the analysis of health outcomes.

4 | PRIMARY OBJECTIVE

The rate of invasive dental treatments in the optimally fluoridated group was 3% lower than that of the non-optimally fluoridated group (IRR 0.969, 95% CI 0.967, 0.971) (Table 2).

5 | SECONDARY OBJECTIVES

5.1 | Oral health

Mean DMFT in the optimally fluoridated group was 2% lower than in the non-optimally fluoridated group (IRR 0.984, 95% CI 0.983, 0.985) (Table 2). There was no evidence of a difference in the predicted mean number of missing teeth as the 95% confidence interval includes the possibility of no effect (IRR 1.001, 95% CI 0.999, 1.003) (Table 2).

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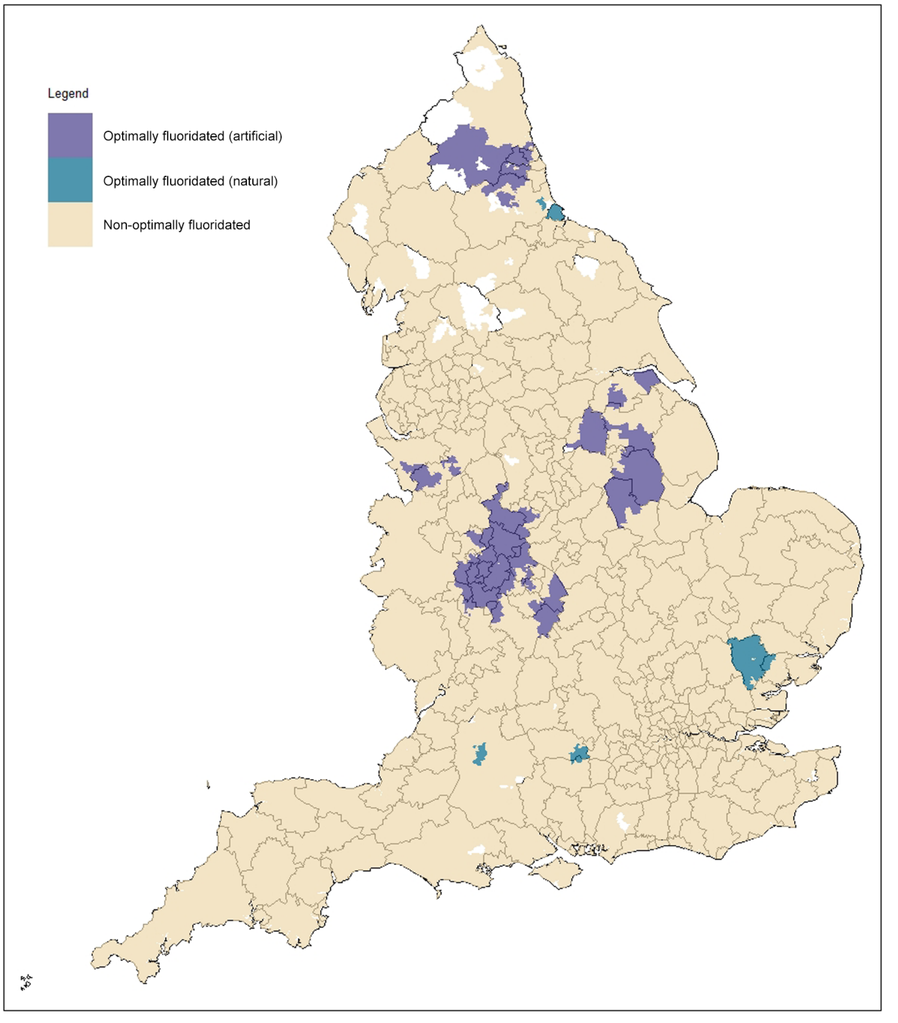

FIGURE 1 Map illustrating LSOAs receiving optimally fluoridated (=/> 0.7 Mg F/L) and non-optimally fluoridated water (<0.7 Mg F/L) in England between 2010 and 2020. Areas that were not covered by the data we obtained included the Isles of Scilly, national parks, mountainous areas and private water supplies. These areas are shown as white on the map. We were not able to source any formal indicator of which areas are intended to receive fluoridated water as a part of a public health programme. The natural/artificial designation on the map was created by visually comparing our maps to published sources which illustrate the areas of natural fluoridation.[22] Local authority district boundaries are overlaid.

5.2 | Social inequalities

The predicted number of invasive treatments was lower in the optimally fluoridated group than the non-optimally fluoridated group in all deciles, but the reductions were very small Figure 3, S2. The largest predicted reduction, of a third of an invasive dental treatment per person (0.34 fewer invasive dental treatments, 95% C.I. −0.37 to −0.30) was in the most deprived decile (IMD 1), a reduction of 5.4% (S2). DMFT did not demonstrate a social inequalities gradient in the expected direction (S2). For mean number of missing teeth, small between-group differences were evident in each decile of deprivation, but the direction of effect was not consistent (S2).

5.3 | Health economics

Total expenditure on water fluoridation between 2010 and 2019 financial years was estimated to be £46 791 388, or £10.30 per person receiving optimally fluoridated water (S2). In a GLM with a log-link and a gamma distribution to account for right-skewed cost data, the marginal effects estimate revealed a saving in NHS treatment costs for optimally fluoridated patients over the study period of £22.26 per person (95% CI −£21.43, −£23.09). This represents a relative reduction in costs to the NHS of 5.5% per person and includes costs recouped by the NHS through patient charges. Patients in the optimally fluoridated group paid on average £7.64 less in total NHS dental charges between 2010 and 2020. (Tables in S2, provide additional detail on NHS utilization and costs by group).

Water fluoridation is a whole-population intervention which cannot be implemented on a per-person basis. Therefore, in terms of cost-effectiveness and ROI, it is important to consider the potential size of the population to whom our within-sample findings might apply. If 62.9% of the population aged 12 years and older use NHS dental services at least twice in 10 years (the estimate considered most likely by our study oversight committee), we estimate that the cost of water fluoridation to avoid one invasive dental treatment (the ICER) was £94.55. The predicted ROI was estimated to be £16 884 595 (a 36% ROI made between 2010 and

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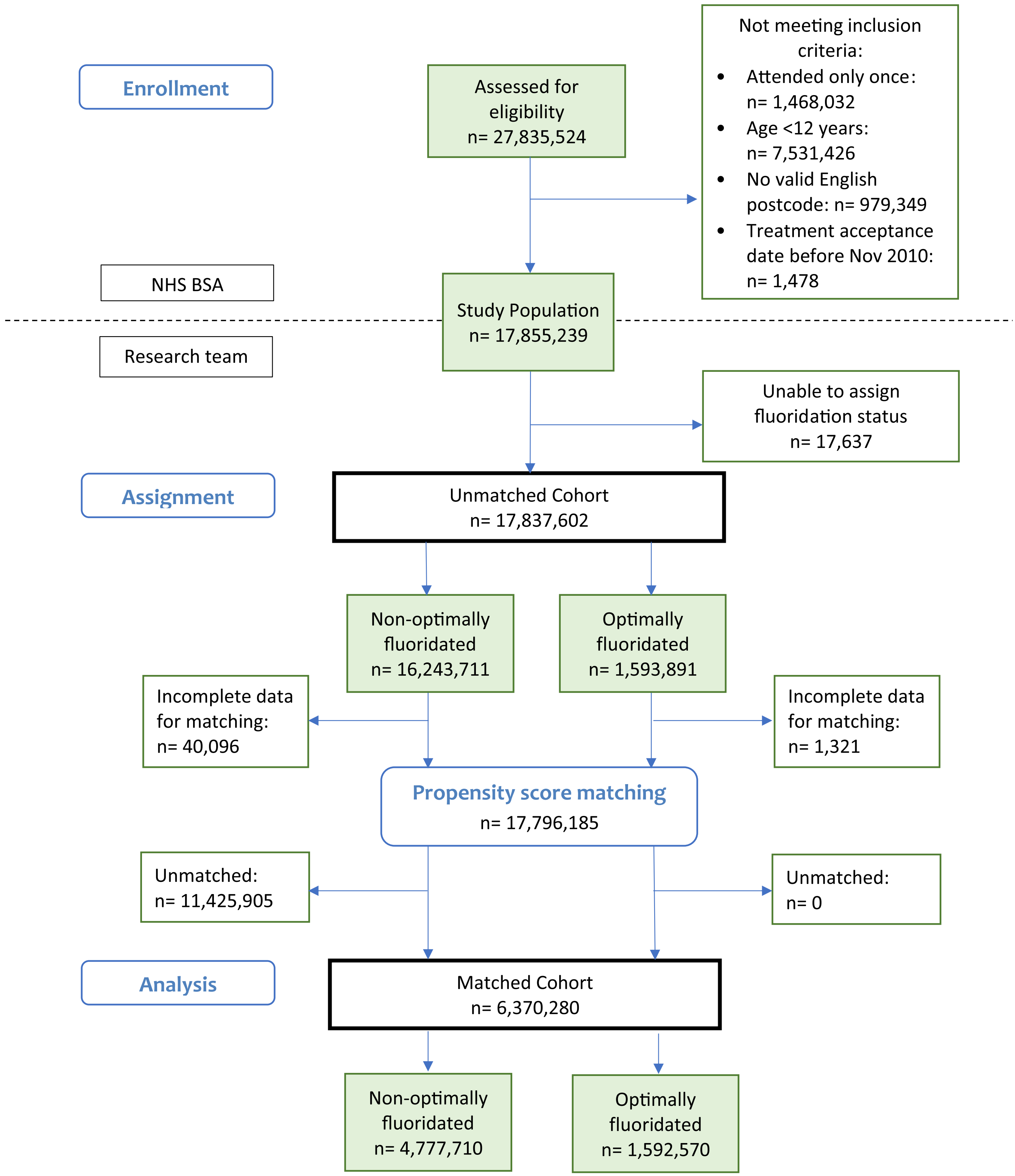

FIGURE 2 Participant flow diagram.

2020). Cost-effectiveness and ROI estimates using 100%, 75% and 50% NHS dental attendance, are presented in S2; all represented a positive return. The sensitivity analysis using Scottish fee-per-item costings for invasive dental treatments only, provided similar relative differences in costs to the English banded cost system (S3).

6 | DISCUSSION

6.1 | Key results

The LOTUS study is the first study conducted in the UK to capture health and economic effects of water fluoridation on adults and

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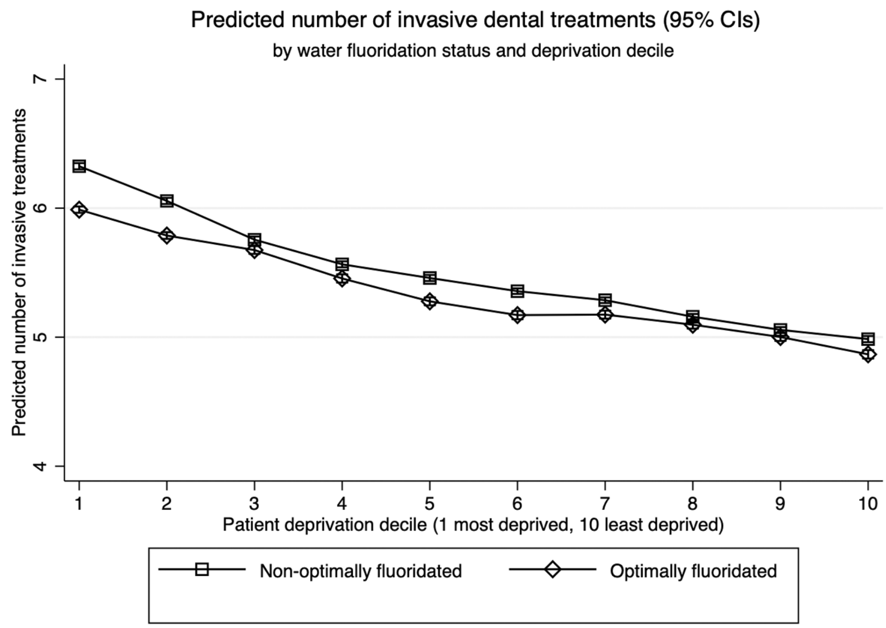

FIGURE 3 Predicted number of invasive dental treatments with 95% CIs by water fluoridation status and patient deprivation decile from negative binomial regression model.

TABLE 2 Predicted mean (SE) and incidence rate ratios (95% CIs) for primary and secondary outcomes by water fluoridation group.

Outcome (*n*)[a]	Non-optimally fluoridated Mean (SE)	Optimally fluoridated Mean (SE)	Difference in predicted means (95% CI)[b]	Incidence rate ratio (95% CI)
Invasive dental treatments (6370280)	5.616 (0.004)	5.443 (0.005)	−0.173 (−0.185, −0.161)	0.969 (0.967, 0.971)
DMFT (5517106)	13.361 (0.006)	13.149 (0.007)	−0.212 (−0.229, −0.194)	0.984 (0.983, 0.985)
Missing teeth (5517106)	6.646 (0.005)	6.652 (0.006)	−0.006 (−0.008, 0.021)	1.001 (0.999, 1.003)

[a]DMFT data were available from 1st of April 2016. DMFT taken from last course of dental treatment (closest to 2020).

[b]Difference in predicted means: Negative values favour water fluoridation.

adolescents with widespread access to topical fluorides. This study suggests that exposure to optimal water fluoridation between 2010 and 20 resulted in 'exceedingly small' health effects, 'very small'[23] reductions in NHS dental service utilization, and no meaningful reduction in social inequalities, in adult and adolescent users of NHS dental services. As the costs of NHS dentistry are much higher than the costs of water fluoridation, the relatively small observed reductions in NHS dental service utilization still resulted in a positive return for the public sector. However, it is important to remember that these returns were calculated for existing programmes, operating between 2010 and 2020, and did not include original set-up costs. We were unable to include original set-up costs in our calculations for the existing schemes as they were mostly incurred in the 1960s and 70s and therefore this information was unavailable.

6.2 | Strengths

Using routinely collected data: (1) allowed us to utilize real cost data, (2) provided a very large sample size which can be generalized to users of NHS dental services, (3) was relatively time and cost-efficient when compared to primary data collection and (4) shed light on outcomes that matter to patients and policymakers.[24] Patient, public, and stakeholder involvement and engagement has informed the design and conduct of this study throughout. Causal assumptions were made explicit prior to analysis, and propensity score matching facilitated a wide range of sufficiently detailed variables to be accounted for. As far as we know this is the largest dataset in oral health research to have employed propensity score matching. The natural experiment design, with individual level assignment of water fluoride exposure (affected by unplanned variability in achieved fluoride concentrations[14] and patient address history), reduces the potential for confounding related to historical decisions on where to implement water fluoridation, by retaining an element of randomness in group assignment. Confounding by individual behaviours such as diet, oral hygiene and fluoride use is unlikely, as exposure to optimal water fluoridation is not influenced by individual health awareness (S1). Finally, the sensitivity analysis using Scottish fee-per-item based costings provides reassurance that the simpler banded system of costing NHS dental treatment in England did not minimize cost-savings (S3).

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Obtaining water fluoride concentration data from 25 water companies took 12 months and necessitated over 90 requests for information, with many follow up emails, internal reviews of decisions and two referrals to the Information Commissioner's Office. The current system for accessing these data is a significant barrier to research on water fluoridation in England. The data we obtained has been made publicly available but without funding it will not be possible to maintain this record in the future.[15] A publicly available, centralized record of water quality data, including water fluoride concentrations, is urgently required.

6.3 | Limitations

NHS BSA are able to trace NHS numbers for 70% of claims submitted, but published work has demonstrated that missed matches in NHS data linkage studies more frequently affect ethnic minority patients, those living in deprived areas, foreign nationals, and those with 'no fixed abode'.[25] DMFT data were automatically extracted from the dentist's electronic patient record and have not been validated against an epidemiological reference standard. Thus, validity depends on the thoroughness of the dentist's examination and record keeping. The absence of a clear social inequality gradient for the DMFT outcome in this study does raise questions regarding the validity of this measure. However, recent secondary analyses of UK and Australian epidemiological surveys have indicated that total caries experience (DMFT/S) may *not be sensitive* to socio-economic inequalities in adults, other than in the youngest adult age groups, and that missing teeth are more sensitive.[26,27] We did indeed observe a clear social inequalities gradient in missing teeth (S2).

The optimally fluoridated group included individuals who received fluoridated water from natural sources. Whilst this group is relatively small (5% of optimally fluoridated), their benefits have been included without any costs. As with any observational study, the likely effect of unmeasured and residual confounding must be considered, here particularly relating to incomplete ethnicity data and the use of an area-based measure of deprivation (although NHS exemption status also provided an individual-level proxy for income). There are also potential errors of misclassification in terms of fluoridation exposure, due to inaccuracies in addresses at NHS dental practices and conversion of WSZs to LSOAs.

Finally, how NHS dental care is remunerated may have contributed to some underestimation of the effect of water fluoridation. The NHS contract for the majority of high street dental practices during the study period offered no incentive to provide multiple items of restorative or surgical treatment during a single course of treatment. For example, one direct restoration accrued the same number of UDAs against the annual 'UDA target' as three direct restorations, one endodontic treatment and one extraction. This has been described as a disincentive to offer appointments to new patients who may require extensive treatment.[28] However, where appropriate, treatment can be phased for patients with extensive disease, to allow for prevention and stabilization, and a new course of treatment (with a new UDA credit) can be provided every 3 months. The longitudinal nature of our study would have picked up such phased courses of treatment. The study cohort also included patients treated by urgent dental care services (provided specifically for those with no regular dental practice), prisons dental services, and community (special care) dental services, which would not be affected by this perverse incentive as these contracts are commissioned and monitored using metrics other than UDAs. See S3 for further details on NHS dental contracts and remuneration.

6.4 | Interpretation

This was a pragmatic, observational study with limitations outlined above. Therefore, it is important to triangulate our findings with 'interlocking evidence'.[29] Our results support the hypothesis that water fluoridation appears to be producing less dramatic impacts on oral health in contemporary UK populations than in historical studies. This finding is echoed by the recently published NIHR CATFISH prospective cohort study in UK children.[13] The majority of recent studies including adults that have reported relatively large absolute effects come from contexts which may have higher levels of dental disease and unmet treatment needs, including those studies conducted in Brazil,[26,30,31,32,33,34,35,36] or in high-need population subgroups such as young offenders or Army recruits.[37,38]

Recent studies more applicable to the UK general population (from Australia, the US, Sweden and South Korea) have demonstrated inconsistent effects across age groups,[39] and/or absolute differences so small that whether they are meaningful is debateable.[40-42] Before conducting our analysis, as an online public engagement activity, we invited patient, public and professional stakeholders to consider the minimum reduction in invasive dental treatments over 10 years they would consider clinically or practically meaningful. Contributors held a wide range of views, indicating this is a highly subjective judgement. However, based on their feedback, the majority would not have considered a relative reduction of 3% as being meaningful.

6.5 | Implications

Both the present study and the recent CATFISH study of the effectiveness of water fluoridation in children support the conclusion that existing schemes in the UK remain cost-saving for the public sector.[13] In high-income countries with widespread access to topical fluorides, water fluoridation may now represent a classic 'prevention paradox'; a preventive measure which can bring benefits for populations and services but 'offers little to each participating individual'.[43] This is in contrast to the historic studies which identified absolute differences in caries severity of 50%–60%.[2,3] The costs of new water fluoridation programmes are extremely variable and depend on local water supply configurations.[44] Any cost estimates for new

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water fluoridation programmes, or significant investment in existing schemes, should be viewed in the context of our estimate that receipt of *optimal* water fluoridation (>/=0.7 mg F/L) over 10 years reduced costs of dental treatment to the NHS by 5.5% per person.

For context, a 2009 estimate for a new water fluoridation programme for Greater Manchester and Merseyside (similar population size to the optimally fluoridated population of England) would be £55.8 m (+/− 30%) in 2023 prices.[44,45] Such significant investment would need to be carefully evaluated against the projected lifespan of the dosing equipment and civil infrastructure and cost-recovery may not be guaranteed in increasingly low caries generations. Breaks in the supply of optimally fluoridated water and sub-optimal dosing are common, and would result in smaller impacts on NHS treatment costs.[16] More fundamentally, whether the case for water fluoridation can be based solely on the potential for reductions in NHS dental service utilization and NHS savings, rather than health gains that are meaningful to patients and the public, may need to be considered by stakeholders. Participatory consultation methods using contemporary estimates of effect, for example, through citizen juries, may be beneficial to explore these issues further.

There is no doubt that population-level, 'mass preventive' interventions for dental caries are still required. Dental caries remains almost universal by adulthood, even in populations that have had access to fluoride toothpastes and fluoridated water from birth.[46] However, in high income countries, we may be reaching the limit of what can be achieved through fluorides alone. A dose–response relationship between free-sugars and dental caries is evident at all levels of intake above zero and fluorides merely attenuate this relationship.[6] Average consumption of free sugars in the UK is more than double the recommended level for adolescents, and is almost double for adults.[47] The discovery of water fluoridation made an unparalleled contribution to oral health in the 20st century. In the 21st century, greater impact may be achieved by advocating for upstream, policy level action to address the commercial determinants of health and create supportive food environments.[48]

AUTHOR CONTRIBUTIONS

Conception, design, and funding acquisition: Dr Deborah Moore, Dr Thomas Allen, Prof Martin Tickle, Prof Stephen Birch, Prof Iain Pretty, Prof Tanya Walsh. *Data aquisition*: Dr Deborah Moore and Mr Blessing Nyakutsikwa. *Data analysis*: Mr Blessing Nyakutsikwa, Dr Thomas Allen, Dr Deborah Moore, Prof Tanya Walsh. *Interpretation of results*: Dr Deborah Moore, Dr Thomas Allen, Mrs Emily Lam, Prof Martin Tickle, Prof Stephen Birch, Prof Iain Pretty, Prof Tanya Walsh. *Drafting of article text*: Dr Deborah Moore, Dr Thomas Allen, Prof Tanya Walsh. *Review and final approval*: Dr Deborah Moore, Dr Thomas Allen, Mrs Emily Lam, Mr Blessing Nyakutsikwa, Prof Martin Tickle, Prof Iain Pretty, Prof Stephen Birch, Prof Tanya Walsh.

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CONFLICT OF INTEREST STATEMENT

Iain A Pretty reports past funding from Colgate-Palmolive Company (New York, NY, USA), grants from NIHR and editorial board member payments from Wiley-Blackwell (Hoboken, NJ, USA). Deborah Moore reports working at the Colgate Palmolive Dental Health Unit 2017–2023 which received grant funding from the Colgate-Palmolive Company (New York, NY, USA). Tanya Walsh reports grant funding from NIHR, institutional consulting fees from FDI and panel membership for NIHR Research for Patient Benefit North West. Martin Tickle reported grant funding from NIHR. Emily Lam reports panel and committee memberships for NIHR.

DATA AVAILABILITY STATEMENT

Due to the terms of the data sharing agreement with NHS Business Services Authority, there is no NHS patient data that can be shared. All data requests should be sent to the corresponding author in the first instance. The annual mean water fluoride concentration data by Lower Super Output Area 2009–2020 that support the findings of this study are openly available in Figshare at https://figshare.manchester.ac.uk/, reference number [https://doi.org/10.48420/15104730.v2].

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