Office for Health Improvement & Disparities

Water fluoridation

Health monitoring report for England 2022

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Abbreviations

AHDH: Attention deficit hyperactivity disorder

A priori: Identified before analysis, based on prior knowledge and evidence

CI: Confidence interval(s)

CMO: Chief Medical Officer

COVID-19: Coronavirus Disease 2019

$d_3$mft: Decayed (at dentinal level), missing due to decay, or filled due to decay primary teeth

DHSC: Department of Health and Social Care

DWI: Drinking Water Inspectorate

EFSA: European Food Safety Authority

EU: European Union

FSTA: Food Science and Technology Abstracts

HES: Hospital Episode Statistics

HMR: Health monitoring report

IMD / IMD19 : Indices of Multiple Deprivation (2019)

IQ: Intelligence quotient

IRR: Incidence rate ratio

LA: Local authority

LSOA: Lower-layer super output area

LTLA: Lower-tier local authority

MRC: Medical Research Council (UK)

MSOA: Middle-layer super output area

MYE: Mid-year population estimate

NASEM: (United States) National Academies of Science, Engineering and Medicine

NHS: National Health Service

OHID: Office for Health Improvement and Disparities (within Department of Health and Social Care)

OHS: Oral health survey

ONS: Office for National Statistics

OR: Odds ratio

PHE: Public Health England

PYAR: Person-years at risk

RRR: Relative risk ratio

UKHSA: United Kingdom Health Security Agency

US NRC: United States National Research Council

WHO: World Health Organization

WSZ: Water supply zone

Short lay summary

Background

This monitoring report was prepared by the Water Fluoridation and Health Monitoring Working Group, on behalf of the Secretary of State for Health and Social Care. It compares data on the health of people living in areas of England who have differing concentrations of fluoride in their drinking water supply.

Fluoride occurs naturally and can be present in water and some foods in varying concentrations. In some areas with low natural fluoride levels, fluoride is added to public drinking water, in line with safe limits, to improve dental health. Dental caries (tooth decay) is a significant public health problem in England. It is more common in the most deprived communities of the country. Nearly a quarter of 5-year-olds experience dental caries and around 38,000 children and young people have teeth removed (due to decay) in hospital every year.

Around one in 10 people in England currently have fluoride added to their drinking water supplies.

Methods

Three dental health outcomes were studied: experience and severity of dental caries in 3- and 5-year-olds children, and hospital admissions for removing teeth (due to decay) in children and young people. These were chosen to continue monitoring the impact of fluoride on dental health.

One non-dental health outcome was studied: hospital admissions for hip fracture in people of any age. This was prioritised because the previous monitoring report found some evidence of a relationship between fluoride and hip fractures which varied by age. No other outcomes were included because resources were focused on responding to the COVID-19 pandemic.

The occurrence of each of the health outcomes was compared across exposures to different concentrations of fluoride and whether fluoride had been added to the water supply. Other factors such as age, sex, and deprivation were taken into account.

Results

Dental health

- Five-year-olds in areas with higher fluoride concentrations were less likely to experience dental caries, and less likely to experience severe dental caries, than in areas with low fluoride concentrations.

- Five-year-olds in areas with a fluoridation scheme in place were less likely to experience dental caries than in areas without a scheme.

- Children and young people in areas with higher fluoride concentrations were less likely to be admitted to hospital to have teeth removed (due to decay) than in areas with low fluoride concentrations.

- Children and young people in areas with a fluoridation scheme in place were less likely to be admitted to hospital to have teeth removed (due to decay) than in areas without a scheme.

- These effects were seen at all levels of deprivation, but children and young people in the most deprived areas benefitted the most.

Hip fractures

Taking wider research and the previous health monitoring reports into account, no convincing evidence was found of higher rates of hip fracture in areas with higher fluoride concentrations, or in areas with a fluoridation scheme in place.

Conclusion

This report supports earlier findings and wider evidence that water fluoridation, at levels recommended in the UK, is a safe and effective public health measure to reduce dental caries and inequalities in dental health.

The Water Fluoridation Health Monitoring Working Group continues to review evidence and will publish a further report within the next four years.

Executive summary

Background

The Water Fluoridation Health Monitoring Working Group, on behalf of the Secretary of State for Health and Social Care, is required by legislation to monitor the effects of water fluoridation schemes on health, and to produce reports at no greater than 4-yearly intervals. This report, the third in the series, fulfils this requirement. The scope of this report has been impacted by the redeployment of members of the working group to support the COVID-19 pandemic response.

Fluoride occurs naturally in the environment and can be present in water and some foods in varying concentrations. In some areas with low natural fluoride levels, fluoride is added to public drinking water to improve dental health. In England, around 10% of the population receives public drinking water served by a fluoridation scheme. Water fluoridation schemes aim to achieve a level of 1mg of fluoride per litre of water. World Health Organization (WHO) guidance recommends a maximum concentration of fluoride in public water supplies of 1.5mg/l, this being protective against any known harmful effect over a lifetime of consumption.

The protective effect of community water fluoridation on dental caries is well established. Dental caries, also known as dental or tooth decay, is a disease that affects people at all life stages and affects both primary (baby) and permanent (adult) teeth. Sizeable inequalities in the prevalence of dental caries exist between affluent and deprived communities, and it is a common cause of hospital admissions in children. The evidence for potential adverse effects of community water fluoridation, at concentrations within WHO guidelines, on non-dental health outcomes is inconclusive.

The aim of the report was to estimate the association between concentration of fluoride in public water supplies in England and selected dental and non-dental health outcomes, to monitor the effects of water fluoridation arrangements.

Methods

The report used an ecological (population-level) study design and included residents of England in its analyses.

The geographical distribution of different concentrations of fluoride in drinking water supplies, as well as the presence or absence of water fluoridation schemes, were described.

Dental health outcomes (prevalence and severity of caries experience in 3- and 5-year-old children, and hospital admissions for carious tooth extraction in children and young people) were included to continue monitoring the impact of fluoride on dental health, and were chosen according to the availability of new data since the 2018 health monitoring report.

An evidence review and the findings of the 2018 health monitoring report were considered in prioritising non-dental health outcomes for analysis. Incidence of hip fractures was prioritised because the 2018 report found some evidence of a relationship between fluoride and hip fractures which varied by age group, and wider evidence suggests a biologically plausible relationship between fluoride and bone-related outcomes. No other non-dental outcomes were included due to the reduced scope of the report.

The frequency of health outcomes was compared across exposures to different concentrations of fluoride, and presence or absence of a water fluoridation scheme. Statistical models, adjusting where possible for age, sex, and deprivation, were used to measure any association between fluoride exposures and health outcomes.

Results and discussion

Distribution of fluoride

Approximately 70% of the population in England lives in areas with <0.2mg/l fluoride in drinking water. There are 35 lower-tier local authority areas (of 309) where fluoride is added to drinking water supplies.

Prevalence and severity of dental caries experience in three- and five-year-olds

Ten per cent of 3-year-olds surveyed in 2020, and 23% of 5-year-olds surveyed in 2017 and 2019, had experience of dental caries.

Five-year-olds were less likely to experience dental caries, and less likely to experience caries of high severity, at higher fluoride concentrations. In the most deprived 20% of areas, the odds of experiencing caries was 25% lower in areas with a fluoridation scheme than in areas without.

Carious tooth extractions

Approximately 38,000 children and young people aged 0 to 19 years were admitted to hospital each year for carious tooth extractions.

Children and young people in areas with higher fluoride concentration were 57 to 63% less likely to be admitted than in areas with low fluoride concentrations. This effect was observed at all levels of deprivation. However, the difference was greatest in the most deprived areas. Children and young people in these areas benefitted the most from higher fluoride concentrations.

The incidence rate of carious tooth extractions was lower in areas with a fluoridation scheme in place than in areas without a scheme. If all children and young people in the most deprived 20% of areas with lower fluoride concentrations (<0.2mg/l) instead received water adjusted by a fluoridation scheme, 56% of carious tooth extractions in these areas would be prevented, assuming the reduction observed was due to fluoridation.

Hip fractures

Approximately 65,000 people were admitted to hospital with hip fracture each year.

The association between fluoride concentration and hip fractures varied by age. For some individual fluoride concentration levels, there was an indication of a decreased risk of admission for hip fracture in younger age groups, and an increased risk of admission in the oldest age group. However, there was no pattern across fluoride concentrations in any age group. When further stratified by sex, there was no consistent change in the incidence rate of hip fracture admissions within sex- and age-specific groups, as the concentration of fluoride increased.

In some age groups, there was an indication of increased risk of admission for hip fracture in areas with a fluoridation scheme in place compared to those without. However, these findings were inconsistent with the results of the analysis using fluoride concentration.

These inconsistencies by fluoride concentration and age, taken together with the overall existing evidence, do not provide convincing evidence of an association.

Limitations

The analysis used an ecological design with public drinking water supplies as the exposure of interest. Though it meets the objectives and statutory requirements of the health monitoring report, the scope was reduced in order to prioritise the response to the COVID-19 pandemic. No water fluoride concentration data were available for analysis from 2016 onwards, meaning some health outcomes analysed do not overlap with the exposure period. However, there have been no changes in legal agreements to schemes since 2017, and fluoride concentrations have previously been shown to be relatively stable over time. Ethnicity, identified as an a priori confounder, could not be included in the analysis. Deprivation could only be accounted for at population-level.

Conclusion

The findings of the 2022 health monitoring report are consistent with the view that water fluoridation at levels within the UK regulatory limit (<1.5mg/l) is an effective, safe, and equitable public health intervention to reduce the prevalence, severity, and consequences of dental caries. It supports previous findings that these benefits are greatest in the most deprived areas, thereby contributing to reducing dental health inequalities.

The methods used in this report are not exactly the same as those followed in the 2018 report. Findings from this report should be viewed in the context of those from previous health monitoring reports, but cannot be directly compared.

Conclusions on causality of relationships rely on not just this report but evidence from multiple studies. The absence of any associations does not provide definitive evidence for a lack of a relationship. This is particularly the case for hip fractures, where wider evidence at fluoride concentrations comparable to those in England is limited.

The Water Fluoridation Health Monitoring Working Group continues to keep the wider evidence under review and will consult with local authorities prior to publication of a further report within the next 4 years.

Background

The Water Fluoridation Health Monitoring Working Group, on behalf of the Secretary of State for Health and Social Care, is required by legislation to monitor the effects of water fluoridation schemes on health and to produce reports at no greater than 4-yearly intervals.[1] This report, the third in the series, fulfils this requirement.

Monitoring the health effects of fluoridation schemes

Section 90A of the Water Industry Act 1991, as amended, requires a “relevant authority”, that has entered into fluoridation arrangements, to monitor the effects of the arrangements on the health of persons living in the area specified in the arrangements. It also requires that such an authority publishes reports containing an analysis of those effects, making available any information, or summaries of information, collected by it for these purposes.[1]

As of 1 April 2013, the Secretary of State for Health and Social Care is the "relevant authority" in England for the purposes of the fluoridation provisions. The Secretary of State's functions in relation to fluoridation health monitoring and reporting are exercised by the Water Fluoridation Health Monitoring Working Group (the working group), whose membership includes epidemiologists, dentists, other clinicians, and scientists from the Office for Health Improvement and Disparities (OHID) and the UK Health Security Agency (UKHSA). The working group was formerly within Public Health England (PHE), which published the previous reports. The first 2 reports monitoring the health effects of fluoride in drinking water were published in March 2014 and March 2018.[2, 3] Further reports are required at no greater than 4-yearly intervals, beginning with the date on which the last report was published, unless the schemes in question are terminated.

The protective effect of community water fluoridation on dental caries is well established. The 2014 and 2018 health monitoring reports found evidence for water fluoridation reducing the prevalence of dental caries, the incidence of hospital admission for removal of carious teeth, and dental health inequalities.[2, 3] The 2018 report also provided an updated understanding of the relationship between water fluoridation and dental fluorosis in England and added to the evidence base regarding possible associations with non-dental health outcomes. Secular changes in diet and oral hygiene, including exposure to fluoride from sources other than drinking water, also affect dental caries risk. Re-assessment of the association between fluoride in drinking water and dental health is therefore important, as well as continuing to monitor possible associations between fluoride and non-dental health outcomes. This report contributes to the assessment of whether the addition of fluoride to public water supplies in England is safe, effective, and where implemented, an equitable public health intervention.

Scope of the 2022 health monitoring report

Throughout 2020 and 2021, COVID-19 has required epidemiologists, dentists, other clinicians, and scientists from UKHSA and OHID (formerly PHE) to redeploy to support the pandemic response.

The preparation of this report necessarily focused the resources available on continued monitoring of dental caries and providing an updated assessment for hip fractures. Other health outcomes included in the 2014 and 2018 reports were considered but not included (rationale below). There were no additional exposure data available for analysis from 2016 onwards; analyses in this report use the exposure data prepared for the 2018 report. There have been no changes in legal agreements to schemes since 2017, and fluoride concentrations have previously been shown to be relatively stable over time, making this a justifiable approach.[4] Ethnicity, which was identified a priori as a potential confounder, has not been included in analysis.

Fluoride

Fluoride occurs naturally in the environment and can be present in water and some foods in varying concentrations.[5] Fluoride is also added to many toothpastes and other preventative dental treatments.

In some areas, fluoride is added to public drinking water to improve dental health. The first water fluoridation scheme was introduced in the USA in 1945; schemes now cover 73% of US residents using public water supplies. Following pilot schemes, the first substantive water fluoridation scheme in the UK was introduced in Birmingham in 1964, with subsequent schemes established since. In England, around 10% of the population receives public drinking water served by a fluoridation scheme.

Water fluoridation schemes in England aim to achieve a level of 1mg of fluoride per litre of water, equivalent to one part fluoride per million of water. This was chosen to reduce dental caries and to guard against dental fluorosis. World Health Organization guidance recommends a maximum concentration of fluoride in public water supplies of 1.5mg/l, this being protective against any harmful effect over a lifetime of consumption.[6] This recommendation is mirrored in UK drinking water standards covering both public and private supplies.[7] Some water supplies in England, serving around a quarter of a million people, contain levels of fluoride that are naturally close to those that fluoridation schemes seek to achieve, due to the underlying geology of the area. Water companies that operate schemes must comply with the requirements of the Code of Practice published by the Drinking Water Inspectorate (DWI), the water quality regulator for England and Wales.[8]

Fluoride and possible impacts on health

The process for deciding which outcomes to include in this report is outlined below. The working group continually keeps scientific literature under review. This informs which dental and non-dental health outcomes are considered and prioritised for inclusion in health monitoring reports. Evidence reviews undertaken by authoritative public health bodies around the world have considered the effectiveness of water fluoridation in reducing the prevalence of dental caries. Such reviews have also considered the evidence in relation to potential adverse effects of fluoride exposure. Recent examples include:

- US Community Preventive Services Task Force 2013 [9]
- Australian National Health and Medical Review Council 2017 [10]
- (EU) Scientific Committee on Health and Environmental Risks 2011 [11]
- Royal Society of New Zealand 2021 [12]
- (Ireland) Health Research Board 2015 [13]
- Cochrane Oral Health Group 2015 [14]
- Canadian Agency for Drugs and Technologies in Health 2019 [15]
- (US) National Institutes of Health 2021 [16]

A more detailed summary of the wider evidence base and links to these reviews can be found in PHE's water fluoridation toolkit.[7]

The common finding of the reviews looking at dental health is that levels of dental caries are lower in fluoridated areas. Dental caries, also known as dental or tooth decay, is a disease that affects people at all life stages and affects both primary (baby) and permanent (adult) teeth. Dental caries occurs when oral bacteria produce acids that demineralise the tooth surface, allowing the bacteria to progressively invade the tooth. Consuming sugary food and drink fuels acid formation by oral bacteria. Unaddressed dental caries can damage the tooth structurally and cause pain and loss of self-esteem, can negatively impact speech, and can require time out of school. Extreme cases can lead to sepsis. Treatment of teeth can involve restoration of the affected tooth, where possible, or extraction. Treated teeth are at increased risk of future failure and retreatment is common, as is loss of the tooth when it can no longer be restored. Dental caries is a significant public health problem internationally and, despite reductions in prevalence since the 1970s, remains so in England. Sizeable inequalities still exist between affluent and deprived communities, and the removal of decayed teeth is one of the most common causes of hospital admission in children.

It is known that increased exposure to fluoride during tooth formation can result in dental fluorosis. Dental fluorosis is mottles or flecks on teeth caused by fluoride and in its most severe forms can be unsightly. Dental fluorosis surveys included in the 2014 and 2018 reports have shown greater levels of dental fluorosis in fluoridated areas but with no greater levels of dissatisfaction with dental appearance.[2, 3]

Various expert evaluations from international organisations have found insufficient evidence to determine an association between drinking water fluoridation schemes, with fluoride concentrations within WHO guidelines, and adverse general health effects, including neurological harms.[11, 12, 17, 18] However, other research has suggested evidence for possible health effects following exposure to fluoride. These include: both adverse and protective associations with neurodevelopmental effects [19, 20]; increased risk of thyroid disorder [21], though a subsequent paper suggests these findings should be interpreted with caution [22]; and increased risk of hypertension in areas with endemic fluorosis [23, 24].

At time of writing, the US National Toxicology Program (US NTP) has produced a draft systematic review of the evidence for fluoride and neurodevelopmental and cognitive health effects.[25] Reviews, including by the US National Academy of Sciences, Engineering and Medicine (US NASEM), have twice recommended improvements to the NTP draft report, and that findings cannot be used to draw conclusions regarding low fluoride exposures, including those typically associated with drinking water fluoridation schemes.[26, 27] Recent reviews have also concluded there is insufficient evidence of an effect of water fluoridation on cognitive outcomes.[12, 18]

Selection of health indicators

There is strong evidence that fluoride in water at levels permitted by UK water quality standards has an effect on 2 dental health outcomes: dental caries and dental fluorosis. This report includes analysis on the association between fluoride and dental caries, using three outcome measures: prevalence of dental caries experience in 3- and 5-year-olds, severity of dental caries in 3- and 5-year-olds, and hospital admissions for carious tooth extractions in those aged under 20 years. The last survey of dental fluorosis in England was conducted in 2015, and was included in the 2018 health monitoring report.[28] Dental fluorosis is therefore not included in this report.

Table 1 summarises health outcomes included in this report. Table 2 summarises those which were considered for inclusion in this report, and the rationale for their exclusion. All had previously been considered for analysis in the 2014 and 2018 reports.[2, 3] An analysis of the possible association between fluoride and intelligence quotient (IQ) is underway, and the options for exploring the possible association between fluoride and thyroid disorder are being investigated by the working group.

This report includes analysis on the association between fluoride and hip fractures. There is international evidence of the adverse health effects of long-term exposure to high levels of fluoride (>3mg/l) on bone, including skeletal fluorosis and fracture.[6] About half of fluoride ingested is taken up by bone.[29] Concentrations of fluoride in bone are expected to increase over time, especially with long-term exposure. However, fluoride is also released during bone remodelling. An impact on bone health is plausible, although the direction of effect remains unclear.

A 2015 meta-analysis found inconsistent results regarding an association between hip fracture and fluoride and highlighted that further high quality studies were needed.[13] Other authoritative evaluations indicate that exposure, through drinking water or diet, to low concentrations of fluoride equivalent to those seen in England's fluoridation schemes, is unlikely to increase the risk of bone fracture.[17, 30]

The 2018 health monitoring report found some evidence of a biphasic relationship between fluoride and hip fractures, with exposure to fluoride being associated with a reduced risk of hip fracture in younger age groups, and with an increased risk in older age groups.[2] Taking into account the wider literature, it concluded that there was no evidence overall of an association between fluoride and hip fracture. However, given the previous findings, hip fracture has been included for analysis again, using subsequent years' data.

Table 1 - Selected health outcome indicators for fluoride monitoring [2, 3]

Outcome	Proposed indicator	Rationale for inclusion
Dental caries	Prevalence of experience of dental caries in 3- and 5-year-olds Severity of dental caries in 3- and 5-year-olds Hospital admission for carious tooth extraction 0- to 19-year-olds	There is strong evidence of a protective association between fluoride and dental caries. The 2018 report found that the greatest benefit was seen in children in the most deprived quintile of geographical areas surveyed. Additional oral health survey data are available from 2017 and 2019 for 5-year-olds, and 2020 for 3-year-olds. Additional data on hospital admissions for carious tooth extractions are available for the financial years 2016/17 to 2020/21. Analysing the association between fluoride and caries prevalence and severity using additional years of data enables ongoing monitoring of a known benefit and of the effect on health inequalities.
Hip fractures	Emergency consultant inpatient episodes with hip fracture	The 2018 report found evidence of an interaction between fluoride and age (that is, the association between fluoride and hip fractures differed by age group). There was evidence of a biphasic

Outcome	Proposed indicator	Rationale for inclusion
		relationship, with a protective association between fluoride and hip fractures in those aged under 50 years, and a positive association (increased risk) in those aged over 80 years. Taken in the context of wider evidence, this was considered unconvincing. Hip fractures are a very common health outcome, and it is worth repeating analysis with subsequent years' hospital data.

Table 2 - Health outcomes considered for analysis but not included [2, 3]

Outcome	Rationale for exclusion
Dental fluorosis	A dental fluorosis survey has not been conducted in England since the 2018 report.
Renal calculi	The 2018 report found inconsistent results when fluoride was considered as a range of concentrations and as a binary exposure. There was evidence of a positive association between fluoride and hospital admissions for renal calculi at low to mid-range concentrations compared to the lowest concentration, but no dose-response relationship was observed.
Down's syndrome	The 2018 report found no convincing evidence of an association between fluoride and Down's syndrome. There was evidence of an association at some concentrations, but without a dose-response relationship.
Bladder cancer	The 2018 report found weak evidence of a protective association between fluoride and bladder cancer and suggested a threshold effect at ≥0.7mg/l. There was no evidence of adverse impact. The most common cause of bladder cancer is tobacco smoking [31], which cannot be sufficiently accounted for in an ecological study.
Osteosarcoma	The 2018 report found no evidence of an association between fluoride and new diagnoses of osteosarcoma.
All cancers	The 2014 report found no evidence of an association between fluoride and new diagnoses of all cancers. It is difficult to interpret or act on results for such a broad outcome measure. For the 2018 report, the working group prioritised more specific cancer outcomes.
Thyroid outcomes	A valid and accessible data source has not been identified but this outcome remains under review. Evidence reviews have concluded that the evidence of an association is inconclusive.[12, 15] Work is

Outcome	Rationale for exclusion
	ongoing in this area.
Skeletal fluorosis	There is no feasible indicator to use for analysis. Evidence suggests that skeletal fluorosis only occurs at far higher concentrations of fluoride than permissible under UK drinking water standards.
Neurodevelopmental and cognitive health	Whilst the evidence is contradictory in relation to these outcomes, there are opportunities for primary studies of possible associations with IQ in UK populations. Work is ongoing in this area.
All-cause mortality	The 2014 report found evidence of a weak protective association between exposure to a fluoridation scheme and all-cause mortality. For the 2018 and 2022 reports, the working group prioritised more specific outcomes.

Aims and objectives

Aim

To estimate the association between concentration of fluoride in public water supplies in England and selected dental and non-dental health outcomes, to monitor the effects of water fluoridation arrangements.

Objectives

- Describe the distribution of fluoride concentrations across England.
- Describe the frequency of dental and non-dental health outcomes in terms of drinking water fluoride concentration and, where available, age, sex, and area-level deprivation.
- Determine and measure the association between water fluoride concentration and dental and non-dental health outcomes, adjusting for age, sex, and deprivation where possible.
- Determine and measure the association between exposure to a water fluoridation scheme and dental and non-dental health outcomes, adjusting for age, sex, and deprivation where possible.

Methods

Study population

Residents of England were included in the analyses. The age of the study population and the time period covered varied according to the health outcome studied and are defined below.

Study design

The study used an ecological design: the exposure, outcomes, and potential confounders were measured and analysed at area-level, rather than individual-level.

The study compared frequency of health outcomes between areas with contrasting drinking water fluoride concentrations. Comparing concentrations captures differences in average fluoride exposure between populations. This is of direct relevance to policy objectives which relate to regulation of the concentration of fluoride in drinking water. However, this is not an individual measure of exposure. A person's individual fluoride intake within an area can vary due to differences in the amount of water consumed and fluoride from other dietary sources such as drinking tea.

Exposure

Definition: Fluoride concentration category

The exposure of interest was the grand mean (mean of annual means) fluoride concentration in the water supply, over the exposure period of interest. The exposure period of interest varied according to the health outcome studied.

Fluoride concentration was grouped a priori into 5 categories:

- <0.1mg/l
- 0.1 - <0.2mg/l
- 0.2 - <0.4mg/l
- 0.4 - <0.7mg/l
- ≥0.7mg/l

These are the same groups as were used in the 2018 health monitoring report.

Definition: Fluoride concentration as a continuous exposure

To assess the trend in the association between fluoride concentration and health outcomes, fluoride concentration was also modelled as a continuous exposure. The exposure of interest is therefore the grand mean fluoride concentration as above, but not further categorised into concentration bands.

This approach tests for a linear association between fluoride concentration as a continuous exposure and the health outcome of interest. Evidence of an association may indicate a dose-response relationship but should be interpreted with caution.

Definition: Fluoride scheme

Exposed: Presence of a fluoridation scheme in any of the years of the exposure period, regardless of the mean fluoride concentration achieved (there were no areas with a fluoridation scheme in place and a grand mean fluoride concentration of <0.2mg/l)

Unexposed: No fluoridation scheme functioning in any of the years of the exposure period, and a grand mean fluoride of <0.2mg/l

Excluded: No fluoridation scheme functioning in any of the years of the exposure period, and a grand mean fluoride of ≥0.2mg/l

This exposure model has been included to directly address the monitoring requirements of the Water Industry Act.[1]

Rationale for fluoride concentration categories

This approach is consistent with that of the 2018 health monitoring report.[2] International evidence suggests that dental caries prevalence decreases with increasing fluoride concentrations, with reductions in dental caries plateauing at higher concentrations.[32]

Pilot work undertaken in the 2018 report to assess the population exposed to different categories of fluoride concentration found the population within each fluoride concentration category varied, resulting in the large majority of the population receiving a water supply with a low fluoride concentration (<0.4mg/l). Therefore, the number of events was high enough to allow categorising fluoride concentration below this level into several groups. This allows for detection of a potential dose-response and/or threshold effect between fluoride and the health outcome.[2]

Further categorising the fluoride concentration of the population receiving water supplies with fluoride >0.4mg/l enables detection of a dose-response, plateau, and threshold effect at higher fluoride levels. Detection of a dose response is important when considering evidence for causality of any potential association with an outcome.

Given the relatively low water fluoride concentrations in England, the population receiving supplies at concentrations >0.4mg/l was thought unlikely to be large enough for division into more than two further categories and still allow meaningful examination of associations with less common health outcomes.

Rationale for exposure model

Fluoride concentration in drinking water is routinely monitored in all water supply zones (WSZ) in England.[33] These data were processed for the 2018 health monitoring report to assign an annual mean fluoride concentration to each lower-level super output area (LSOA) in England for the years 2005 to 2015, for which WSZ boundary data were available. The methodology for this is published in full elsewhere.[2, 4] WSZ boundaries are not the same as local authority boundaries. Fluoride concentrations, and delivery of a water fluoridation scheme, is likely to vary within a local authority. LSOAs are much smaller geographical areas than local authorities. Variation of fluoride concentration within the LSOA is less likely, but is addressed in the methodology.[4]

There have been no changes in legal agreements to any schemes since 2017. Therefore, unless there were any unplanned stoppages in water fluoridation plants since then, the fluoride levels by WSZ before 2017 (used for the exposure classification) should correlate very well with the more recent levels. However, we have not been able to confirm this either from information on any possible disruptions in fluoridation nor from actual measurements.

Fluoride in drinking water is one of several sources of fluoride, including diet, fluoride-containing toothpastes, and fluoride-containing dental treatments. Drinking water with more than 0.3mg/l fluoride is considered to be one of the main sources of human total fluoride intake; this is especially true at higher concentrations (for example, greater than 0.7mg/l).[11]

Where the fluoride concentration in drinking water is less than 0.3mg/l, other sources may be more important. However, data on fluoride intake from sources such as toothpastes and diet or estimates of exposure from biological measures (for example, urinary fluoride) are not available at a population level. Similarly, an individual's exposure to fluoride from drinking water depends on whether they consume water from sources other than mains water (for example, private borehole or bottled water, both of which may contain higher fluoride concentrations) and what volume, if any, of mains drinking water they consume. Data on this are not available at a population level.

Fluoride concentration of mains drinking water is therefore considered as the main exposure to fluoride in this report.

Health outcomes and potential confounders

Health outcome indicators

Table 3 presents the health outcomes investigated in this report, and for each: the source of data, indicator measure, geographical level, time-period studied, and potential a priori confounders.

Each of these outcomes was also analysed in the 2018 health monitoring report.[2] The time periods studied in this report are therefore the periods for which data were available and which directly follow those previously analysed.

Table 3 – Health outcomes and data source, outcome indicator, geographical level of analysis, time period studied and potential confounders

Health Outcome	Source of Data	Outcome Indicator	Geographical level of outcome data for analysis	Time period	A priori potential confounders
Dental caries experience (prevalence)	National Dental Epidemiology Programme for England – Oral health survey	Prevalence of $d_3$mft>0 in 3- and 5-year-olds	LSOA	2017 (5-year-olds) 2019 (5-year-olds) 2020 (3-year-olds)	Deprivation Ethnicity
Dental caries experience (severity)	National Dental Epidemiology Programme for England – Oral health survey	Mean $d_3$mft score in 3- and 5-year-olds	LSOA	2017 (5-year-olds) 2019 (5-year-olds) 2020 (3-year-olds)	Deprivation Ethnicity
Admissions for extraction due to dental caries	Hospital Episodes Statistics	Incidence of hospital admission of 0- to 19-year-olds for extraction of one or more primary or permanent teeth due to dental caries	MSOA	2016/17 to 2020/21	Age Sex Deprivation Ethnicity
Hip fracture	Hospital Episodes Statistics	Incidence of emergency admissions; 1st or 2nd diagnosis	MSOA	2016/17 to 2020/21	Age Sex Deprivation Ethnicity

Potential confounders

All health outcomes were studied by aggregating data for each concentration category of exposure to fluoride in the water supply. Risk of illness is highly dependent on factors that vary between different areas of England, including age and sex distribution, deprivation, and ethnicity.

Confounders were considered for inclusion when:

- an effect on the direction and size of the association between fluoride and the health outcome was considered likely
- data were available at the same geographic level as the outcome

Deprivation was found to be an important confounder and effect modifier of several health outcomes in the 2018 health monitoring report.[2] Analyses in this report used the 2019 Index of Multiple Deprivation (IMD), an ecological measure based on income, employment, education, health and disability, crime, barriers to housing and services, and the living environment.[34] The IMD score has been documented to correlate with multiple other potential confounders, including smoking, diet, tooth brushing, alcohol consumption, and bone mineral density.[35-39]

Ethnicity was considered as an a priori confounder. It was excluded because the most recent and complete ethnicity data available at the same geographic level as the outcome was from the 2011 census, a decade old at the time of analysis, and because of the necessarily reduced scope of the 2022 report. Ethnicity may be considered for inclusion as a confounder in future work of the working group. In the 2018 report, ethnicity was included as an area-level characteristic defined as the proportion of the population which was of white ethnicity as recorded in the 2011 census.[2]

Prevalence of dental caries

Dental caries prevalence data were obtained from the most recent oral health surveys of 3-year-old (2020) and 5-year-old (2017 and 2019) children carried out by the National Dental Epidemiology Programme for England.[40-42] These surveys involved visual examination of children's teeth by trained dental examiners, who followed a nationally agreed protocol. Data were available at LSOA-level. Survey methods are described in full in the national protocol.[43]

Dental caries experience is measured by the dmft index, which counts decayed, missing, or filled primary teeth, due to caries. This is denoted as $d_3$mft; the '3' indicates the threshold of decay measured, which is at the dentine level. The prevalence of caries is reported as the count of children with one or more $d_3$mft per number of children examined in each geographical area.

The 2020 survey on three-year-olds was conducted in the academic year 2019/20 and was curtailed by the outbreak of COVID-19 and the closure (except to children of key workers) of all schools and nurseries in England in March 2020. Therefore the survey had to be terminated and the final three months of data collection were lost. This meant 20 of 151 upper tier and 67 of 314 lower-tier local authorities were unable to return usable data. Additionally 30 upper-tier local authorities did not commission the survey. Very few areas reached the minimum sample size of 250 children and the results should be interpreted with caution, particularly when making comparisons with other surveys.[42]

The 2017 and 2019 surveys on 5-year-olds were combined for this analysis, to increase the available sample size.

Severity of dental caries

Dental caries severity data were obtained from the oral health surveys, described above. Severity was defined as the mean $d_3$mft of all children examined in each LSOA.[43]

Admissions for dental extractions

Data on admissions to hospital for carious tooth extraction in children and young people aged 0 to 19 years were obtained from Hospital Episode Statistics (HES) for the financial years 2016/17 to 2020/21, at MSOA-level. The denominator was person-years at risk, calculated by summing the Office for National Statistics (ONS) mid-year population estimates (MYE) for these age groups and years in each MSOA. For example, the MYE for 2016 provided the denominator population for hospital admissions which occurred in 2016/17.

Admission for hip fracture

HES data on emergency admissions to hospital for hip fracture were obtained for the financial years 2016/17 to 2020/21. The denominator was person-years at risk, calculated as above.

Time period of exposure

The time period of the exposure of interest varied by the outcome being investigated. Exposure data were available for the years 2005 to 2015 inclusive. A 5-year exposure period (2011 to 2015) was used in the analysis of dental outcomes. A 10-year exposure period (2006 to 2015) was used in the analysis of hip fractures, as the induction period is expected to be relevant to a chronic exposure of at least this long.

Data management

Data cleaning, management, and visualisation were conducted in STATA 16, R 4.1, and R Studio 2021.09.0. Data analysis was conducted in STATA 16.

Descriptive epidemiology

Distribution of fluoride concentration

LSOA-level mean fluoride concentrations and presence of a fluoridation scheme in 2015 were mapped to LSOA and lower-tier local authority boundaries for 2020.

Prevalence and severity of dental caries

Data on 5-year-olds from the 2 oral health surveys conducted in 2017 and 2019 were analysed together. Data on 3-year-olds from the survey conducted in 2020 were analysed separately.

Summary statistics of the survey coverage (number of children examined), prevalence of dental caries experience (number of children with $d_3$mft>0 per children examined), and severity of dental caries experience (grand mean of LSOA-level mean $d_3$mft) were calculated for each category of fluoride exposure and each deprivation decile. Summary statistics of the 3- or 5-year-old population by fluoride exposure and deprivation decile were also presented, using MYEs for the years corresponding to the surveys.

Admissions for carious tooth extraction

Case counts were aggregated by fluoride exposure category, age group, sex, and deprivation decile. The crude incidence of extractions per 100,000 person-years at risk was calculated at each fluoride exposure category.

Admissions for hip fracture

Case counts were aggregated by fluoride exposure category, age group, sex, and deprivation decile. The crude incidence of hip fracture per 100,000 person-years at risk was calculated at each fluoride exposure category.

Analytic epidemiology

Distribution of fluoride concentration

The association between presence of a fluoridation scheme and deprivation was estimated using univariate logistic regression. The association between mean fluoride concentration and deprivation was estimated using linear regression.

All health outcomes

Univariate regression was used to determine crude regression coefficients of the outcomes of interest for each category increase of fluoridation exposure, and each of the potential confounders (sex, age group, and deprivation decile).

Multivariable models were constructed to determine regression coefficients and their 95% confidence intervals, adjusted for all a priori selected potential confounders or effect modifiers. P values were calculated using Wald or composite Wald tests. Confidence intervals and p values were used to interpret the strength of the evidence against the null hypothesis that the regression coefficient did not vary by exposure to fluoride.

While smaller p values are helpful as a guide to indicate associations where the evidence is stronger, values above or below the conventional cut-off of $p<0.05$ should not be treated as a threshold to distinguish whether or not there is an association. It should be noted that very many results are presented here. Given so many comparisons, some will have smaller p values due to chance alone. Confidence intervals can be more informative as they show the degree of uncertainty around relative risk measures.

Fluoride exposure was modelled in three ways, described above. The main analyses used fluoride concentration as an ordered categorical variable. However, fluoride as a continuous variable using mean fluoride concentration values, rather than categories of concentration, was also used. The binary exposure of the presence or absence of a fluoridation scheme was analysed for the following health outcomes: prevalence of dental caries in 5-year-olds, hospital admissions for carious tooth extractions, and hospital admissions for hip fractures. The binary analysis was not carried out in relation to prevalence of dental caries in 3-year-olds due to the acknowledged limitations of the dataset.

Confounders (age, sex, and deprivation) were modelled as categorical variables. The age bands were defined a priori to be consistent with past analyses.

The regression technique used depended on the distribution of the outcome variable data.

Count data (hospital admissions for carious tooth extractions and hip fractures) were inspected using histograms. If the data appeared to fit a Poisson distribution, a Poisson model was fitted to the data aggregated at that geographic level of analysis. Where there was over-dispersion (defined here as deviance/degrees of freedom ≥2), a negative binomial model was used. Regression coefficients were converted to incidence rate ratios.

Proportion data (prevalence of $d_3$mft in 3- and 5-year-olds) were analysed using a binomial model with logit link, using the number of children examined per LSOA as the denominator. Odds ratios were calculated for each category of fluoride concentration relative to the lowest.

Mean $d_3$mft scores were severely skewed. Therefore an ordered logistic regression approach was taken, by grouping the outcome into ordered categories of 'zero' for zero values, and 'low', 'medium' and 'high', formed by splitting the remaining outcome data into non-overlapping groups each representing a third of the distribution of the data. This approach was also taken in the 2018 health monitoring report. The proportional odds assumption was tested across response categories using an approximate likelihood ratio test; the proportionality of odds was rejected when the p value was <0.05. Where the proportional odds assumption was violated, a generalised ordered logistic regression model was used.[44]

For all outcomes, a cluster option using the local authority area to which LSOAs or MSOAs belonged was adopted. This was to inflate the standard error to account for likely non-independence between the values of the outcome variable for LSOAs or MSOAs within the same local authority.

Results

Distribution of fluoride concentration

There were 3,877 LSOAs (of 32,844), in 35 local authority areas across England, participating in fluoridation schemes.

There were 142 LSOAs which received water with fluoride concentrations ≥0.7mg/l through natural fluoridation relating to underlying geology, accounting for public water supplied to 0.4% of the population (tables 4, 5, and 6).

Table 4 - Number of lower layer super output areas (LSOAs) and corresponding mid-year population estimate in England in 2020, by fluoride concentration and fluoridation schemes status in 2015

Mean fluoride concentration (mg/l)	LSOAs (count)	LSOAs (%)	Population (count, millions)	Population (%)	LSOAs with a scheme (count)	LSOAs with a scheme (%)
<0.1	12,602	38	21.1	37	3	0
0.1 - <0.2	11,129	34	19.7	35	84	2
0.2 - <0.4	4,422	13	7.7	14	126	3
0.4 - <0.7	1,415	4	2.5	4	587	15
≥0.7	3,219	10	5.5	10	3,077	79
No data	57	0	0.1	0	0	0
Total	32,844	100	56.6	100	3,877	100

May not sum exactly due to rounding

Table 5 - Number of middle layer super output areas (MSOAs) and corresponding mid-year population estimate in England in 2020, by fluoride concentration and fluoridation schemes status in 2015

Mean fluoride concentration (mg/l)	MSOAs (count)	MSOAs (%)	Population (count, millions)	Population (%)	MSOAs with a scheme (count)	MSOAs with a scheme (%)
<0.1	2,630	39	21.2	38	1	0
0.1 - <0.2	2,294	34	19.7	35	18	2
0.2 - <0.4	892	13	7.5	13	28	3
0.4 - <0.7	289	4	2.4	4	121	15
≥0.7	673	10	5.6	10	640	79
No data	13	0	0.1	0	0	0
Total	6,791	100	56.6	100	808	100

May not sum exactly due to rounding

Table 6 - Number of lower-tier local authority areas (LTLAs) and corresponding mid-year population estimate in England in 2020, by fluoride concentration and fluoridation schemes status in 2015

Mean fluoride concentration (mg/l)	LTLAs (count)	LTLAs (%)	Population (count, millions)	Population (%)	LTLAs with a scheme (count)	LTLAs with a scheme (%)
<0.1	113	37	21.2	37	1	0
0.1 - <0.2	106	34	19.9	35	1	3
0.2 - <0.4	48	16	8.7	14	2	6
0.4 - <0.7	11	4	1.6	3	3	9
≥0.7	30	10	5.8	10	28	82
No data	10	0	0	0	0	0
Total	309	100	56.6	100	35	100

May not sum exactly due to rounding

Fluoride concentration varied across England, with much of the North and the South West having fluoride concentrations of <0.1mg/l (figure 1). Fluoridation schemes largely operated in the North West, North East, West Midlands, and South Yorkshire. Areas with naturally high water fluoride concentrations (≥0.7mg/l) were in Suffolk, parts of the South West, and parts of the North East (figure 2)

Figure 1 - Mean fluoride concentration in LSOAs in England, with 2020 LTLA boundaries

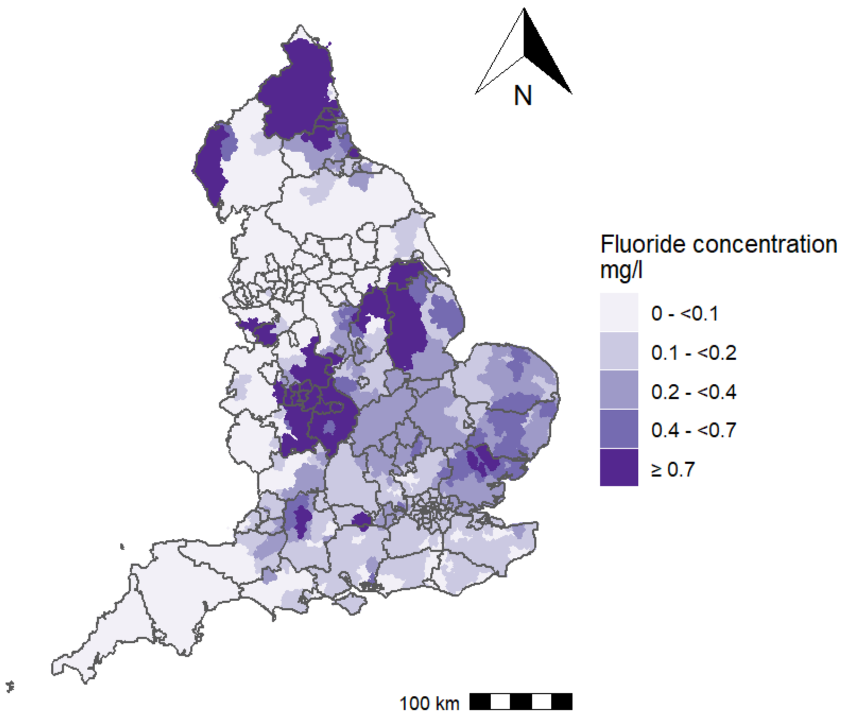
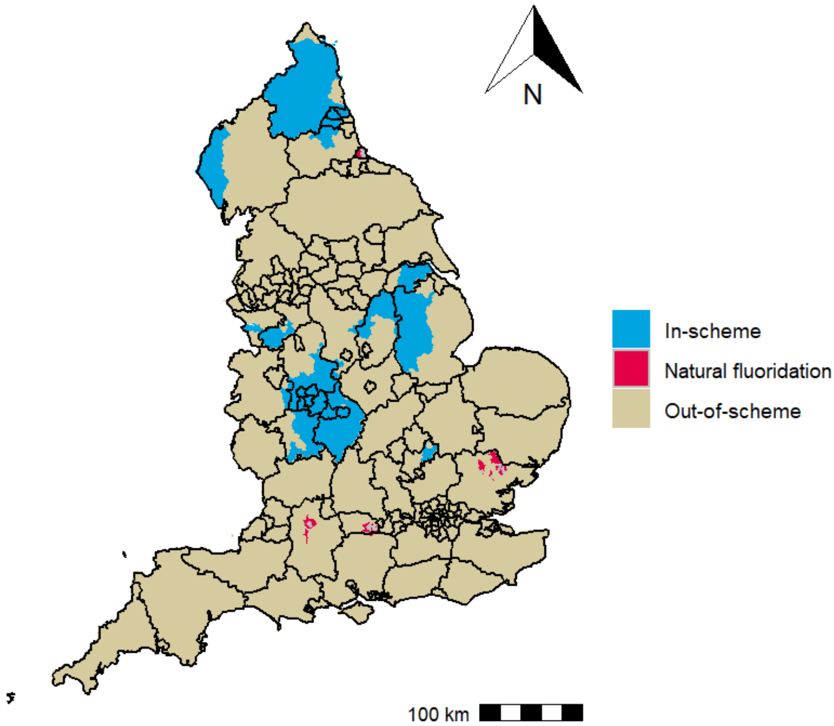


Figure 2 - LSOAs with a fluoridation scheme (yes/no) or with fluoride concentration naturally 0.7mg/l in England in 2015, with LA boundaries.



No association was identified between deprivation and either mean fluoride concentration or the presence of a fluoridation scheme.

Dental health outcomes

For all dental health outcomes, the interaction between fluoride concentration and deprivation was assessed using deprivation (IMD) deciles. For ease of reading, where the association between fluoride concentration and the outcome of interest varied by IMD decile (that is, the interaction was significant at the 5% level), results are presented in this section stratified by IMD quintile. However, this underestimates the effect of deprivation. Full results tables, stratified by IMD decile, are presented in appendix 1.

Prevalence and severity of dental caries experience in three-year-olds in 2020

Descriptive epidemiology

Dental survey data were collected for 19,479 three-year-olds across 8,093 LSOAs, 19,444 (>99%) of whom were assigned a fluoride exposure category for 2011 to 2015. Distribution of surveyed children by LSOA-level deprivation score was broadly similar to the general population. Surveyed children with exposure to the highest level of fluoride may be under-represented as large areas of the West Midlands, which has fluoridation schemes in place, did not complete the survey (tables 7 and 8).

Table 7 – Distribution of 3-year-olds surveyed in the oral health survey in 2020 and estimated population of 3-year-olds in England using mid-year 2020 population estimates, by mean fluoride concentration 2011 to 2015

Mean fluoride concentration 2011 to 2015 (mg/l)	Surveyed (count)	Surveyed (%)	Population (count)	Population (%)
<0.1	6,569	33.72	223,313	33.59
0.1 - <0.2	6,693	34.36	256,240	38.54
0.2 - <0.4	4,315	22.15	96,853	14.57
0.4 - <0.7	758	3.89	22,854	3.44
≥0.7	1,109	5.69	65,444	9.84
missing	35	0.18	186	0.03
Total	19,479	100.00	664,890	100.00

Table 8 – Distribution of 3-year-olds surveyed in the oral health survey in 2020 and estimated population of 3-year-olds in England using mid-year 2020 population estimates, by index of multiple deprivation 2019 (IMD) decile

IMD decile	Surveyed (count)	Surveyed (%)	Population (count)	Population (%)
10 (least deprived)	1,594	8.18	54,668	8.22
9	1,895	9.73	57,167	8.60
8	1,958	10.05	58,477	8.79
7	1,898	9.74	58,573	8.81
6	1,926	9.89	62,751	9.44
5	1,849	9.49	64,625	9.72
4	1,967	10.10	67,714	10.18
3	2,269	11.65	74,524	11.21
2	2,056	10.55	79,064	11.89
1 (most deprived)	2,067	10.61	87,327	13.13
Total	19,479	100.00	664,890	100.00

Prevalence of caries experience, defined as the presence of one or more $d_3$mft, varied by fluoride exposure category. The highest prevalence (12%) was in areas with the lowest fluoride concentration, and the lowest prevalence (8%) in areas with the highest fluoride concentration (table 9).

Table 9 - Prevalence of caries experience (presence of one or more $d_3$mft) in 3-year-old children surveyed in the oral health survey 2020, by fluoride concentration category

Fluoride concentration 2011-2015 (mg/l)	Number of children examined	Number of children with dental caries	Prevalence of caries experience %	95% confidence intervals
<0.1	6,569	812	12.36	11.53 – 13.24
0.1 - <0.2	6,693	697	10.41	9.66 – 11.22
0.2 - <0.4	4,315	349	8.09	7.26 – 8.98
0.4 - <0.7	758	72	9.50	7.43 – 11.96
≥0.7	1,109	89	8.03	6.44 – 9.88
Total	194,444	2,019	10.38	9.94 – 10.85

Severity of dental caries experience also reduced with increasing fluoride concentration, from 0.34 in the lowest concentration category to 0.21 in the highest (table 10).

Table 10 - Mean dental caries severity score in 3-year-old children surveyed in the oral health survey 2020, by fluoride concentration category, weighted by sample size

Mean fluoride concentration 2011 to 2015 (mg/l)	Number of children examined	Mean severity score	95% confidence intervals
<0.1	6,569	0.34	0.31 – 0.36
0.1 - <0.2	6,693	0.31	0.29 – 0.34
0.2 - <0.4	4,315	0.25	0.22 – 0.27
0.4 - <0.7	758	0.35	0.27 – 0.43
≥0.7	1,109	0.21	0.17 – 0.25
Total	194,444	0.30	0.29 – 0.31

Analytic epidemiology: prevalence of dental caries experience

The crude odds of dental caries experience tended to decrease with increasing fluoride concentration. The crude odds of caries experience increased with increasing LSOA-level deprivation, with the most deprived eight groups having clearly increased odds of caries experience compared to the least deprived group (table 11).

Table 11 - Crude odds ratios of experiencing carious teeth ($d_3$mft>0) in 3-year-olds surveyed in the oral health survey in 2020, standard errors adjusted for 257 local authority clusters

Characteristic	odds ratio	95% CI	p value[1]	composite p value[2]
Mean fluoride concentration mg/l 2011 to 2015				
<0.1	reference			0.006
0.1 - <0.2	0.82	0.68 – 1.00		
0.2 - <0.4	0.62	0.48 – 0.82		
0.4 - <0.7	0.74	0.42 – 1.31		
≥0.7	0.62	0.37 – 1.05		
Continuous	0.49	0.24 – 1.00	0.049	
IMD decile				
10 (least deprived)	reference			<0.001
9	1.10	0.84 – 1.44		
8	1.01	0.74 – 1.40		
7	1.37	1.02 – 1.84		
6	1.59	1.21 – 2.09		
5	1.86	1.36 – 2.54		
4	2.19	1.63 – 2.94		
3	2.51	1.90 – 3.30		
2	2.79	2.11 – 3.69		
1 (most deprived)	3.87	2.91 – 5.16		

1. Wald p value for association with fluoride as a continuous variable
2. Composite Wald p value for overall association with a categorical variable

The association between fluoride concentration and prevalence of dental caries experience varied by LSOA-level deprivation status (p <0.001 for interaction between IMD decile and fluoride concentration). Stratum-specific odds ratios are presented by deprivation quintile (table 12). The strength of evidence of the overall association between fluoride and dental caries experience varied by deprivation strata (see composite p values). In the most deprived 2 quintiles, there was a general trend that the odds of experiencing dental caries reduced as fluoride concentration increased, but confidence intervals were generally quite wide.

Table 12 - Odds ratios for experiencing dental caries ($d_3mft>0$) in 3-year-olds surveyed in the oral health survey in 2020, stratified by IMD quintile, standard errors adjusted for 257 local authority clusters

IMD quintile	Mean fluoride concentration mg/l 2011 to 2015	OR	95% CI	p value[1]	Composite p value[2]
5 (least deprived)	<0.1	ref			0.162
	0.1 - <0.2	0.91	0.62 – 1.32		
	0.2 - <0.4	0.75	0.46 – 1.23		
	0.4 - <0.7	1.26	0.47 – 3.35		
	≥0.7	0.14	0.02 – 0.79		
	Continuous	0.19	0.05 – 0.83	0.026	
4	<0.1	ref			0.002
	0.1 - <0.2	0.88	0.66 – 1.16		
	0.2 - <0.4	0.50	0.36 – 0.71		
	0.4 - <0.7	0.59	0.25 – 1.35		
	≥0.7	0.63	0.37 – 1.05		
	Continuous	0.35	0.15 – 0.82	0.015	
3	<0.1	ref			0.069
	0.1 - <0.2	1.07	0.79 – 1.45		
	0.2 - <0.4	0.57	0.35 – 0.93		
	0.4 - <0.7	0.65	0.34 – 1.24		
	≥0.7	0.99	0.37 – 2.62		
	Continuous	0.56	0.18 – 1.79	0.329	
2	<0.1	ref			0.116
	0.1 - <0.2	0.87	0.67 – 1.13		
	0.2 - <0.4	0.77	0.58 – 1.02		
	0.4 - <0.7	0.52	0.26 – 1.03		
	≥0.7	0.61	0.34 – 1.10		
	Continuous	0.49	0.27 – 0.89	0.020	
1 (most deprived)	<0.1	ref			0.005
	0.1 - <0.2	0.90	0.70 – 1.16		
	0.2 - <0.4	0.74	0.51 – 1.09		
	0.4 - <0.7	0.85	0.36 – 2.01		
	≥0.7	0.64	0.46 – 0.88		
	Continuous	0.61	0.38 – 0.99	0.043	

1. Wald p value for association with fluoride as a continuous variable
2. Composite Wald p value for overall association with fluoride as a categorical variable at each stratum

Analytic epidemiology: dental caries severity

In order to analyse severity of dental caries experience, the LSOA-level mean $d_3$mft was categorised into 4 groups (table 13).

Table 13 - Range and mean $d_3$mft score for each severity category, n=19,479 3-year-olds examined in 8,093 LSOAs in the oral health survey 2020

Severity category	Minimum score	Maximum score	Mean score	Children examined (n)	LSOAs (n)
Zero	0.00	0.00	0.00	13,333	6,437
Low	0.05	0.46	0.27	2,424	398
Medium	0.50	1.29	0.81	2,452	699
High	1.33	14.00	3.11	1,270	559

The crude odds of 3-year-olds being in a higher severity category (for example, low compared to zero, high compared to medium) were generally lower in areas with higher concentrations of fluoride than in those with the lowest. The odds of being in a higher severity category increased with increasing deprivation (table 14).

Table 14 - Crude odds ratios of having a higher severity score category in 3-year-olds surveyed for the oral health survey in 2020, standard errors adjusted for 257 local authority clusters

Characteristic	OR	95% confidence intervals	p value[1]	Composite p value[2]
Mean fluoride concentration mg/l 2011-2015				
<0.1	reference			0.010
0.1 - <0.2	0.80	0.65 – 0.98		
0.2 - <0.4	0.71	0.53 – 0.95		
0.4 - <0.7	0.69	0.43 – 1.11		
≥0.7	0.67	0.39 – 1.14		
Continuous	0.53	0.26 – 1.10	0.087	
IMD decile				
10 (least deprived)	reference			<0.001
9	1.14	0.86 – 1.53		
8	1.17	0.86 – 1.58		
7	1.42	1.05 – 1.94		
6	1.78	1.34 – 2.37		
5	1.82	1.33 – 2.50		

4	2.42	1.76 – 3.32
3	2.59	1.93 – 3.49
2	2.83	2.11 – 3.80
1 (most deprived)	4.73	3.44 – 6.51

1. Wald p value for association with fluoride as a continuous variable
2. Composite Wald p value for overall association with a categorical variable

The association between fluoride and dental caries severity differed by deprivation status (p value for interaction <0.001). There was no evidence for an association between fluoride concentration and dental caries severity at the 5% level (table 15).

Table 15 - Odds ratios for experiencing a higher severity score category in 3-year-olds surveyed in the oral health survey in 2020, by IMD quintile, standard errors adjusted for 257 local authority clusters

IMD quintile	mean fluoride concentration mg/l 2011 to 2015	OR	95% Confidence intervals	p value[1]	Composite p value[2]
5 (least deprived)	<0.1	Reference			0.157
	0.1 - <0.2	1.04	0.72 – 1.50		
	0.2 - <0.4	0.84	0.51 – 1.38		
	0.4 - <0.7	1.38	0.50 – 3.80		
	≥0.7	0.22	0.06 – 0.84		
	Continuous	0.30	0.09 – 1.01	0.051	
4	<0.1	Reference			0.214
	0.1 - <0.2	0.98	0.72 – 1.34		
	0.2 - <0.4	0.66	0.43 – 1.01		
	0.4 - <0.7	0.51	0.21 – 1.24		
	≥0.7	0.84	0.45 – 1.54		
	Continuous	0.51	0.21 – 1.26	0.144	
3	<0.1	Reference			0.221
	0.1 - <0.2	0.94	0.67 – 0.31		
	0.2 - <0.4	0.63	0.40 – 0.99		
	0.4 - <0.7	0.61	0.32 – 1.17		
	≥0.7	1.01	0.38 – 2.70		
	Continuous	0.59	0.20 – 1.74	0.341	
2	<0.1	Reference			0.156
	0.1 - <0.2	0.76	0.56 – 1.03		
	0.2 - <0.4	0.93	0.64 – 1.37		
	0.4 - <0.7	0.48	0.21 – 1.08		
	≥0.7	0.61	0.33 – 1.13		
	Continuous	0.55	0.27 – 1.11	0.096	
1 (most deprived)	<0.1	Reference			0.258

	0.1 - <0.2	0.81	0.59 – 1.12	
	0.2 - <0.4	0.77	0.49 – 1.22	
	0.4 - <0.7	0.89	0.38 – 2.08	
	≥0.7	0.64	0.41 – 1.01	
	Continuous	0.64	0.33 – 1.22	0.177

1. Wald p value for association with fluoride as a continuous variable
2. Composite Wald p value for overall association with fluoride as a categorical variable at each stratum

Prevalence and severity of dental caries experience in five-year-olds in 2017 and 2019

Descriptive epidemiology

Dental survey data were collected for 96,005 5-year-olds across 32,504 LSOAs in 2017 and 78,767 5-year-olds across 31,179 LSOAs in 2019. Results of the 2 surveys were analysed together. 174,667 examined children (>99%) were assigned a fluoride exposure category for 2011 to 2015. The distribution of surveyed children by LSOA-level deprivation score was broadly similar to the general population (tables 16 and 17).

Table 16 - Distribution of 5-year-olds sampled in the national oral health surveys in 2017 and 2019 and estimated population of 5-year-olds in England using mid-year 2017 and 2019 population estimates, by mean fluoride concentration 2011 to 2015

Mean fluoride concentration 2011 to 2015 (mg/l)	Surveyed (count)	Surveyed (%)	Population (count)	Population (%)
<0.1	50,193	28.72	473,622	33.82
0.1 - <0.2	56,264	32.19	536,631	38.32
0.2 - <0.4	30,833	17.64	204,630	14.61
0.4 - <0.7	9,525	5.45	48,112	3.44
≥0.7	27,852	15.94	137,134	9.79
missing	105	0.06	345	0.02
Total	174,772	100.00	1,400,474	100.00

Table 17 – Distribution of 5-year-olds sampled in the national oral health surveys in 2017 and 2019 and estimated population of 5-year-olds in England using mid-year 2017 and 2019 population estimates, by index of multiple deprivation 2019 (IMD) decile

IMD decile	Surveyed (count)	Surveyed (%)	Population (count)	Population (%)
10 (least deprived)	15,680	8.97	123,052	8.79
9	16,472	9.42	124,025	8.86
8	16,784	9.60	122,901	8.78
7	16,082	9.20	123,068	8.79
6	16,572	9.48	130,338	9.31
5	16,885	9.66	133,030	9.50
4	16,960	9.70	141,261	10.09
3	19,502	11.16	155,715	11.12
2	20,247	11.58	166,204	11.87
1 (most deprived)	19,588	11.21	180,880	12.92
Total	174,772	100.00	1,400,474	100.00

There was an absolute reduction of 4.7% in the prevalence of dental caries experience from the lowest fluoride concentration to the highest (a relative reduction of 18.6%). This difference in prevalence between the lowest and highest exposure categories was clearly evident, with non-overlapping confidence intervals (table 18).

Table 18 - Prevalence of dental caries experience (presence of one or more $d_3$mft) in 5-year-olds surveyed in the oral health survey in 2017 and 2019

Mean fluoride concentration 2011-2015 (mg/l)	Number of children examined	Number of children with dental caries	Prevalence of caries experience %	95% confidence intervals
<0.1	50,193	12,627	25.16	24.72 – 25.60
0.1 - <0.2	56,264	12,862	22.86	22.47 – 23.26
0.2 - <0.4	30,833	6,629	21.50	20.99 – 22.02
0.4 - <0.7	9,525	2,280	23.94	22.96 – 24.94
≥0.7	27,852	5,707	20.49	19.96 – 21.03
Total	174,667	28,745	22.96	22.74 – 23.19

The mean $d_3$mft score also decreased from the lowest fluoride concentration to the highest (table 19).

Table 19 - Mean dental caries severity score in 5-year-olds surveyed for the oral health survey in 2017 and 2019 weighted by sample size

Mean fluoride concentration 2011 to 2015 (mg/l)	Number of children examined	Mean severity score	95% confidence intervals
<0.1	50,193	0.88	0.87 – 0.89
0.1 - <0.2	56,264	0.79	0.78 – 0.80
0.2 - <0.4	30,833	0.71	0.69 – 0.72
0.4 - <0.7	9,525	0.77	0.75 – 0.80
≥0.7	27,852	0.60	0.59 – 0.62
Total	174,667	0.77	0.76 – 0.78

Both the prevalence of dental caries experience and the caries severity score showed a general reduction from the lowest category of fluoride exposure to the highest. However, both measures showed a deviation from this trend in the second highest fluoride concentration category (0.4 - <0.7mg/l) (tables 18 and 19).

Analytic epidemiology: prevalence of dental caries experience

The crude odds of experiencing dental caries were lowest in areas with fluoride concentrations of ≥0.7mg/l compared to areas with concentrations of <0.1mg/l. Odds of experiencing caries increased with deprivation (table 20).

Table 20 - Crude odds ratios of experiencing carious teeth ($d_3mft>0$) in 5-year-olds surveyed in the OHS in 2017 and 2019, standard errors adjusted for 315 local authority clusters

Characteristic	OR	95% confidence intervals	p value[1]	Composite p value[2]
mean fluoride concentration mg/l 2011-2015				
<0.1	reference			0.009
0.1 - <0.2	0.88	0.77 – 1.01		
0.2 - <0.4	0.81	0.70 – 0.95		
0.4 - <0.7	0.94	0.75 – 1.17		
≥0.7	0.77	0.65 – 0.90		
Continuous	0.78	0.63 – 0.95	0.015	
IMD decile				
10 (least deprived)	reference			<0.001
9	1.21	1.12 – 1.31		
8	1.36	1.26 – 1.47		
7	1.45	1.34 – 1.58		
6	1.70	1.56 – 1.84		
5	2.00	1.80 – 2.21		
4	2.42	2.19 – 2.67		

3	2.74	2.51 – 2.99
2	3.16	2.88 – 3.47
1 (most deprived)	4.11	3.67 – 4.61

1. Wald p value for association with fluoride as a continuous variable
2. Composite Wald p value for overall association with a categorical variable

The association between fluoride and dental caries experience varied markedly by deprivation ($p < 0.001$). In the most deprived 20% of areas, odds of caries experience were reduced at all fluoride concentrations compared to the lowest. The greatest reduction in odds was seen in areas with fluoride of at least 0.7mg/l in all deprivation strata (table 21).

Table 21 - Odds ratios for experiencing dental caries ($d_3mft>0$) in 5-year-olds surveyed in the OHS in 2017 and 2019, stratified by IMD quintile, standard errors adjusted for 315 local authority clusters

IMD	mean fluoride concentration mg/l 2011 to 2015	OR	95% confidence intervals	p value[1]	Composite p value[2]
5 (least deprived)	<0.1	reference			0.002
	0.1 - <0.2	1.01	0.89 – 1.15		
	0.2 - <0.4	0.97	0.84 – 1.12		
	0.4 - <0.7	0.87	0.65 – 1.15		
	≥0.7	0.74	0.63 – 0.88		
	Continuous	0.66	0.55 – 0.81	<0.001	
4	<0.1	reference			<0.001
	0.1 - <0.2	0.99	0.88 – 1.12		
	0.2 - <0.4	0.93	0.82 – 1.05		
	0.4 - <0.7	0.90	0.72 – 1.12		
	≥0.7	0.73	0.60 – 0.88		
	Continuous	0.71	0.61 – 0.82	<0.001	
3	<0.1	reference			<0.001
	0.1 - <0.2	1.12	0.98 – 1.28		
	0.2 - <0.4	1.00	0.84 – 1.17		
	0.4 - <0.7	0.95	0.76 – 1.19		
	≥0.7	0.80	0.70 – 0.91		
	Continuous	0.71	0.59 – 0.86	<0.001	
2	<0.1	reference			<0.001
	0.1 - <0.2	1.04	0.92 – 1.17		
	0.2 - <0.4	0.92	0.77 – 1.10		
	0.4 - <0.7	0.92	0.77 – 1.11		
	≥0.7	0.77	0.68 – 0.88		
	Continuous	0.71	0.61 – 0.84	<0.001	
1 (most deprived)	<0.1	reference			<0.001

0.1 - <0.2	0.75	0.64 – 0.64	
0.2 - <0.4	0.73	0.63 – 0.84	
0.4 - <0.7	0.80	0.67 – 0.96	
≥0.7	0.61	0.54 – 0.70	
Continuous	0.63	0.54 – 0.73	<0.001

1. Wald p value for association with fluoride as a continuous variable
2. Composite Wald p value for overall association with fluoride as a categorical variable at each stratum

Figures 3, 4, and 5 present the mean dental caries prevalence in 5-year-olds in the surveyed LSOAs, predicted by the regression model.

Figure 3 shows the association between fluoride concentration and caries prevalence, stratified by deprivation quintile. The greatest reduction was seen in the most deprived quintile.

Figure 3 - Mean dental caries prevalence (proportion) by fluoride concentration category in 5-year-olds surveyed in the OHS 2017 and 2019, stratified by IMD quintile (1=most deprived, 5=least deprived), standard errors adjusted for 315 local authority clusters

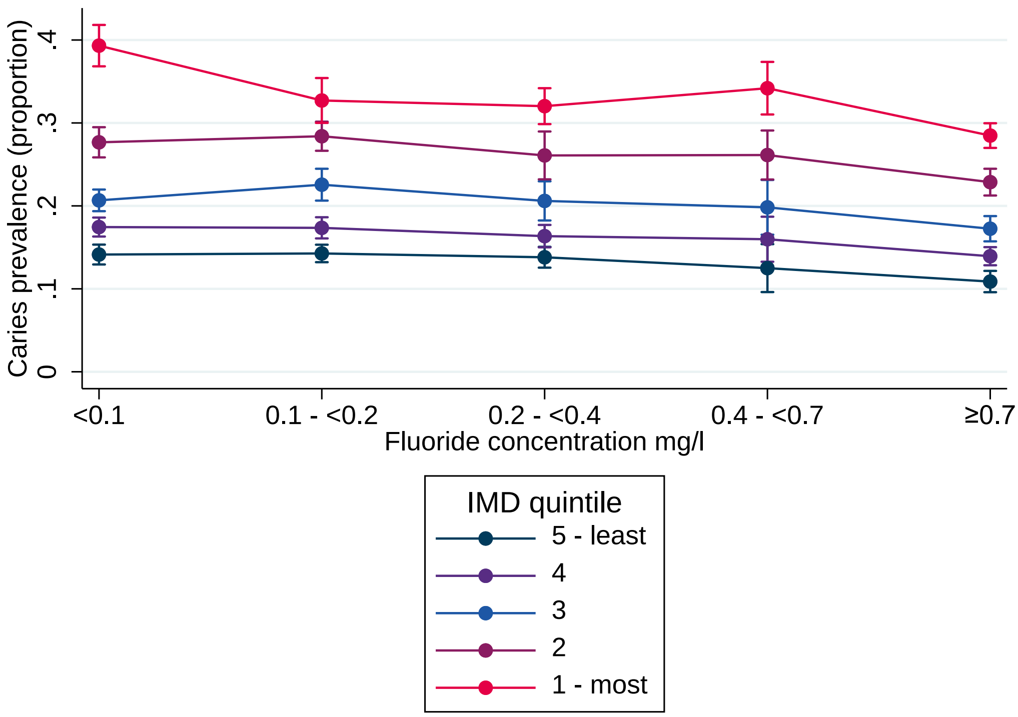


Figure 4 shows the association between deprivation and caries prevalence, stratified by fluoride concentration. The greatest increase in prevalence was seen in areas with the lowest fluoride concentration.

Figure 4 - Mean dental caries prevalence (proportion) in 5-year-olds surveyed in the OHS 2017 and 2019 by IMD quintile, stratified by fluoride concentration, standard errors adjusted for 315 local authority clusters

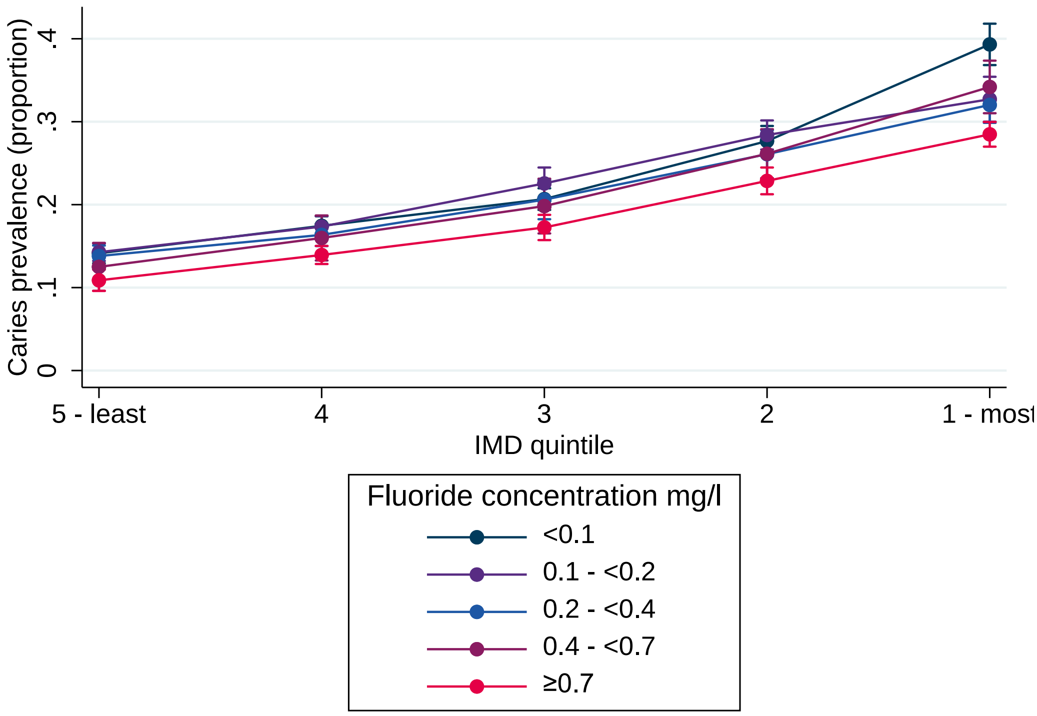
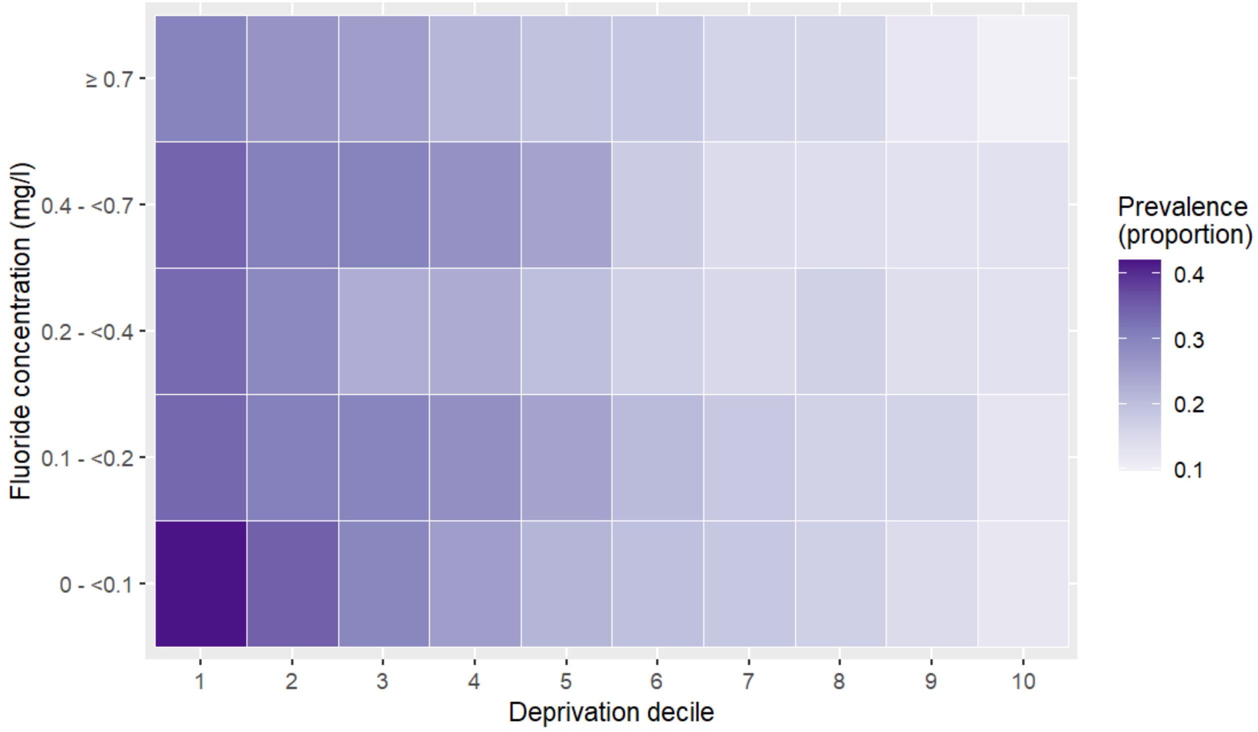


Figure 5 shows this relationship in a heatmap, using deprivation deciles rather than quintiles. The bottom left corner shows high prevalence in 5-year-olds in areas with the highest deprivation and the lowest fluoride concentrations.

Figure 5 - Mean dental caries prevalence amongst 5-year-olds surveyed in the OHS 2017 and 2019, by fluoride concentration and deprivation decile



Analytic epidemiology: dental caries severity

As described for the OHS of 3-year-olds, the LSOA-level mean $d_3$mft was categorised into 4 groups for analysis (table 22).

Table 22 - Range and mean dental caries severity score for each category, n=174,772 5-year-olds examined in 26,902 LSOAs in 2017 and 2019

Severity category	Minimum score	Maximum score	Mean score	Number examined	LSOAs
Zero	0.00	0.00	0.00	35,136	10,073
Low	0.04	0.49	0.26	48,070	4,911
Medium	0.50	1.22	0.79	53,704	6,304
High	1.22	16.00	2.49	37,862	5,614

The unadjusted risk ratio of having higher severity scores relative to lower ones was lower in areas with higher fluoride concentrations compared to areas with the lowest concentration (table 23).

Table 23 - Crude relative risk ratios of having a higher severity score relative to lower scores in 5-year-olds surveyed for the OHS 2017 and 2019, by 2011 to 2015 period mean fluoride concentration (mg/l), standard errors adjusted for 315 local authority clusters

Dental caries severity score (category)	Mean fluoride concentration mg/l 2011 to 2015	RRR	95% confidence intervals	p value[1]	Composite p value[2]
High / medium / low relative to zero	<0.1	ref			0.025
	0.1 - <0.2	0.84	0.70 – 0.99		
	0.2 - <0.4	1.06	0.86 – 1.31		
	0.4 - <0.7	1.27	0.90 – 1.80		
	≥0.7	1.34	0.90 – 1.99		
	Continuous	1.60	1.03 – 2.49	0.037	
High / medium relative to low / zero	<0.1	ref			0.185
	0.1 - <0.2	0.85	0.71 – 1.01		
	0.2 - <0.4	0.85	0.70 – 1.03		
	0.4 - <0.7	0.96	0.69 – 1.34		
	≥0.7	0.78	0.60 – 1.02		
	Continuous	0.80	0.58 – 1.11	0.188	
High relative to medium / low / zero	<0.1	ref			<0.001
	0.1 - <0.2	0.77	0.63 – 0.94		
	0.2 - <0.4	0.67	0.53 – 0.84		
	0.4 - <0.7	0.65	0.47 – 0.90		
	≥0.7	0.44	0.33 – 0.59		
	Continuous	0.39	0.27 – 0.56	<0.001	

1. Wald p value for association with fluoride as a continuous variable
2. Composite Wald p value for overall association with fluoride as a categorical variable

There was a strong association between deprivation and dental caries severity, with the risk ratio of all severity scores relative to lower ones greatest in the most deprived areas, with high severity scores particularly likely in these areas (table 24).

Table 24 - Crude relative risk ratios of having a higher severity score relative to lower scores in 5-year-olds surveyed for the OHS in 2017 and 2019, by IMD quintile, standard errors adjusted for 315 local authority clusters

Dental caries severity score (category)	Deprivation quintile	RRR	95% confidence intervals	Composite p value[1]
High / medium / low relative to zero	5 (least deprived)	reference		<0.001
	4	1.31	1.21 – 1.41	
	3	1.75	1.59 – 1.93	
	2	2.58	2.24 – 2.97	
	1 (most deprived)	3.93	3.27 – 4.72	
High / medium relative to low / zero	5 (least deprived)	reference		<0.001
	4	1.50	1.37 – 1.64	
	3	2.22	2.01 – 2.45	
	2	3.64	3.20 – 4.14	
	1 (most deprived)	6.35	5.51 – 7.32	
High relative to medium / low / zero	5 (least deprived)	reference		<0.001
	4	1.59	1.38 – 1.83	
	3	2.71	2.34 – 3.13	
	2	4.66	4.01 – 5.43	
	1 (most deprived)	8.34	7.04 – 9.88	

1. Composite Wald p value for overall association with IMD as a categorical variable

The association between fluoride concentration and dental caries severity varied by deprivation (p 0.0035). Across all deprivation quintiles, the risk ratios of having the highest caries severity score relative to lower scores were lower in areas with greater fluoride concentration (table 25).

Table 25 - Relative risk ratios of having the highest caries severity score relative to scores of medium, low, or zero, in 5-year-olds surveyed for the OHS in 2017 and 2019, by IMD quintile, standard errors adjusted for 315 local authority clusters

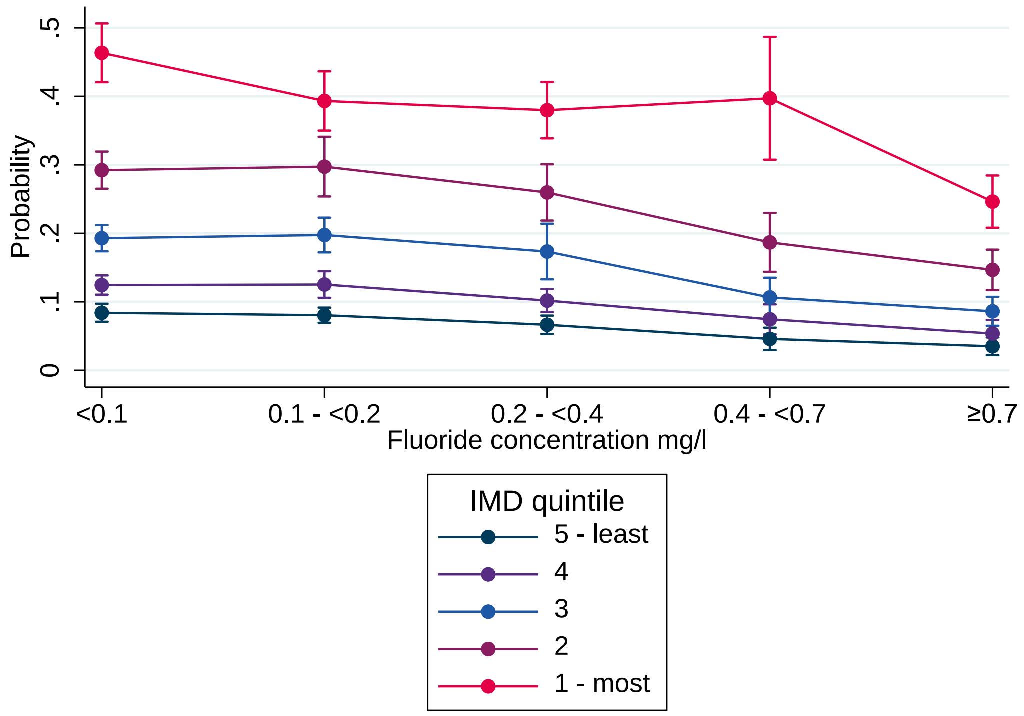
IMD quintile	Mean fluoride concentration mg/l 2011 to 2015	RRR	95% confidence intervals	p value[1]	Composite p value[2]
5 (least deprived)	<0.1	reference			0.037
	0.1 - <0.2	0.95	0.80 – 1.14		

	0.2 - <0.4	0.78	0.60 – 1.00		
	0.4 - <0.7	0.52	0.36 – 0.76		
	≥0.7	0.40	0.26 – 0.60		
	Continuous	0.30	0.20 – 0.45	<0.001	
4	<0.1	reference			<0.001
	0.1 - <0.2	1.01	0.84 – 1.21		
	0.2 - <0.4	0.80	0.65 – 0.98		
	0.4 - <0.7	0.57	0.41 – 0.78		
	≥0.7	0.40	0.26 – 0.60		
	Continuous	0.31	0.20 – 0.47	<0.001	
3	<0.1	reference			<0.001
	0.1 - <0.2	1.03	0.87 – 1.22		
	0.2 - <0.4	0.88	0.66 – 1.17		
	0.4 - <0.7	0.50	0.36 – 0.68		
	≥0.7	0.39	0.30 – 0.53		
	Continuous	0.29	0.21 – 0.41	<0.001	
2	<0.1	reference			<0.001
	0.1 - <0.2	1.03	0.80 – 1.31		
	0.2 - <0.4	0.85	0.67 – 1.09		
	0.4 - <0.7	0.56	0.41 – 0.75		
	≥0.7	0.42	0.32 – 0.54		
	Continuous	0.33	0.24 – 0.45	<0.001	
1 (most deprived)	<0.1	reference			<0.001
	0.1 - <0.2	0.75	0.59 – 0.96		
	0.2 - <0.4	0.71	0.56 – 0.90		
	0.4 - <0.7	0.76	0.51 – 1.15		
	≥0.7	0.38	0.29 – 0.50		
	Continuous	0.35	0.26 – 0.48	<0.001	

1. Wald p value for association with fluoride as a continuous variable
2. Composite Wald p value for overall association with fluoride as a categorical variable at each stratum

Figure 6 presents the probability of having a high dental caries severity score by fluoride concentration, as predicted by the regression model. The greatest reduction in probability was seen in the most deprived 20% of areas.

Figure 6 - Probability (proportion) of having the highest dental caries severity score, amongst surveyed 5-year-olds in 2017 and 2019, by fluoride concentration, stratified by IMD quintile, standard errors adjusted for 315 local authority clusters



Exposure to a water fluoridation scheme

Considering public water supplies where fluoride was adjusted as part of a fluoridation scheme over the period 2011 to 2015, the odds of experiencing dental caries amongst 5-year-olds surveyed in 2017 and 2019 were generally lower than in those in areas not subject to a fluoridation scheme and where the mean fluoride concentration was <0.2mg/l. The association with fluoride varied by deprivation, but only marginally. The reduction was slightly more evident in the most deprived quintile (table 26).

Table 26 - Odds ratios of dental caries experience in 5-year-olds surveyed in 2017 and 2019 in areas with a fluoridation scheme compared to those without, stratified by deprivation quintile

IMD quintile	OR	95% confidence intervals	p value
5 (least deprived)	0.78	0.67 – 0.91	0.001
4	0.84	0.75 – 0.94	0.002
3	0.82	0.71 – 0.95	0.009
2	0.81	0.72 – 0.91	0.001

1 (most deprived)	0.75	0.67 – 0.84	<0.001

Hospital admissions for carious tooth extractions in 0- to 19-year-olds 2016/17 to 2020/21

Descriptive epidemiology

The majority of 0- to 19-year-olds (72%) over the financial years 2016/17 to 2020/21 lived in areas which had mean water fluoride concentrations of <0.2mg/l in the years 2011 to 2015. Characteristics of those admitted to hospital for carious tooth extractions and the population at risk are summarised in tables 27, 28, 29, and 30.

Table 27 - Distribution of 0- to 19-year-olds admitted for carious tooth extractions 20116/17 to 2020/21 and the 0- to 19-year-old population (person-years) at risk (PYAR) 2016 to 2020, by mean fluoride concentration 2011 to 2015

Mean fluoride concentration mg/l 2011 to 2015	Admissions (count)	Admissions (%)	PYAR (count)	PYAR (%)
<0.1	81,745	49.56	22,536,510	34.08
0.1 - <0.2	55,751	33.80	24,892,245	37.64
0.2 - <0.4	13,670	8.29	9,779,125	14.79
0.4 - <0.7	4,767	2.89	2,479,575	3.75
≥0.7	8,992	5.45	6,440,840	9.74
Missing	2	0.00	1,940	0.00
Total	164,927	100.00	66,130,235	100.00

Table 28 - Distribution of 0- to 19-year-olds admitted for carious tooth extractions 20116/17 to 2020/21 and the 0- to 19-year-old population (person-years) at risk (PYAR) 2016 to 2020, by age group

Age group (years)	Admissions (count)	Admissions (%)	PYAR (count)	PYAR (%)
0 to 4	29,065	17.62	16,699,870	25.25
5 to 9	98,472	59.71	17,527,100	26.50
10 to 14	26,194	15.88	16,300,265	24.65
15 to 19	11,196	6.79	15,603,000	23.59
Total	164,927	100.00	66,130,235	100.00

Table 29 - Distribution of 0- to 19-year-olds admitted for carious tooth extractions 20116/17 to 2020/21 and the 0- to 19-year-old (person-years) at risk (PYAR) 2016 to 2020, by sex

Sex	Admissions (count)	Admissions (%)	PYAR (count)	PYAR (%)
Male	86,484	52.44	33,908,150	51.27
Female	78,443	47.56	32,222,085	48.73
Total	164,927	100.00	66,130,235	100.00

Table 30 - Distribution of 0- to 19-year-olds admitted for carious tooth extractions 20116/17 to 2020/21 and the 0- to 19-year-old population (person-years) at risk (PYAR) 2016 to 2020, by index of multiple deprivation 2019 (IMD) decile

IMD decile	Admissions (count)	Admissions (%)	PYAR (count)	PYAR (%)
10 (least deprived)	6,622	4.02	6,319,195	9.56
9	8,508	5.16	6,169,560	9.33
8	9,296	5.64	5,917,775	8.95
7	11,707	7.10	6,052,355	9.15
6	12,557	7.61	6,117,545	9.25
5	14,832	8.99	6,323,330	9.56
4	18,153	11.01	6,603,465	9.99
3	21,868	13.26	6,965,060	10.53
2	26,409	16.01	7,643,060	11.56
1 (most deprived)	34,975	21.21	8,018,890	12.13
Total	164,927	100.00	66,130,235	100.00

The crude incidence of admissions for dental extractions was highest in areas with fluoride concentration <0.1mg/l, and lowest in those with concentration ≥0.7mg/l (table 31).

Table 31 - Crude incidence of admissions for carious tooth extractions among 0- to 19-year olds, 2016/17 to 2020/21, by fluoride concentration

Mean fluoride concentration mg/l 2011-2015	Admissions for carious tooth extraction	Person-years (millions)	Crude incidence per 100,000	95% confidence intervals
<0.1	81,745	22.54	362.72	360.24 – 365.22
0.1 - <0.2	55,751	24.89	223.97	222.11 – 225.84
0.2 - <0.4	13,670	9.78	139.79	137.45 – 142.15
0.4 - <0.7	4,767	2.48	192.25	186.83 – 197.79
≥0.7	8,992	6.44	139.61	136.74 – 142.53
Total	164,925	66.13	249.40	248.20 – 250.60

Analytic epidemiology

The crude incidence rate ratio (IRR) of admissions for dental extraction was 60% lower in areas with fluoride concentrations of ≥0.7mg/l than in areas of <0.1mg/l. IRR varied across age groups; the incidence rate in 5- to 9-year-olds was 3.4 times that in 0- to 4-year-olds. There was a reduced incidence rate in females compared to males. The IRR in the most deprived 10% of areas was 4.3 times that of the least deprived 10% (table 32).

Table 32 - Crude incidence rate ratios by fluoride concentration, age band, sex, and deprivation decile, standard errors adjusted for 316 local authority clusters

Characteristic	Crude IRR	95% confidence intervals	p value[1]	Composite p value[2]
Mean fluoride concentration mg/l 2011 to 2015				
<0.1	reference			<0.001
0.1 - <0.2	0.62	0.51 – 0.76		
0.2 - <0.4	0.41	0.31 – 0.53		
0.4 - <0.7	0.56	0.40 – 0.77		
≥0.7	0.40	0.23 – 0.69		
Continuous	0.36	0.20 – 0.64	<0.001	
Age group				
0-4	reference			<0.001
5-9	3.38	3.23 – 3.53		
10-14	0.99	0.93 – 1.05		
15-19	0.45	0.41 – 0.50		
Sex				
Male	reference			
Female	0.95	0.94 – 0.98	<0.001	
IMD				
10 (least deprived)	reference			<0.001
9	1.30	1.16 – 1.46		
8	1.46	1.27 – 1.67		
7	1.82	1.58 – 2.10		
6	1.93	1.69 – 2.21		
5	2.20	1.89 – 2.56		
4	2.61	2.24 – 3.04		
3	2.93	2.48 – 3.47		
2	3.33	2.80 – 3.97		
1 (most deprived)	4.29	3.33 – 5.52		

1. Wald p value for association
2. Composite Wald p value for overall association with a categorical variable

The association between fluoride concentration and hospital admissions for carious tooth extractions varied by MSOA-level deprivation status (p 0.039 for interaction between IMD decile and fluoride concentration). Stratum-specific odds ratios are presented by deprivation quintile (table 33). In all deprivation quintiles, there was a general trend of reducing incidence with increasing fluoride.

Table 33 - Incidence rate ratios of admissions for carious tooth extractions among 0- to 19-year-olds 2016/17 to 2020/21, by deprivation quintile, adjusted for age and sex, standard errors adjusted for 316 local authority clusters

IMD quintile	Mean fluoride concentration mg/l 2011-2015	Adjusted IRR	95% confidence intervals	p value[1]	Composite p value[2]
5 (least deprived)	<0.1	Reference			<0.001
	0.1 - <0.2	0.77	0.63 – 0.94		
	0.2 - <0.4	0.52	0.39 – 0.69		
	0.4 - <0.7	0.71	0.42 – 1.20		
	≥0.7	0.43	0.24 – 0.77		
	Continuous	0.32	0.15 – 0.66	0.002	
4	<0.1	Reference			<0.001
	0.1 - <0.2	0.77	0.64 – 0.93		
	0.2 - <0.4	0.53	0.42 – 0.67		
	0.4 - <0.7	0.60	0.40 – 0.88		
	≥0.7	0.41	0.26 – 0.64		
	Continuous	0.31	0.19 – 0.52	<0.001	
3	<0.1	Reference			<0.001
	0.1 - <0.2	0.81	0.66 – 0.99		
	0.2 - <0.4	0.51	0.39 – 0.67		
	0.4 - <0.7	0.67	0.48 – 0.93		
	≥0.7	0.49	0.29 – 0.83		
	Continuous	0.41	0.23 – 0.72	0.002	
2	<0.1	Reference			<0.001
	0.1 - <0.2	0.82	0.67 – 1.00		
	0.2 - <0.4	0.49	0.37 – 0.66		
	0.4 - <0.7	0.59	0.41 – 0.84		
	≥0.7	0.40	0.22 – 0.72		
	Continuous	0.31	0.17 – 0.58	<0.001	
1 (most deprived)	<0.1	Reference			<0.001
	0.1 - <0.2	0.66	0.52 – 0.84		
	0.2 - <0.4	0.41	0.29 – 0.58		
	0.4 - <0.7	0.55	0.37 – 0.82		
	≥0.7	0.37	0.18 – 0.74		
	Continuous	0.32	0.15 – 0.70	0.004	

1. Wald p value for association
2. Composite Wald p value for overall association with a categorical variable

Figures 7, 8, and 9 present the number of admissions for carious tooth extractions per MSOA, by fluoride concentration and deprivation, as predicted by the regression model.

Figure 7 shows the association with fluoride, stratified by deprivation quintile. Although the most deprived quintile experiences the greatest number of admissions at all fluoride concentrations, the relative reduction is greatest.

Figure 7 - Number of admissions for carious tooth extraction per MSOA by fluoride concentration, stratified by IMD quintile, adjusted for age and sex, standard errors adjusted for 316 local authority clusters

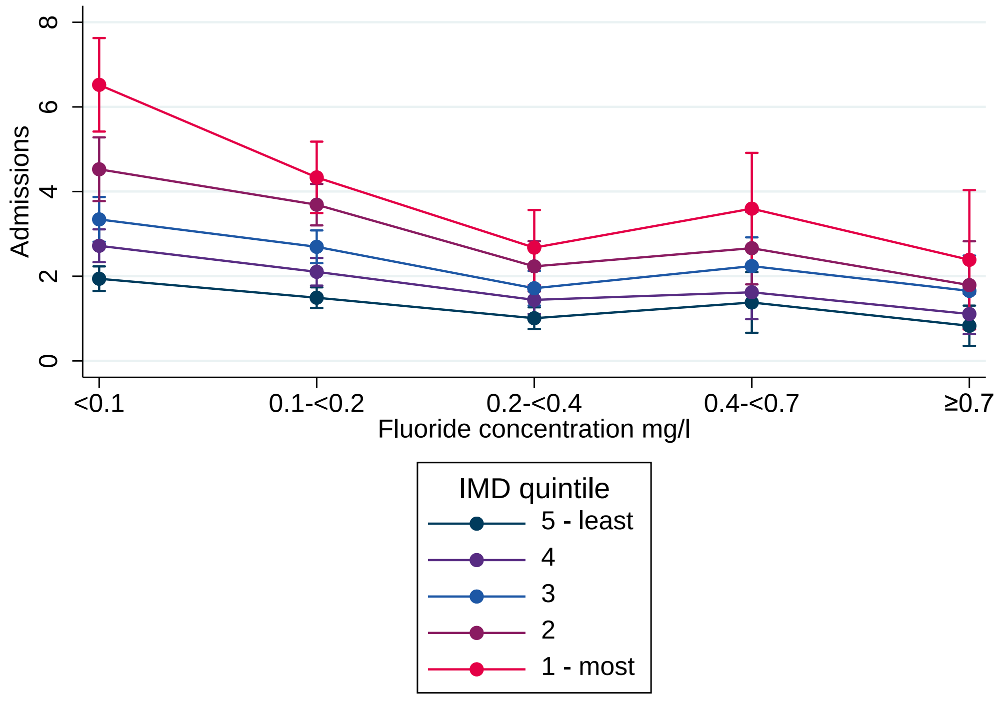


Figure 8 shows the association with deprivation quintile, stratified by fluoride.

Figure 8 - Number of admissions for carious tooth extractions per MSOA by IMD quintile, stratified by fluoride concentration, adjusted for age and sex, standard errors adjusted for 316 local authority clusters

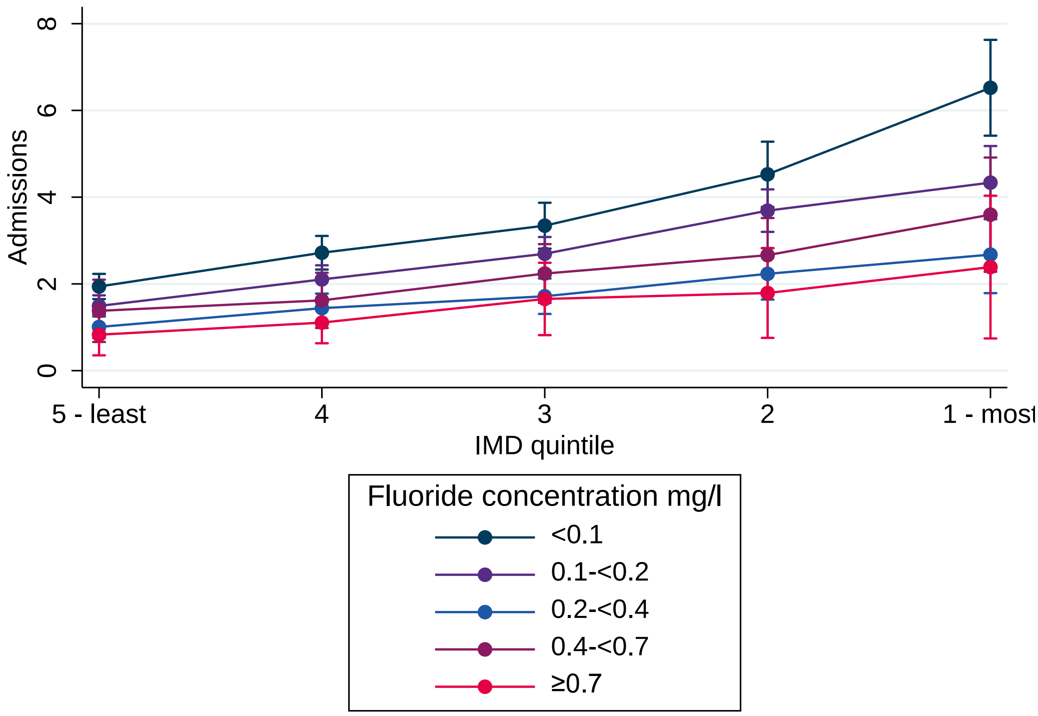
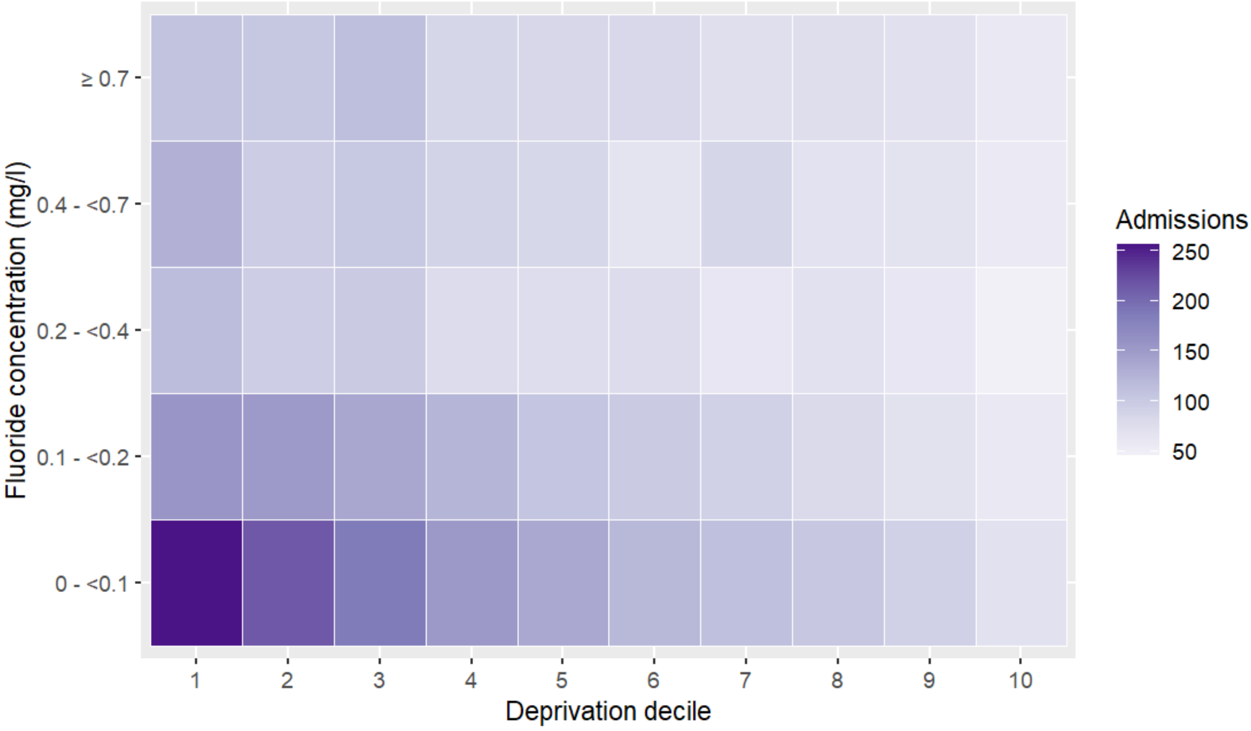


Figure 9 shows the admissions incidence, by fluoride concentration and deprivation decile: the highest incidence was in areas which were the most deprived and had the lowest fluoride concentrations (bottom left).

Figure 9 - Incidence of hospital admissions for carious tooth extractions amongst 0- to 19-year-olds in England in 2016/17 to 2020/21 by fluoride concentration and IMD decile, adjusted for age and sex



In the financial year 2020/21, the number of hospital admissions among 0- to 19-year-olds for carious tooth extraction decreased by more than half, due to the COVID-19 pandemic. A sensitivity analysis was conducted using data from the 4-year period 2016/17 to 2019/20 and found results very similar to those presented above for the full 5-year period.

Exposure to a water fluoridation scheme

Considering public water supplies where fluoride was adjusted as part of a fluoridation scheme in the period 2011 to 2015, the crude incidence of hospital admissions for carious tooth extraction in 0- to 19-year-olds was 47% lower than in areas with no fluoridation scheme and with a mean fluoride concentration of <0.2mg/l (table 34).

Table 34 - Crude incidence per 100,000 person-years at risk (PYAR) of admissions for carious tooth extraction in 0- to 19-year-olds in 2016/17 to 2020/21, by presence of a water fluoridation scheme in 2011 to 2015

Fluoridation scheme 2011 to 2015	Admissions for carious tooth extraction	Person-years (millions)	Incidence per 100,000 PYAR	95% confidence intervals
No	137,496	47.43	289.90	288.37 – 291.44
Yes	12,379	8.13	152.33	149.66 – 155.04
Total	149,875	55.56	269.78	268.41 – 271.15

The relationship between exposure to a fluoridation scheme and dental extractions varied depending on deprivation decile (p <0.0001). Incidence rate ratios for dental extractions in areas with a fluoridation scheme compared to areas without are presented by deprivation quintile (table 35).

Table 35 - Incidence rate ratio of admission for carious tooth extraction in those in a fluoride scheme compared to those not in a fluoride scheme, by deprivation quintile, adjusted for age and sex, 2016/17 to 2020/21

IMD quintile	Adjusted IRR	95% confidence intervals	p value
5 (least deprived)	0.51	0.31 – 0.82	0.005
4	0.47	0.32 – 0.69	<0.001
3	0.63	0.43 – 0.92	0.016
2	0.51	0.32 – 0.81	0.005
1 (most deprived)	0.44	0.24 – 0.80	0.008

Assuming that reduction is caused by fluoridation, if all children and young people in the most deprived 20% of areas with fluoride concentrations <0.2mg/l instead received water with adjusted fluoride, 56% of dental extractions in these areas would have been prevented (table 36). As the most deprived areas have the highest incidence of admission, they would thus have seen the greatest public health impact.

Table 36 - Preventive fraction of admissions for carious tooth extraction in 0- to 19-year-olds in areas with a fluoridation scheme, by deprivation quintile, 2016/17 to 2020/21, adjusted for age and sex

IMD quintile	Preventive fraction (%)	95% confidence intervals
5 (least deprived)	49	18 – 69
4	53	31 – 68
3	37	8 – 57
2	49	19 – 68
1 (most deprived)	56	20 – 76

Non-dental health outcomes

Hospital admissions for hip fractures 2016/17 to 2020/21

Descriptive epidemiology

The majority (72%) of the population over the period 2016/17 to 2020/21 (summarised as the person-years at risk) lived in areas with a mean water fluoride concentration of <0.2mg/l in the years 2006 to 2015. Characteristics of those admitted to hospital for hip fracture and the population are summarised in tables 37, 38, 39, and 40.

Table 37 - Distribution of people admitted with hip fracture 2016/17 to 2020/21 and the population (person-years) at risk (PYAR) 2016 to 2020, by mean fluoride concentration 2006 to 2015

Mean fluoride concentration mg/l 2006 to 2015	Admissions (count)	Admissions (%)	PYAR (count)	PYAR (%)
<0.1	128,876	39.83	101,834,196	36.41
0.1 - <0.2	99,022	30.60	99,535,523	35.59
0.2 - <0.4	47,378	14.64	39,861,277	14.25
0.4 - <0.7	14,774	4.57	10,839,985	3.88
≥0.7	33,495	10.35	27,619,511	9.87
Missing	21	0.01	11,282	0.00
Total	323,566	100.00	279,701,774	100.00

Table 38 - Distribution of people admitted with hip fracture 2016/17 to 2020/21 and the population (person-years) at risk (PYAR) 2016 to 2020, by age group

Age group (years)	Admissions (count)	Admissions (%)	PYAR (count)	PYAR (%)
0-49	7,939	2.45	176,183,509	62.99
50-64	21,501	6.65	52,607,925	18.81
65-79	86,448	26.72	37,053,682	13.25
≥80	207,678	64.18	13,856,658	4.95
Total	323,566	100.00	279,701,774	100.00

Table 39 - Distribution of people admitted with hip fracture 2016/17 to 2020/21 and the population (person-years) at risk (PYAR) 2016 to 2020, by sex

Sex	Admissions (count)	Admissions (%)	PYAR (count)	PYAR (%)
Male	99,628	30.79	138,260,564	49.43
Female	223,938	69.21	141,441,210	50.57
Total	323,566	100.00	279,701,774	100.00

Table 40 - Distribution of people admitted with hip fracture 2016/17 to 2020/21 and the population (person-years) at risk (PYAR) 2016 to 2020, by index of multiple deprivation 2019 (IMD) decile

IMD decile	Admissions (count)	Admissions (%)	PYAR (count)	PYAR (%)
10 (least deprived)	34,162	10.56	27,096,968	9.69
9	34,811	10.76	27,691,069	9.90
8	34,817	10.76	27,123,584	9.70
7	35,498	10.97	27,421,818	9.80
6	33,655	10.40	27,744,357	9.92
5	33,010	10.20	28,229,135	10.09
4	29,664	9.17	28,449,059	10.17
3	29,393	9.08	28,693,957	10.26
2	28,916	8.94	29,337,845	10.49
1 (most deprived)	29,640	9.16	27,913,982	9.98
Total	323,566	100.00	279,701,774	100.00

The crude incidence of acute inpatient admissions with hip fracture was 121 per 100,000 person-years at risk in areas with the highest fluoride concentration, and 127 in areas with the lowest fluoride concentration (table 41). The crude incidence fluctuates between fluoride concentration categories, with no clear pattern.

Table 41 - Crude incidence of admissions for hip fracture, 2016/17 to 2020/21, by fluoride concentration

Mean fluoride concentration mg/l 2006 to 2015	Admissions for hip fracture	Person-years (millions)	Crude incidence per 100,000	95% confidence intervals
<0.1	128,876	101.83	126.55	125.86 – 127.25
0.1 - <0.2	99,022	99.54	99.48	98.87 – 100.11
0.2 - <0.4	47,378	39.86	118.86	117.79 – 119.93
0.4 - <0.7	14,774	10.84	136.29	134.1 – 138.51
≥0.7	33,495	27.62	121.27	119.98 – 122.58
Total	323,545	279.69	115.68	115.28 – 116.08

Analytic epidemiology

By fluoride level there is no trend in the crude incidence rate of admissions for hip fracture, though there is a suggestion of a lower rate of admissions for hip fracture in the second lowest fluoride concentration group (0.1 - <0.2mg/l) compared to the lowest concentration (<0.1mg/l) (table 42).

There was a significant increase in hip fractures associated with increasing age, with those aged 80 and over having 325 times the incidence of those in the youngest age group. The incidence rate in females was double that of males. Those in the 4 most deprived deciles had a decreased incidence rate compared to those in the least deprived decile, which was significant at the 5% level.

Table 42 - Crude incidence rate ratios of admission for hip fracture by fluoride concentration, age band, sex, and deprivation decile, standard errors adjusted for 316 local authority clusters

Characteristic	Crude IRR	95% confidence intervals	p value[1]	Composite p value[2]
Mean fluoride concentration mg/l 2006 to 2015				
<0.1	reference			<0.001
0.1 - <0.2	0.80	0.74 – 0.87		
0.2 - <0.4	0.95	0.88 – 1.01		
0.4 - <0.7	1.07	0.98 – 1.17		
≥0.7	0.96	0.87 – 1.07		
continuous	1.06	0.95 – 1.18	0.326	
Age group (years)				
0-49	reference			<0.001
50-64	9.10	8.78 – 9.43		
65-79	52.47	50.71 – 54.29		
≥80	324.67	314.71 – 334.94		
Sex				
Male	reference			
Female	2.18	2.16 – 2.20	<0.001	
IMD decile				
10 (least deprived)	reference			<0.001
9	1.00	0.95 – 1.05		
8	1.02	0.97 – 1.06		
7	1.03	0.98 – 1.08		
6	0.97	0.92 – 1.03		
5	0.94	0.88 – 1.01		

4	0.85	0.79 – 0.92		
3	0.84	0.77 – 0.91		
2	0.80	0.74 – 0.86		
1 (most deprived)	0.86	0.79 – 0.94		

1. Wald p value for association
2. Composite Wald p value for overall association with a categorical variable

There was evidence that the association between fluoride concentration and admissions for hip fracture varied by age (p<0.001 for interaction between age group and fluoride). There was some evidence of a protective effect of fluoride in the youngest age group, with a modest reduction in incidence rate in areas with fluoride concentrations of 0.1 - <0.2mg/l, 0.2 - <0.4mg/l, and ≥0.7mg/l compared to the lowest concentration (table 33).

Conversely, in the oldest age group, there was a slightly increased incidence rate in areas with fluoride concentrations of 0.2 - <0.4mg/l and 0.4 - <0.7mg/l compared to the lowest concentration. However, there was no pattern across fluoride concentrations and no evidence of association with fluoride as a continuous variable (table 43).

Table 43 - Incidence rate ratios of admissions for hip fracture 2016/17 to 2020/21, adjusted for sex and deprivation, by age category, standard errors adjusted for 316 local authority clusters

Age (years)	Mean fluoride concentration mg/l 2006 to 2015	Adjusted IRR	95% confidence intervals	p value[1]	Composite p value[2]
0-49	<0.1	reference			<0.001
	0.1 - <0.2	0.83	0.77 – 0.89		
	0.2 - <0.4	0.89	0.81 – 0.98		
	0.4 - <0.7	0.93	0.80 – 1.09		
	≥0.7	0.87	0.77 – 0.98		
	continuous	0.88	0.77 – 1.00	0.053	
50-64	<0.1	reference			<0.001
	0.1 - <0.2	0.84	0.80 – 0.89		
	0.2 - <0.4	0.90	0.85 – 0.96		
	0.4 - <0.7	0.98	0.89 – 1.08		
	≥0.7	1.01	0.94 – 1.08		
	continuous	1.05	0.96 – 1.14	0.276	
65-79	<0.1	reference			0.003
	0.1 - <0.2	0.99	0.95 – 1.02		
	0.2 - <0.4	0.98	0.95 – 1.01		
	0.4 - <0.7	1.03	0.98 – 1.08		
	≥0.7	1.04	1.00 – 1.08		
	continuous	1.05	1.01- 1.10	0.029	

≥80	<0.1	reference			0.010
	0.1 - <0.2	0.98	0.94 – 1.03		
	0.2 - <0.4	1.04	1.01 – 1.08		
	0.4 - <0.7	1.08	1.02 – 1.14		
	≥0.7	1.02	0.96 – 1.09		
	continuous	1.05	0.97 – 1.13	0.245	

1. Wald p value for association
2. Composite Wald p value for overall association with a categorical variable

The a priori defined interaction between age group and fluoride concentration was also tested in each sex. The interaction remained significant in both females and males (p <0.001 in both). Adjusted incidence rate ratios are therefore presented stratified by both age group and sex (tables 44 and 45).

In females aged 0 to 49 years, there was statistical evidence of a reduction in incidence of hip fractures in areas with fluoride concentration of 0.1 - <0.2mg/l compared to the lowest concentration. However, there was no pattern across fluoride concentration categories, and no evidence of an association between fluoride concentration and hip fractures when fluoride was modelled as a continuous variable. In males aged 0 to 49 years, there was some reduction in incidence of hip fractures in areas with higher fluoride concentrations, compared to the lowest concentration, and evidence of a weak protective association when fluoride was modelled as a continuous variable.

In both females and males aged 50 to 64 years, no pattern was seen across fluoride concentration categories, and there was no evidence of a linear association between fluoride concentration and hip fracture.

In females and males aged 65 to 79 years no pattern was seen across fluoride concentration categories. When fluoride was modelled as a continuous variable, there was weak evidence (significant at the 10% level) of a linear relationship, with increased incidence of hip fractures at higher fluoride concentrations.

In both females and males aged 80 years and older, there was a slightly increased risk of hip fracture in mid-range fluoride concentrations, compared to the lowest concentration. However, there was no pattern across fluoride concentration categories, and no evidence of an association when fluoride was modelled as a continuous exposure.

Table 44 - Age-stratified incidence rate ratios of admissions for hip fracture in females by fluoride concentration, adjusted for deprivation, standard errors adjusted for 316 local authority clusters

Age (years)	Mean fluoride concentration mg/l 2006 to 2015	Adjusted IRR	95% confidence intervals	p value[1]	Composite p value[2]
0-49	<0.1	reference			<0.001
	0.1 - <0.2	0.70	0.63 – 0.79		
	0.2 - <0.4	0.91	0.78 – 1.06		
	0.4 - <0.7	0.87	0.68 – 1.12		
	≥0.7	0.87	0.72 – 1.04		
	continuous	0.91	0.74 – 1.13	0.394	
50-64	<0.1	reference			<0.001
	0.1 - <0.2	0.81	0.76 – 0.87		
	0.2 - <0.4	0.89	0.84 – 0.94		
	0.4 - <0.7	0.97	0.87 – 1.08		
	≥0.7	1.02	0.92 – 1.13		
	continuous	1.07	0.95 – 1.20	0.251	
65-79	<0.1	reference			0.003
	0.1 - <0.2	0.95	0.91 – 0.99		
	0.2 - <0.4	0.98	0.94 – 1.01		
	0.4 - <0.7	1.06	1.01 – 1.11		
	≥0.7	1.02	0.98 – 1.07		
	continuous	1.05	0.99 – 1.11	0.084	
≥80	<0.1	reference			0.010
	0.1 - <0.2	0.97	0.93 – 1.01		
	0.2 - <0.4	1.03	1.00 – 1.06		
	0.4 - <0.7	1.08	1.01 – 1.14		
	≥0.7	1.02	0.95 – 1.09		
	continuous	1.05	0.97 – 1.13	0.271	

1. Wald p value for association
2. Composite Wald p value for overall association with a categorical variable

Table 45 - Age-stratified incidence rate ratios of admissions for hip fracture in males by fluoride concentration, adjusted for deprivation, standard errors adjusted for 316 local authority clusters

Age (years)	Mean fluoride concentration mg/l 2006 to 2015	Adjusted IRR	95% confidence intervals	p value[1]	Composite p value[2]
0-49	<0.1	reference			0.015
	0.1 - <0.2	0.89	0.82 – 0.96		
	0.2 - <0.4	0.89	0.80 – 0.98		
	0.4 - <0.7	0.97	0.81 – 1.14		
	≥0.7	0.86	0.76 – 0.98		
	continuous	0.86	0.74 – 0.99	0.041	
50-64	<0.1	reference			0.002
	0.1 - <0.2	0.88	0.82 – 0.94		
	0.2 - <0.4	0.92	0.84 – 1.00		
	0.4 - <0.7	0.99	0.88 – 1.11		
	≥0.7	0.99	0.90 – 1.09		
	continuous	1.02	0.91 – 1.14	0.732	
65-79	<0.1	reference			0.003
	0.1 - <0.2	1.03	0.99 – 1.08		
	0.2 - <0.4	0.97	0.92 – 1.01		
	0.4 - <0.7	0.99	0.93 – 1.06		
	≥0.7	1.07	1.02 – 1.02		
	continuous	1.05	1.00 – 1.11	0.059	
≥80	<0.1	reference			0.033
	0.1 - <0.2	1.00	0.95 – 1.05		
	0.2 - <0.4	1.06	1.01 – 1.11		
	0.4 - <0.7	1.08	1.01 – 1.16		
	≥0.7	1.03	0.96 – 1.10		
	continuous	1.05	0.97 – 1.14	0.217	

1. Wald p value for association
2. Composite Wald p value for overall association with a categorical variable

Exposure to a water fluoridation scheme

Considering public water supplies where fluoride was adjusted as part of a fluoridation scheme during the period 2006 to 2015, crude incidence was 7% higher compared to areas where there was no scheme and mean fluoride was below 0.2mg/l (table 46).

Table 46 - Crude incidence of hospital admissions for hip fractures in 2016/17 to 2020/21 in those exposed and not exposed to a fluoridation scheme in 2006 to 2015

Fluoridation scheme 2006 to 2015	Admissions for hip fracture	Person-years (millions)	Crude incidence per 100,000 PYAR	95% confidence intervals
No	227,898	201.37	113.17	112.71 – 113.64
Yes	31,546	26.12	120.78	119.45 – 122.12
Total	259,444	227.49	114.05	113.61 – 114.49

The association between presence of a fluoridation scheme and hip fractures varied by age. When deprivation and sex are taken into account, there was evidence of an increased incidence rate of admissions for hip fracture in those aged 50 to 79 years (table 47).

Table 47 - Incidence rate ratio of admissions for hip fractures in those exposed to a fluoride scheme compared to those who are not, adjusted for deprivation and sex, stratified by age category

Age (years)	Adjusted IRR	95% confidence intervals	p value
0-49	0.92	0.84 – 1.01	0.078
50-64	1.10	1.03 – 1.17	0.003
65-79	1.05	1.02 – 1.09	0.004
≥80	1.05	0.99 – 1.11	0.137

Discussion

Value of this report

This is the third health monitoring report published by the working group. The 2014 report concluded that water fluoridation is a safe and effective dental public health intervention, with no evidence of higher rates of non-dental health indicators in areas with fluoridation schemes compared to areas without. The 2018 report updated that assessment and investigated possible associations between a range of health outcomes and fluoride concentrations, rather than just the presence or absence of a fluoridation scheme. Its findings were consistent with the conclusions of the 2014 report.

The 2022 report continued the approach of using fluoride concentration as an exposure, as well as whether or not the fluoride has been adjusted by a scheme, which allows for a more detailed investigation of the relationship between fluoride and health outcomes. However, the methods used were not exactly the same as those followed in 2018. In particular, the exposure classification and inclusion of an indicator for ethnicity at population-level in some of the models. Therefore, individual numerical results should not be directly compared. Overall, this report corroborates the findings of the 2018 report.

Dental outcomes

The main finding of this report is of strong statistical evidence for a clinically significant reduction in dental caries, indicated by prevalence, severity, and hospital admissions for extraction, with increasing fluoride concentration. The greatest benefit was seen in the most deprived areas, supporting previous conclusions that drinking water fluoridation is an effective public health intervention for tackling dental health inequalities.

Prevalence and severity of dental caries experience

Dental caries is a common oral disease affecting children in England; 23% of 5-year-olds and 11% of 3-year-olds have evidence of dental caries. Prevalence is distributed unequally across the country: in 2019, 51% of five-year-olds surveyed in Blackburn with Darwen had dental caries, compared with 9% in East Sussex.[41, 42] The unadjusted odds of experiencing dental caries was 4 times higher in the most deprived 10% of LSOAs compared to the least deprived, in both 3- and 5-year-olds.

This analysis showed the unadjusted prevalence of dental caries experience in 3-year-olds fell by 4%, a relative reduction of 35%, as fluoride concentration increased from <0.1mg/l to ≥0.7mg/l. In 5-year-olds prevalence fell by 5%, a relative reduction of 19%. The dental caries severity score fell by 0.13 (38% relative reduction) and 0.28 (32% relative reduction) from the lowest to the highest fluoride concentration areas, in 3- and 5-year-olds respectively.

At all levels of deprivation there was a clear reduction in the risk of 5-year-olds experiencing dental caries in areas with the highest fluoride concentration compared to areas with the lowest. In the most deprived quintile, a reduction was seen at all levels of fluoride concentration compared to the lowest, with the greatest effect seen at the highest concentration. A similar effect was seen on the severity of dental caries in 5-year-olds. The risk of being in the highest severity score group relative to the lowest was clearly lower at the highest fluoride concentration compared to the lowest.

The overall trend in 3- and 5-year-olds was a reduction in dental caries prevalence and severity with increasing fluoride concentration. Children in the most deprived quintile, saw the greatest overall reduction. However patterns in most analyses do not show smooth linear trends, with numbers of observations in some strata being rather small.

At all deprivation levels, odds of experiencing dental caries were lower in areas with a fluoridation scheme in place than in those without. The exposed group included areas with a fluoridation scheme in place, but which achieved any fluoride concentration over the exposure period. Viewed in the context of the analysis using different levels of fluoride concentration, it could be expected that the benefit of a fluoridation scheme would be greater if schemes had achieved the target fluoride concentration (1mg/l).

From a public health perspective, it is significant that the greatest benefit is seen in children living in the most deprived areas. These findings are in keeping with those from the 2018 health monitoring report, which analysed OHS data for 5-year-olds in 2015.

Hospital admissions for carious tooth extractions

The crude incidence of admission to hospital for carious tooth extraction in 0- to 19-year-olds over the 5-year period (2016/17 to 2020/21) was 249 admissions per 100,000 person-years. The crude incidence rate was 60% lower in areas with the highest fluoride concentration compared to the lowest. Deprivation is an important factor in tooth extractions, with the incidence rate in the most deprived decile of areas being more than 4 times greater than in the least deprived areas.

At all levels of deprivation, there was a clear reduction in admissions as fluoride concentration increased. The greatest effect was seen in the most deprived quintile. As with dental caries prevalence and severity (described above), this was not a smooth linear trend.

If all children and young people in the most deprived 20% of areas with fluoride concentrations <0.2mg/l instead received water with adjusted fluoride of at least 0.2mg/l, 56% of dental extractions in those areas would be prevented, assuming the reduction is due to fluoridation. Those in the most deprived areas benefit the most from this intervention. Although the relative reduction in the most deprived areas was not different to the reduction achieved at other deprivation levels, it represented a greater absolute number of admissions which could be prevented. As above, the effect of water fluoridation could be expected to be greater than observed in this analysis if fluoridation schemes achieved target fluoride concentrations.

The findings are in keeping with the analysis of the OHS data, and with the 2018 health monitoring report. Increasing fluoride concentration in drinking water is associated with a decreased risk of carious tooth extraction, with the greatest benefit seen in the most deprived areas.

Hip fractures

The crude incidence of hip fracture over the 5-year period (2016/17 to 2020/21) was 115 per 100,000 person-years. As in 2018, there was no difference between the crude incidence rates at different fluoride concentrations, compared to the lowest concentration, and no evidence of an association found when fluoride concentration was modelled as a continuous exposure.[2] Age and sex are important factors in hip fracture.

A complex relationship between fluoride and hip fracture was found when the association was stratified by age, and is consistent with the 2018 findings which found an interaction between fluoride concentration and age.[2] In the youngest age group (0 to 49 years), adjusting for sex and deprivation, evidence of a reduction in incidence of hip fractures was seen at higher fluoride concentrations. This did not follow a pattern across concentrations of fluoride. A similar picture was seen in those aged 50 to 64 years. There was no clear pattern of association in those aged 65 to 79 years. In the oldest age group (≥80 years), although there was evidence that the adjusted incidence rate was 4 to 8% higher in areas with mid-range fluoride concentrations (0.2 - <0.4mg/l and 0.4 - <0.7mg/l) compared to the lowest concentration (<0.1mg/l), this association was not seen at the highest fluoride concentration and no pattern was observed. When further stratified by sex, the protective association between fluoride and hip fractures was observed in males aged 0 to 49 years. However, this was not apparent in females of the same age group. In those aged over 80 years, the association between fluoride and hip fractures was seen at some fluoride concentrations. However, these are sporadic and do not follow a trend. When modelled as a continuous variable, there was a protective association found between fluoride and hip fractures in males aged 0 to 49 years. However, no evidence of an association was observed at any other sex- and age-group.

Results of the all-sex analysis suggest there may be an association between fluoride and hip fracture, the direction of which changes across the life course. This is less convincing when the analysis is stratified by sex, with no clear pattern across fluoride concentrations at any age- and sex-specific group.

In some age groups, there was an increased risk of admission for hip fracture in areas with a fluoridation scheme in place compared to those without. However, these findings were inconsistent with the results of the analysis using fluoride concentration.

Taken in the context of the findings of the 2014 and 2018 reports, and wider literature, there is no new evidence to indicate an increased risk of hip fracture at the drinking water fluoride concentrations seen in England.[2, 3, 12, 45]

Limitations

Exposure misclassification

No additional exposure data were available for the years following 2015. It was assumed, based on previous analysis and that there have been no changes in legal agreements to schemes since 2017, that fluoride concentration, and the presence of fluoridation schemes, has remained stable over time.[4] However, if concentrations have changed, geographical areas may have been wrongly assigned to an exposure category.

Further, this means that for some health outcomes there was little or no overlap between the exposure period of interest and the outcome period of interest. This is most extreme in the prevalence and severity of dental caries experience in 3-year-olds, where the outcome of interest was measured in the academic year ending 2020 and the exposure period was 2011 to 2015 inclusive, before the children surveyed were born.

Use of an ecological and indirect estimate of exposure to fluoride and fluoridation of water supplies may result in misclassification of exposure. Comparing the drinking water concentrations captures differences in average fluoride exposure between populations. However, this is not an individual measure of exposure. A person's individual fluoride intake within an area can vary due to variations in the amount of water consumed, and fluoride exposure from other dietary sources such as drinking tea and using toothpaste or mouthwash. As fluoride in water is only the dominant source at relatively high fluoride concentrations, this misclassification is likely more important in the lower fluoride concentration ranges. Consequently, interpretation of differences in relative risk/odds between populations exposed to differing fluoride concentrations in the lower ranges (for example, <0.2mg/l compared to <0.4mg/l) is more uncertain, particularly in the absence of a clear trend. However, an ecological study design is appropriate in that the findings are relevant to policy objectives which relate to the regulation of the concentration of fluoride in drinking water.

It is not possible to account for the length of exposure at person-level. Individuals may have moved geographically during the exposure period of interest, and thereby not been exposed for the time period included in analysis. Individuals may live in an area with a given fluoride concentration, but work or attend school somewhere with a different fluoride concentration, thus altering their exposure.

Sampling error, non-sampling error and selection bias

The prevalence and severity of dental caries in 3- and 5-year-olds was measured using survey data, rather than data on the whole population. There is a possibility that there are important differences between the children included in the surveys and the general population of children of that age. This is especially true of the survey of 3-year-olds conducted in 2020, which was terminated early due to the COVID-19 pandemic. Limitations of the methods of the oral health surveys are discussed fully in their respective reports.[40-42] Of note, a potential selection bias could stem from sampling only state-maintained schools and the requirement for positive consent; children who attend private schools, are home-schooled, or whose parents did not consent, were excluded from the surveys. Although the populations are unlikely to differ by fluoride concentrations, there may be a difference in the overall prevalence and severity of dental caries experienced in sampled children compared to those who were not sampled. This may affect the generalisability of the findings.

Hospital admissions for carious tooth extraction and for hip fracture were measured using HES data, which is available at population level and does not rely on sampling. HES data, which uses consistent diagnostic codes and is used by hospitals to submit claims for payment, is likely to be highly complete. This is especially true of admissions for hip fracture, which cannot be managed in the community. In some instances, HES data may underestimate the number of admissions for tooth extraction; it is recognised that there are dental extractions conducted by community dental services in hospital settings, and that these data are not always included in HES. It is unlikely that this under-reporting correlates with fluoride concentration, though there may be a risk of non-differential error. Both carious tooth extractions and hip fractures are unlikely to be misdiagnosed.

It was noted that hospital admissions for dental extractions decreased in the financial year 2020/21 due to the COVID-19 pandemic. Although it is unlikely that this decrease would have been differential by fluoride exposure, it was possible that it could have been differential by other important population factors (for example, deprivation), resulting in findings that may not be generalisable to other time periods. However, a sensitivity analysis using 4 years' data (2016/17 to 2019/20 inclusive) found very similar results.

Information bias

Routine data sources used in these analyses (HES data and ONS population data) are likely to be of high completeness and accuracy. The HES data covered the financial years 2016/17 to 2020/21 and had been through quality assurance processes at the time of analysis. If there were information errors, these would be unlikely to differ by fluoride exposure, but could lead to non-differential error obscuring the exposure-outcome relationship.

Residual and unmeasured confounding

Associations between environmental exposures and non-communicable disease outcomes are typically of low strength and easily obscured by confounding factors. Where possible, age and sex were controlled for as a priori confounders. However, other confounding factors are only measured at ecological level (for example, deprivation) and some are not measured at all (for example, sugar consumption, access to primary dental care). This means not all important confounders could be controlled for, possibly leading to residual or unadjusted confounding. This may result in either under- or over-estimation of the association between exposures and outcomes.

The Index of Multiple Deprivation 2019 was used to adjust for differences in socioeconomic status, because this has been demonstrated to correlate well with potential confounders for which data were not available. However, as an area-level composite indicator, this may not always accurately reflect individual level socioeconomic status, nor all the facets of socioeconomic status that are most important for health outcomes.

Multiple comparisons

Many results are presented in this report. Given so many comparisons, some will have smaller p values due to chance alone. While smaller p values are helpful as a guide to indicate associations where the evidence is stronger, values above or below the conventional cut-off of $p<0.05$ should not be treated as a threshold to distinguish whether or not there is an association. Results in this report have been discussed with reference to the degree of uncertainty around the point estimates (provided by confidence intervals), the strength of the slope, and the pattern across the range of fluoride concentrations.

Conclusion

The findings of the 2022 health monitoring report are consistent with the view that water fluoridation at levels prescribed within the UK regulatory limit (<1.5mg/l) is an effective, safe, and equitable public health intervention to reduce the prevalence, severity, and consequences of dental caries. It supports previous findings that these benefits are greatest in the most deprived areas, thereby contributing to reducing dental health inequalities.

The 2022 report continued the approach of using fluoride concentration as an exposure, as well as whether or not the fluoride has been adjusted by a scheme, which allows for a more detailed investigation of the relationships between fluoride and health outcomes.

The ecological design of the analyses has some limitations: exposure to fluoride from sources other than public drinking water supplies could not be accounted for, and nor could the length of exposure period. No water fluoride concentration data were available from 2016 onwards, meaning some health outcomes analysed do not overlap with the exposure period. Both of these factors may have led to exposure misclassification. Residual or unmeasured confounding, due to potential confounders being excluded from analysis or included only at population-level, may have led to under- or over-estimation of the results. Therefore, this report alone does not allow conclusions to be drawn regarding any causative or protective role of fluoride. Similarly, the absence of any associations does not provide definitive evidence for a lack of a relationship. This is particularly the case for hip fractures, where wider epidemiological evidence for any relationship at drinking water fluoride concentrations typical of those in England is more limited.

The Water Fluoridation Health Monitoring Working Group continues to keep the wider evidence under review and will consult with local authorities prior to publication of a further report within the next 4 years.

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Appendix 1

Results tables presented by Index of Multiple Deprivation decile

Table 48 - Odds ratios for experiencing dental caries ($d_3mft>0$) in 3-year-olds surveyed in the OHS in 2020, stratified by IMD decile, standard errors adjusted for 257 local authority clusters

IMD decile	mean fluoride concentration mg/l 2011 to 2015	Adjusted OR	95% confidence intervals	p value[1]	composite p value[2]
10 (least deprived)	<0.1	reference			0.886
	0.1 - <0.2	1.08	0.64 – 1.79		
	0.2 - <0.4	0.96	0.50 – 1.86		
	0.4 - <0.7	1.07	0.25 – 4.57		
	≥0.7	0.44	0.08 – 2.45		
	continuous	0.43	0.08 – 2.20	0.308	
9	<0.1	reference			<0.001
	0.1 - <0.2	0.80	0.51 – 1.26		
	0.2 - <0.4	0.62	0.34 – 1.12		
	0.4 - <0.7	1.27	0.45 – 3.57		
	≥0.7	0.00	0.00 – 0.00		
	continuous	0.10	0.02 – 0.61	0.013	
8	<0.1	reference			0.001
	0.1 - <0.2	0.70	0.44 – 1.13		
	0.2 - <0.4	0.30	0.17 – 0.54		
	0.4 - <0.7	0.59	0.16 – 2.22		
	≥0.7	1.19	0.61 – 2.32		
	continuous	0.62	0.17 – 2.28	0.469	
7	<0.1	reference			0.030
	0.1 - <0.2	1.04	0.72 – 1.49		
	0.2 - <0.4	0.72	0.48 – 1.09		
	0.4 - <0.7	0.59	0.16 – 2.09		
	≥0.7	0.20	0.06 – 0.65		
	continuous	0.21	0.08 – 0.56	0.002	
6	<0.1	reference			0.013
	0.1 - <0.2	1.19	0.80 – 1.76		
	0.2 - <0.4	0.54	0.33 – 0.89		
	0.4 - <0.7	0.61	0.28 – 1.33		

	≥0.7	0.94	0.19 – 4.70		
	continuous	0.38	0.07 – 2.11	0.267	
5	<0.1	reference			0.564
	0.1 - <0.2	0.97	0.63 – 1.48		
	0.2 - <0.4	0.59	0.32 – 1.11		
	0.4 - <0.7	0.79	0.27 – 2.29		
	≥0.7	1.01	0.45 – 2.25		
	continuous	0.75	0.27 – 2.11	0.586	
4	<0.1	reference			0.658
	0.1 - <0.2	0.84	0.55 – 1.26		
	0.2 - <0.4	0.94	0.63 – 1.42		
	0.4 - <0.7	0.50	0.18 – 1.41		
	≥0.7	0.73	0.36 – 1.49		
	continuous	0.62	0.27 – 1.38	0.239	
3	<0.1	reference			0.033
	0.1 - <0.2	0.89	0.66 – 1.18		
	0.2 - <0.4	0.65	0.46 – 0.92		
	0.4 - <0.7	0.52	0.20 – 1.35		
	≥0.7	0.52	0.30 – 0.90		
	continuous	0.40	0.21 – 0.77	0.006	
2	<0.1	reference			0.024
	0.1 - <0.2	1.03	0.74 – 1.42		
	0.2 - <0.4	0.63	0.44 – 0.90		
	0.4 - <0.7	0.71	0.32 – 1.59		
	≥0.7	0.64	0.40 – 1.01		
	continuous	0.52	0.23 – 1.18	0.116	
1 (most deprived)	<0.1	reference			0.003
	0.1 - <0.2	0.87	0.64 – 1.20		
	0.2 - <0.4	0.92	0.59 – 1.43		
	0.4 - <0.7	1.23	0.52 – 2.88		
	≥0.7	0.62	0.41 – 0.93		
	continuous	0.65	0.42 – 1.01	0.054	

1. Wald test for the association with fluoride as a continuous variable
2. Composite Wald test for the overall association with fluoride concentration categories at each IMD stratum

Table 49 - Odds ratios for experiencing a higher dental caries severity score category in 3-year-olds surveyed in the OHS in 2020, by IMD decile, standard errors adjusted for 257 local authority clusters

IMD decile	mean fluoride concentration mg/l 2011 to 2015	OR	95% confidence intervals	p value[1]	composite p value[2]

10 (least deprived)	<0.1	reference			0.977
	0.1 - <0.2	1.10	0.66 – 1.83		
	0.2 - <0.4	0.99	0.52 – 1.91		
	0.4 - <0.7	1.07	0.26 – 4.45		
	≥0.7	0.72	0.18 – 2.77		
	continuous	0.67	0.16 – 2.78	0.583	
9	<0.1	reference			<0.001
	0.1 - <0.2	1.01	0.61 – 1.65		
	0.2 - <0.4	0.74	0.39 – 1.40		
	0.4 - <0.7	1.48	0.49 – 4.52		
	≥0.7	0.00	0.00 – 0.00		
	continuous	0.16	0.03 – 0.81	0.027	
8	<0.1	reference			0.044
	0.1 - <0.2	0.90	0.54 – 1.47		
	0.2 - <0.4	0.45	0.25 – 0.83		
	0.4 - <0.7	0.44	0.12 – 1.57		
	≥0.7	1.43	0.66 – 3.09		
	continuous	0.83	0.27 – 2.61	0.754	
7	<0.1	reference			0.317
	0.1 - <0.2	1.05	0.69 – 1.61		
	0.2 - <0.4	0.84	0.48 – 1.47		
	0.4 - <0.7	0.57	0.13 – 2.47		
	≥0.7	0.29	0.08 – 1.11		
	continuous	0.30	0.09 – 1.05	0.059	
6	<0.1	reference			0.184
	0.1 - <0.2	1.14	0.75 – 1.75		
	0.2 - <0.4	0.61	0.35 – 1.05		
	0.4 - <0.7	0.72	0.30 – 1.72		
	≥0.7	0.73	0.13 – 4.19		
	continuous	0.36	0.08 – 1.70	0.197	
5	<0.1	reference			0.247
	0.1 - <0.2	0.77	0.48 – 1.23		
	0.2 - <0.4	0.64	0.36 – 1.14		
	0.4 - <0.7	0.51	0.19 – 1.38		
	≥0.7	1.28	0.57 – 2.87		
	continuous	0.90	0.31 – 2.56	0.837	
4	<0.1	reference			0.323
	0.1 - <0.2	0.78	0.49 – 1.24		
	0.2 - <0.4	1.17	0.67 – 2.03		
	0.4 - <0.7	0.38	0.12 – 1.16		
	≥0.7	0.78	0.35 – 1.74		
	continuous	0.65	0.24 – 1.73	0.387	

3	<0.1	reference			0.206
	0.1 - <0.2	0.73	0.52 – 1.04		
	0.2 - <0.4	0.78	0.48 – 1.25		
	0.4 - <0.7	0.58	0.20 – 1.68		
	≥0.7	0.48	0.24 – 0.98		
	continuous	0.47	0.21 – 1.08	0.076	
2	<0.1	reference			0.467
	0.1 - <0.2	0.95	0.63 – 1.43		
	0.2 - <0.4	0.75	0.49 – 1.14		
	0.4 - <0.7	0.85	0.44 – 1.64		
	≥0.7	0.55	0.24 – 1.28		
	continuous	0.54	0.21 – 1.36	0.190	
1 (most deprived)	<0.1	reference			0.423
	0.1 - <0.2	0.87	0.57 – 1.33		
	0.2 - <0.4	0.90	0.48 – 1.67		
	0.4 - <0.7	1.13	0.34 – 3.80		
	≥0.7	0.68	0.45 – 1.04		
	continuous	0.70	0.41 – 1.20	0.199	

1. Wald test for the association with fluoride as a continuous variable
2. Composite Wald test for the overall association with fluoride concentration categories at each IMD stratum

Table 50 - Odds ratios for experiencing dental caries ($d_3$mft>0) in 5-year-olds surveyed in the OHS in 2017 and 2019, stratified by IMD decile, standard errors adjusted for 315 local authority clusters

IMD decile	mean fluoride concentration mg/l 2011 to 2015	OR	95% confidence intervals	p value[1]	composite p value[2]
10 (least deprived)	<0.1	reference			0.031
	0.1 - <0.2	1.01	0.85 – 1.20		
	0.2 - <0.4	1.08	0.89 – 1.30		
	0.4 - <0.7	1.22	0.82 – 1.80		
	≥0.7	0.78	0.63 – 0.96		
	continuous	0.76	0.59 – 0.98	0.037	
9	<0.1	reference			<0.001
	0.1 - <0.2	1.04	0.90 – 1.20		
	0.2 - <0.4	0.91	0.76 – 1.09		
	0.4 - <0.7	0.63	0.40 – 0.99		
	≥0.7	0.73	0.60 – 0.88		
	continuous	0.60	0.48 – 0.75	<0.001	
8	<0.1	reference			0.045
	0.1 - <0.2	1.05	0.92 – 1.20		

	0.2 - <0.4	1.03	0.88 – 1.21		
	0.4 - <0.7	0.87	0.66 – 1.16		
	≥0.7	0.84	0.72 – 0.99		
	continuous	0.77	0.64 – 0.92	0.005	
7	<0.1	reference			<0.001
	0.1 - <0.2	0.94	0.81 – 1.09		
	0.2 - <0.4	0.83	0.71 – 0.96		
	0.4 - <0.7	0.90	0.70 – 1.16		
	≥0.7	0.70	0.61 – 0.80		
	continuous	0.65	0.55 – 0.77	<0.001	
6	<0.1	reference			0.083
	0.1 - <0.2	1.07	0.94 – 1.23		
	0.2 - <0.4	1.02	0.85 – 1.23		
	0.4 - <0.7	0.90	0.69 – 1.18		
	≥0.7	0.80	0.66 – 0.98		
	continuous	0.74	0.58 – 0.94	0.013	
5	<0.1	reference			<0.001
	0.1 - <0.2	1.15	0.97 – 1.37		
	0.2 - <0.4	0.97	0.79 – 1.19		
	0.4 - <0.7	0.99	0.81 – 1.20		
	≥0.7	0.79	0.68 – 0.91		
	continuous	0.68	0.56 – 0.83	<0.001	
4	<0.1	reference			<0.001
	0.1 - <0.2	1.08	0.93 – 1.26		
	0.2 - <0.4	1.04	0.84 – 1.28		
	0.4 - <0.7	0.76	0.62 – 0.93		
	≥0.7	0.74	0.62 – 0.87		
	continuous	0.63	0.52 – 0.75	<0.001	
3	<0.1	reference			<0.001
	0.1 - <0.2	0.99	0.86 – 1.13		
	0.2 - <0.4	0.82	0.69 – 0.98		
	0.4 - <0.7	1.06	0.89 – 1.26		
	≥0.7	0.78	0.68 – 0.90		
	continuous	0.77	0.65 – 0.91	0.002	
2	<0.1	reference			<0.001
	0.1 - <0.2	0.86	0.74 – 1.01		
	0.2 - <0.4	0.84	0.72 – 0.98		
	0.4 - <0.7	0.93	0.75 – 1.15		
	≥0.7	0.70	0.60 – 0.81		
	continuous	0.71	0.59 – 0.85	<0.001	
1 (most deprived)	<0.1	reference			<0.001

0.1 - <0.2	0.76	0.62 – 0.93	
0.2 - <0.4	0.69	0.59 – 0.81	
0.4 - <0.7	0.76	0.63 – 0.91	
≥0.7	0.59	0.51 – 0.68	
continuous	0.57	0.49 – 0.68	<0.001

1. Wald test for the association with fluoride as a continuous variable
2. Composite Wald test for the overall association with fluoride concentration categories at each IMD stratum

Table 51 - Crude relative risk ratios of having a higher dental caries severity score relative to lower scores in 5-year-olds surveyed for the OHS in 2017 and 2019, by IMD decile, standard errors adjusted for 315 local authority clusters

Dental caries severity score (category)	IMD decile	RRR	95% confidence intervals	composite p value[1]
High / medium / low relative to zero	10 (least deprived)	reference		<0.001
	9	1.26	1.13 – 1.41	
	8	1.40	1.25 – 1.56	
	7	1.56	1.38 – 1.76	
	6	1.78	1.57 – 2.02	
	5	2.20	1.93 – 2.50	
	4	2.56	2.19 – 2.98	
	3	3.31	2.77 – 3.96	
	2	4.01	3.30 – 4.86	
	1 (most deprived)	4.95	3.85 – 6.37	
High / medium relative to low / zero	10 (least deprived)	reference		<0.001
	9	1.26	1.13 – 1.41	
	8	1.58	1.40 – 1.78	
	7	1.81	1.60 – 2.06	
	6	2.15	1.90 – 2.43	
	5	2.91	2.55 – 3.32	
	4	3.53	3.05 – 4.08	
	3	4.78	4.07 – 5.61	
	2	5.95	5.09 – 6.95	
	1 (most deprived)	8.86	7.20 – 10.90	
High relative to medium / low / zero	10 (least deprived)	reference		<0.001
	9	1.26	1.13 – 1.41	
	8	1.66	1.40 – 1.96	
	7	1.95	1.63 – 2.32	
	6	2.45	2.08 – 2.88	
	5	3.72	3.13 – 4.43	
	4	4.60	3.90 – 5.44	

	3	5.99	5.03 – 7.13
	2	7.56	6.36 – 8.98
	1 (most deprived)	11.82	9.56 – 14.62

Composite Wald p value for overall association with a categorical variable

Table 52 - Relative risk ratios of having a high, medium, or low dental caries severity score relative to a zero score, in 5-year-olds surveyed for the OHS in 2017 and 2019, by IMD decile, standard errors adjusted for 315 local authority clusters

IMD decile	mean fluoride concentration mg/l 2011 to 2015	OR	95% confidence intervals	p value[1]	composite p value[2]
10 (least deprived)	<0.1	reference			0.015
	0.1 - <0.2	0.93	0.74 - 1.17		
	0.2 - <0.4	1.26	0.94 - 1.69		
	0.4 - <0.7	1.72	1.07 - 2.74		
	≥0.7	1.35	0.87 - 2.09		
	continuous	1.66	1.03 - 2.69	0.038	
9	<0.1	reference			0.393
	0.1 - <0.2	1.01	0.83 - 1.24		
	0.2 - <0.4	1.14	0.89 - 1.46		
	0.4 - <0.7	0.87	0.51 - 1.47		
	≥0.7	1.36	0.94 - 1.97		
	continuous	1.30	0.86 - 1.97	0.219	
8	<0.1	reference			0.262
	0.1 - <0.2	1.04	0.83 - 1.29		
	0.2 - <0.4	1.31	0.99 - 1.74		
	0.4 - <0.7	1.15	0.73 - 1.82		
	≥0.7	1.30	0.95 - 1.79		
	continuous	1.39	0.97 - 2.01	0.075	
7	<0.1	reference			0.159
	0.1 - <0.2	0.91	0.72 - 1.15		
	0.2 - <0.4	1.13	0.87 - 1.47		
	0.4 - <0.7	1.42	0.86 - 2.32		
	≥0.7	1.37	0.95 - 1.98		
	continuous	1.57	1.03 - 2.39	0.034	
6	<0.1	reference			0.406
	0.1 - <0.2	0.88	0.70 - 1.10		
	0.2 - <0.4	1.09	0.82 - 1.47		
	0.4 - <0.7	0.95	0.67 - 1.36		
	≥0.7	1.28	0.77 - 2.14		
	continuous	1.38	0.81 - 2.35	0.240	

5	<0.1	reference			0.115
	0.1 - <0.2	1.07	0.86 - 1.33		
	0.2 - <0.4	1.36	1.01 - 1.84		
	0.4 - <0.7	1.33	0.84 - 2.11		
	≥0.7	1.63	1.06 - 2.52		
	continuous	1.41	0.87 - 2.30	0.163	
4	<0.1	reference			0.172
	0.1 - <0.2	1.01	0.79 - 1.28		
	0.2 - <0.4	1.47	1.07 - 2.02		
	0.4 - <0.7	1.05	0.72 - 1.54		
	≥0.7	1.31	0.65 - 2.64		
	continuous	1.45	0.69 - 3.03	0.327	
3	<0.1	reference			0.521
	0.1 - <0.2	1.03	0.77 - 1.38		
	0.2 - <0.4	1.15	0.86 - 1.55		
	0.4 - <0.7	1.60	0.88 - 2.92		
	≥0.7	1.39	0.73 - 2.65		
	continuous	1.63	0.80 - 3.30	0.179	
2	<0.1	reference			0.051
	0.1 - <0.2	0.88	0.68 - 1.13		
	0.2 - <0.4	1.27	0.90 - 1.80		
	0.4 - <0.7	1.92	1.07 - 3.47		
	≥0.7	1.44	0.74 - 2.79		
	continuous	1.91	0.92 - 3.95	0.083	
1 (most deprived)	<0.1	reference			0.220
	0.1 - <0.2	0.81	0.57 - 1.16		
	0.2 - <0.4	1.06	0.70 - 1.60		
	0.4 - <0.7	1.81	0.93 - 3.52		
	≥0.7	1.16	0.52 - 2.57		
	continuous	1.50	0.62 - 3.62	0.364	

1. Wald test for the association with fluoride as a continuous variable
2. Composite Wald test for the overall association with fluoride concentration categories at each IMD stratum

Table 53 - Relative risk ratios of having a high or medium dental caries severity score relative to a low or zero score, in 5-year-olds surveyed for the OHS in 2017 and 2019, by IMD decile, standard errors adjusted for 315 local authority clusters

IMD decile	mean fluoride concentration mg/l 2011 to 2015	OR	95% confidence intervals	p value[1]	composite p value[2]
10 (least deprived)	<0.1	reference			0.415
	0.1 - <0.2	0.93	0.74 - 1.17		
	0.2 - <0.4	0.99	0.75 - 1.30		

	0.4 - <0.7	1.21	0.77 - 1.91		
	≥0.7	0.76	0.54 - 1.08		
	continuous	0.77	0.53 - 1.12	0.169	
9	<0.1	reference			0.108
	0.1 - <0.2	1.01	0.83 - 1.24		
	0.2 - <0.4	0.89	0.70 - 1.15		
	0.4 - <0.7	0.61	0.36 - 1.04		
	≥0.7	0.77	0.58 - 1.02		
	continuous	0.60	0.43 - 0.83	0.002	
8	<0.1	reference			0.264
	0.1 - <0.2	1.04	0.83 - 1.29		
	0.2 - <0.4	1.03	0.81 - 1.31		
	0.4 - <0.7	0.81	0.53 - 1.26		
	≥0.7	0.73	0.54 - 1.00		
	continuous	0.64	0.45 - 0.92	0.015	
7	<0.1	reference			0.221
	0.1 - <0.2	1.05	0.83 - 1.32		
	0.2 - <0.4	0.88	0.70 - 1.12		
	0.4 - <0.7	1.00	0.63 - 1.60		
	≥0.7	0.77	0.59 - 1.02		
	continuous	0.73	0.53 - 1.00	0.053	
6	<0.1	reference			0.032
	0.1 - <0.2	1.06	0.85 - 1.32		
	0.2 - <0.4	1.15	0.87 - 1.52		
	0.4 - <0.7	0.68	0.49 - 0.93		
	≥0.7	0.73	0.51 - 1.02		
	continuous	0.64	0.44 - 0.93	0.019	
5	<0.1	reference			0.018
	0.1 - <0.2	1.07	0.86 - 1.33		
	0.2 - <0.4	1.06	0.79 - 1.43		
	0.4 - <0.7	0.94	0.61 - 1.44		
	≥0.7	0.63	0.46 - 0.87		
	continuous	0.65	0.47 - 0.9.0	0.010	
4	<0.1	reference			0.242
	0.1 - <0.2	1.01	0.79 - 1.28		
	0.2 - <0.4	1.15	0.86 - 1.54		
	0.4 - <0.7	0.74	0.51 - 1.07		
	≥0.7	0.74	0.47 - 1.17		
	continuous	0.67	0.40 - 1.10	0.115	
3	<0.1	reference			0.619
	0.1 - <0.2	1.03	0.77 - 1.38		

	0.2 - <0.4	0.90	0.69 - 1.18		
	0.4 - <0.7	1.13	0.66 - 1.92		
	≥0.7	0.79	0.54 - 1.16		
	continuous	0.75	0.48 - 1.19	0.220	
2	<0.1	reference			0.328
	0.1 - <0.2	0.88	0.68 - 1.13		
	0.2 - <0.4	0.99	0.74 - 1.33		
	0.4 - <0.7	1.36	0.80 - 2.32		
	≥0.7	0.81	0.54 - 1.23		
	continuous	0.88	0.55 - 1.42	0.601	
1 (most deprived)	<0.1	reference			0.237
	0.1 - <0.2	0.81	0.57 - 1.16		
	0.2 - <0.4	0.83	0.58 - 1.19		
	0.4 - <0.7	1.28	0.71 - 2.33		
	≥0.7	0.65	0.39 - 1.08		
	continuous	0.69	0.39 - 1.24	0.217	

1. Wald test for the association with fluoride as a continuous variable
2. Composite Wald test for the overall association with fluoride concentration categories at each IMD stratum

Table 54 - Relative risk ratios of having a high dental caries severity score relative to a medium, low, or zero score, in 5-year-olds surveyed for the OHS in 2017 and 2019, by IMD decile, standard errors adjusted for 315 local authority clusters

IMD decile	mean fluoride concentration mg/l 2011 to 2015	OR	95% confidence intervals	p value[1]	composite p value[2]
10 (least deprived)	<0.1	reference			0.009
	0.1 - <0.2	0.93	0.74 - 1.17		
	0.2 - <0.4	0.82	0.60 - 1.12		
	0.4 - <0.7	0.75	0.46 - 1.23		
	≥0.7	0.42	0.26 - 0.68		
	continuous	0.35	0.22 - 0.57	<0.001	
9	<0.1	reference			<0.001
	0.1 - <0.2	1.01	0.83 - 1.24		
	0.2 - <0.4	0.74	0.55 - 1.00		
	0.4 - <0.7	0.38	0.22 - 0.64		
	≥0.7	0.42	0.27 - 0.65		
	continuous	0.27	0.18 - 0.43	<0.001	
8	<0.1	reference			<0.001
	0.1 - <0.2	1.04	0.83 - 1.29		
	0.2 - <0.4	0.85	0.66 - 1.10		
	0.4 - <0.7	0.50	0.32 - 0.80		

	≥0.7	0.40	0.24 - 0.66		
	continuous	0.29	0.18 - 0.48	<0.001	
7	<0.1	reference			<0.001
	0.1 - <0.2	1.12	0.84 - 1.49		
	0.2 - <0.4	0.73	0.55 - 0.97		
	0.4 - <0.7	0.62	0.39 - 0.97		
	≥0.7	0.42	0.28 - 0.64		
	continuous	0.33	0.22 - 0.50	<0.001	
6	<0.1	reference			<0.001
	0.1 - <0.2	1.19	0.93 - 1.53		
	0.2 - <0.4	1.14	0.79 - 1.63		
	0.4 - <0.7	0.42	0.31 - 0.57		
	≥0.7	0.40	0.27 - 0.58		
	continuous	0.29	0.19 - 0.43	<0.001	
5	<0.1	reference			<0.001
	0.1 - <0.2	1.07	0.86 - 1.33		
	0.2 - <0.4	0.88	0.63 - 1.23		
	0.4 - <0.7	0.58	0.41 - 0.83		
	≥0.7	0.34	0.22 - 0.53		
	continuous	0.30	0.21 - 0.42	<0.001	
4	<0.1	reference			<0.001
	0.1 - <0.2	1.01	0.79 - 1.28		
	0.2 - <0.4	0.95	0.71 - 1.29		
	0.4 - <0.7	0.46	0.32 - 0.66		
	≥0.7	0.40	0.28 - 0.58		
	continuous	0.30	0.20 - 0.46	<0.001	
3	<0.1	reference			<0.001
	0.1 - <0.2	1.03	0.77 - 1.38		
	0.2 - <0.4	0.75	0.57 - 0.98		
	0.4 - <0.7	0.70	0.45 - 1.08		
	≥0.7	0.43	0.32 - 0.58		
	continuous	0.34	0.24 - 0.49	<0.001	
2	<0.1	reference			<0.001
	0.1 - <0.2	0.88	0.68 - 1.13		
	0.2 - <0.4	0.82	0.64 - 1.06		
	0.4 - <0.7	0.84	0.52 - 1.36		
	≥0.7	0.44	0.33 - 0.59		
	continuous	0.40	0.29 - 0.56	<0.001	
1 (most deprived)	<0.1	reference			<0.001
	0.1 - <0.2	0.81	0.57 - 1.16		
	0.2 - <0.4	0.69	0.50 - 0.94		

	0.4 - <0.7	0.79	0.46 - 1.36	
	≥0.7	0.36	0.25 - 0.51	
	continuous	0.32	0.21 - 0.49	<0.001

1. Wald test for the association with fluoride as a continuous variable
2. Composite Wald test for the overall association with fluoride concentration categories at each IMD stratum

Table 55 - Incidence rate ratios of admissions for carious tooth extractions among 0- to 19-year-olds 2016/17 to 2020/21, by deprivation quintile, adjusted for age and sex, standard errors adjusted for 316 local authority clusters

IMD decile	mean fluoride concentration mg/l 2011 to 2015	OR	95% confidence intervals	p value[1]	composite p value[2]
10 (least deprived)	<0.1	reference			<0.001
	0.1 - <0.2	0.73	0.57 - 0.94		
	0.2 - <0.4	0.46	0.31 - 0.67		
	0.4 - <0.7	0.32	0.18 - 0.58		
	≥0.7	0.40	0.18 - 0.91		
	continuous	0.25	0.08 - 0.73	0.011	
9	<0.1	reference			<0.001
	0.1 - <0.2	0.82	0.66 - 1.02		
	0.2 - <0.4	0.57	0.43 - 0.76		
	0.4 - <0.7	0.79	0.48 - 1.31		
	≥0.7	0.44	0.26 - 0.77		
	continuous	0.35	0.18 - 0.70	0.003	
8	<0.1	reference			<0.001
	0.1 - <0.2	0.85	0.68 - 1.05		
	0.2 - <0.4	0.58	0.43 - 0.80		
	0.4 - <0.7	0.75	0.46 - 1.22		
	≥0.7	0.33	0.21 - 0.52		
	continuous	0.26	0.15 - 0.43	<0.001	
7	<0.1	reference			<0.001
	0.1 - <0.2	0.73	0.59 - 0.89		
	0.2 - <0.4	0.49	0.38 - 0.63		
	0.4 - <0.7	0.50	0.33 - 0.76		
	≥0.7	0.45	0.28 - 0.73		
	continuous	0.34	0.19 - 0.61	<0.001	
6	<0.1	reference			<0.001
	0.1 - <0.2	0.77	0.63 - 0.94		
	0.2 - <0.4	0.48	0.35 - 0.66		
	0.4 - <0.7	0.68	0.47 - 0.97		
	≥0.7	0.42	0.25 - 0.70		
	continuous	0.35	0.19 - 0.62	<0.001	

5	<0.1	reference			<0.001
	0.1 - <0.2	0.83	0.66 - 1.04		
	0.2 - <0.4	0.54	0.40 - 0.72		
	0.4 - <0.7	0.66	0.46 - 0.95		
	≥0.7	0.58	0.32 - 1.05		
	continuous	0.47	0.24 - 0.91	0.026	
4	<0.1	reference			<0.001
	0.1 - <0.2	0.84	0.67 - 1.06		
	0.2 - <0.4	0.46	0.33 - 0.63		
	0.4 - <0.7	0.63	0.43 - 0.91		
	≥0.7	0.36	0.19 - 0.67		
	continuous	0.26	0.13 - 0.50	<0.001	
3	<0.1	reference			<0.001
	0.1 - <0.2	0.79	0.64 - 0.98		
	0.2 - <0.4	0.52	0.38 - 0.72		
	0.4 - <0.7	0.55	0.38 - 0.80		
	≥0.7	0.42	0.21 - 0.83		
	continuous	0.35	0.17 - 0.72	0.005	
2	<0.1	reference			<0.001
	0.1 - <0.2	0.75	0.60 - 0.94		
	0.2 - <0.4	0.48	0.33 - 0.68		
	0.4 - <0.7	0.59	0.39 - 0.89		
	≥0.7	0.50	0.29 - 0.88		
	continuous	0.47	0.24 - 0.89	0.021	
1 (most deprived)	<0.1	reference			<0.001
	0.1 - <0.2	0.64	0.42 - 0.95		
	0.2 - <0.4	0.38	0.22 - 0.65		
	0.4 - <0.7	0.56	0.38 - 0.85		
	≥0.7	0.29	0.13 - 0.65		
	continuous	0.24	0.10 - 0.60	0.002	

1. Wald test for the association with fluoride as a continuous variable
2. Composite Wald test for the overall association with fluoride concentration categories at each IMD stratum