engineering proceedings

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Proceedings Paper

Assessing Disparities in Community Water Fluoridation Across US States: A Spectral Clustering Approach †

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† Presented at the The 4th International Electronic Conference on Applied Sciences, 27 Oct–10 Nov 2023; Available online: https://asec2023.sciforum.net/

Abstract: Community water fluoridation (CWF) adjusts fluoride levels in public water supplies to prevent tooth decay and promote dental health, irrespective of socioeconomic status or dental care access. Regular sampling by community water systems (CWS) ensures compliance with regulations and standards. Centers for Disease Control and Prevention (CDC) provide biennial reports for health statistics surveillance by monitoring CWF status in US water systems. It's important to note that specific policies and practices related to CWF can vary between countries. Therefore, this research applies the spectral clustering method to group and analyse the reception of fluorinated water by CWS between populations of US countries. The data from the National Water Fluoridation Statistics (2016-2018-2020) reported by the CDC have been considered. The spectral clustering approach identified five clusters of US countries, which represent the different percentages of the population served by CWS receiving fluorinated water. Among the results, one cluster has the lowest value of the percentage (33.3%) and it includes Hawaii, New Jersey, Oregon, Idaho, Montana, Louisiana, New Hampshire, Alaska, and Utah. Conversely, the cluster of countries Ohio, Indiana, Maryland, South Dakota, Georgia, Virginia, North Dakota, Illinois, Minnesota, Kentucky, District of Columbia had the highest percentage (96.1%). These findings reveal relevant variations in the implementation of CWF across different US countries, with some states having a notably lower percentage of their population receiving fluorinated water than others. This could inform policy and public health efforts to improve access to fluoridated water and enhance dental health outcomes in areas with lower coverage.

Keywords: Community Water Fluoridation; Dental Health Promotion; Spectral Clustering

Citation: To be added by editorial staff during production.

Academic Editor: Firstname Lastname

Published: date

1. Introduction

Community water fluoridation (CWF) in the United States is recognized as a significant public health achievement due to its effectiveness in preventing dental caries [1]. The U.S. Preventive Services Task Force and Healthy People 2020 initiative endorses and promotes its coverage to address dental caries, which remains a serious global health problem [2,3]. Despite the decline in caries prevalence over time, untreated caries still affects a substantial number of individuals and communities, particularly those with lower socioeconomic status [4]. Inequalities in dental caries prevalence are evident both globally and in the US [5,6]. Addressing these oral health disparities is a priority in national health goals and so interventions targeting multiple levels are essential [3,7,8]. Structural changes in the environment, such as CWF and promoting healthy nutrition, are crucial strategies in addition to addressing behavioral factors [7,9].

Fluoride is well-known for its role in preventing dental caries, and community water fluoridation has been a key strategy in this regard [10]. Water fluoridation is practiced in about 25 countries, with 72.7% of the US population on public water systems receiving fluorinated water [11]. The Centers for Disease Control and Prevention (CDC) and the American Dental Association (ADA) serve as excellent sources of community water fluoridation information grounded in evidence. The promotion of continuous investigation is endorsed, and proficient interpretation of the foremost scientific insights into fluoridation practice is undertaken by specialists for the implementation of public health strategies. The U.S. Public Health Service advocates for a concentration of 0.7 mg/L for optimal water fluoridation [12,13]. This suggested concentration delivers the utmost advantage for oral health while safeguarding other bodily aspects from potential risks [13].

The rationale behind CWF is to provide a preventive intervention at the environmental level, benefiting both children and adults, regardless of their socioeconomic status or access to care. Interventions at the environmental level can have a greater impact on populations than individual and clinical-level interventions [10]. Community water systems (CWS), responsible for providing clean and safe drinking water to communities, neighborhoods and urban or rural areas, play a crucial role in ensuring public health and well-being by providing treated and often fluorinated water directly to households, businesses and public facilities. The presence of fluoride in the oral cavity aids in enamel remineralization and impedes demineralization, contributing to caries prevention [14]. The effectiveness of fluoridated water and other fluoride sources, such as toothpaste and varnishes, has been well-documented [15–17]. The relationship between the oral DMFT and fluoridation status is well established. Generally, areas with water fluoridation has lower DMFT scores than areas without fluoridation [18]. The fluoride can help reduce the prevalence and severity of dental caries, leading to better oral health. However, severe dental fluorosis has been associated with supra-optimal fluoride levels. In addition, adverse effects on systemic health were also highlighted. Indeed, there is currently convincing evidence on the potential cognitive risks of exposure to fluorinated water during early development [19], the increased risk of elderly hip fracture with increased mineral density due to excess fluoride that does not indicate improved bone strength [20] and the role of fluoride as a potential risk factor for chronic kidney disease [21].

Despite the successes of community water fluoridation in preventing dental caries, continued research is essential to assess its impact on oral health disparities and ensure that its benefits are balanced with potential adverse effects. The aim of this paper is to investigate the reception of fluorinated water by CWS across different populations of US states. The research applies the spectral clustering method [22,23] to group and analyze the distribution of fluoridated water reception by CWS.

2. Methods

2.1. Data Sources

The Water Fluoridation Reporting System (WFRS) is a tool used to compile and manage information about EU initiatives on water fluoridation in the United States. Developed and supported by the CDC, WFRS operates as a centralized hub to collect data from local and state water systems engaged in the implementation of fluoridation programs. Through WFRS, water services and public health agencies have the means to present crucial data on fluorine concentration levels in public water distributions, thus ensuring compliance with approved oral health guidelines. This reporting mechanism aims to monitor the progress made in community water fluoridation efforts and assess their effectiveness in combating dental cavities in different geographical areas. The CDC oversees the fluoridation status of CWS and publishes comprehensive biennial reports that serve as indispensable tools for monitoring health statistics.

For our analysis, data on the percentage of population served by the CWS receiving fluorinated water from 51 in the United States were considered. Statistical reports corresponding to the years 2016, 2018 and 2020 have been included [11,24,25]. This statistical information was formulated using water system data that states reported to the CDC

Water Fluoridation Reporting System, as well as population estimates provided by the US Census Bureau for state populations and populations served by public water supplies.

2.2. Statistical Method: Spectral clustering

The spectral clustering method relies on graph theory, in practice, the objects of the data can be considered as vertices in an undirect graph and the clustering problem is reformulated as a cut partition problem [22,23].

More formally, let $V = \{\boldsymbol{v}_1, \boldsymbol{v}_2, \dots, \boldsymbol{v}_n\}$ be a set of vertices in a space $\mathcal{V} \subseteq \mathbb{R}^p$. In order to group the data in K cluster, the first step concerns the construction of a *similarity matrix* $S = (s_{ij})$, for $i, j = 1, \dots, n$. To this aim, in this paper, a quite well-known kernel function for the spectral clustering algorithms has been considered, it is called *Gaussian kernel* and its expression is given by $s_{ij} = exp(-\| \boldsymbol{v}_i - \boldsymbol{v}_j \|^2/2)$, for $i, j = 1, \dots, n$.

Once computed the similarity matrix S, the normalized graph Laplacian matrix $L_{sym} \in \mathbb{R}^{n \times n}$ is defined as $L_{sym} = I - D^{-1/2} S D^{-1/2}$, where $D = diag(d_1, d_2, \dots, d_n) \in \mathbb{R}^{n \times n}$ is the degree matrix and d_i is the degree of the vertex $\boldsymbol{v}_i$ defined as $d_i = \sum_j s_{ij}$, for $i = 1, \dots, n$, and I denotes the $n \times n$ identity matrix. The Laplacian matrix L_{sym} is positive semi-definite with n non-negative eigenvalues.

Given $K \ll n$, let $\{\boldsymbol{\omega}_1, \dots, \boldsymbol{\omega}_K\}$ be the first K smallest eigenvectors associated to the first smallest K eigenvalues of L_{sym}. Then, the normalized Laplacian embedding is defined as $\Phi_\Omega : \{\boldsymbol{v}_1, \boldsymbol{v}_2, \dots, \boldsymbol{v}_n\} \rightarrow \mathbb{R}^K$, $\Phi_\Omega(\boldsymbol{v}_i) = (\omega_{1i}, \dots, \omega_{Ki})$, for $i = 1, \dots, n$, where $\omega_{1i}, \dots, \omega_{Ki}$ are the i-th components of $\boldsymbol{\omega}_1, \dots, \boldsymbol{\omega}_K$, respectively.

Afterwards, let $X = (\boldsymbol{x}'_1, \dots, \boldsymbol{x}'_n)$ be the $n \times K$ matrix given by the embedded data, where $\boldsymbol{x}_i = \Phi_\Omega(\boldsymbol{v}_i)$, for $i = 1, \dots, n$.

Definitively, as usually in the spectral clustering literature [22,23], the embedded data X are clustered according to the *k-means algorithm*.

Finally, it is worth noting that the spectral approach requires setting in input: *i)* the number of clusters K, *ii)* the kernel function (with the possible corresponding parameter).

3. Results and Discussion

The analysis reveals interesting patterns in the percentages of the population served by the CWS receiving fluorinated water over the period from 2016 to 2020 across various US states (Table 1). The spectral clustering method identifies a total of five distinct clusters each characterized by its specific fluoridated water coverage (Figure 1), where the number of clusters has been selected by using the *eigengap method* [23].

Table 1. Description of clusters in US states.

CLUSTER	US States	Percentage of population served by CWS receiving fluorinated water (%)
1	Kansas	65.63
	Oklahoma	68.37
	Texas	70.43
	New York	71.57
	Nebraska	73.03
	Missouri	74.87
	Colorado	75.00
	Nevada	75.47
	New Mexico	76.83
	Florida	77.77
	Alabama	77.90
	Maine	79.37
2	Hawaii	9.53

	New Jersey	15.63
	Oregon	25.10
	Idaho	31.77
	Montana	31.93
	Louisiana	40.40
	New Hampshire	46.47
	Alaska	47.10
	Utah	51.93
3	Vermont	56.23
	Wyoming	56.60
	Pennsylvania	56.77
	Massachusetts	57.67
	Arizona	57.83
	California	59.13
	Mississippi	60.93
	Washington	64.30
4	Delaware	83.10
	Rhode Island	83.47
	Arkansas	85.60
	Wisconsin	87.43
	North Carolina	87.73
	Tennessee	88.67
	Michigan	89.50
	Connecticut	89.80
	Iowa	90.10
	West Virginia	90.63
	South Carolina	91.67
5	Ohio	92.57
	Indiana	93.03
	Maryland	93.60
	South Dakota	93.70
	Georgia	95.43
	Virginia	96.03
	North Dakota	96.27
	Illinois	98.37
	Minnesota	98.80
	Kentucky	99.87
	District of Columbia	100.00

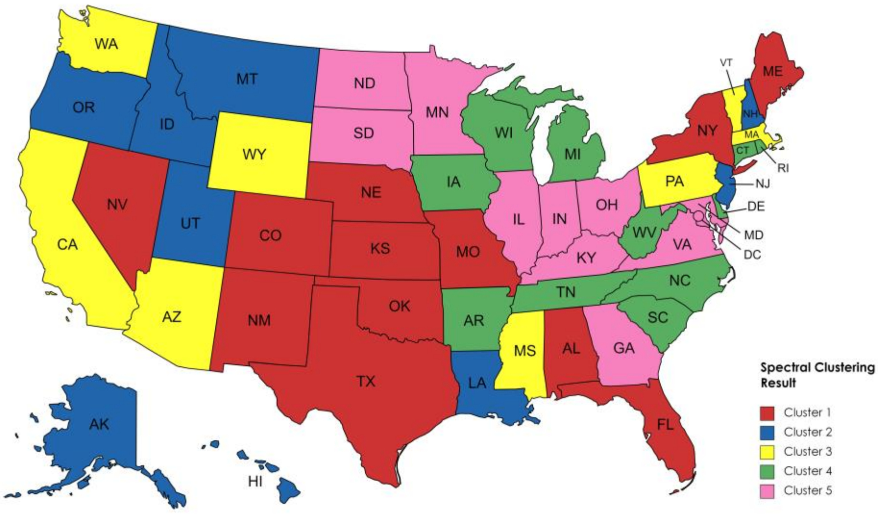

Figure 1. Spectral Clustering of US countries involved in the community water fluoridation.

Cluster 1 encompasses states such as Kansas, Oklahoma, Texas, New York, Nebraska, Missouri, Colorado, Nevada, New Mexico, Florida, Alabama, and Maine. In this cluster, approximately 73.8% of the population served by CWS receives fluorinated water. These states demonstrate a relatively high level of fluoridated water coverage, suggesting a strong commitment to community water fluoridation. On the other hand, cluster 2 includes states like Hawaii, New Jersey, Oregon, Idaho, Montana, Louisiana, New Hampshire, Alaska, and Utah. This cluster exhibits a significantly lower percentage, with only 33.3% of their populations receiving fluorinated water. This indicates that these states face challenges or have chosen not to implement fluoridation to the same extent as cluster 1. Cluster 4 (Delaware, Rhode Island, Arkansas, Wisconsin, North Carolina, Tennessee, Michigan, Connecticut, Iowa, West Virginia, and South Carolina) demonstrates a relatively high fluoridated water coverage, with 87.9% of their population served by CWS receiving fluorinated water. Cluster 5, including states such as Ohio, Indiana, Maryland, South Dakota, Georgia, Virginia, North Dakota, Illinois, Minnesota, Kentucky, and the District of Columbia, exhibits the highest percentage, with 96.1% of their populations receiving fluorinated water. These states have achieved nearly universal coverage of fluoridated water through their CWS.

These findings highlight substantial variations in the implementation of community water fluoridation across different US states. While some states have successfully provided access to fluoridated water to most of their populations, others lag behind. These disparities may have implications for oral health outcomes, with states in cluster 2 potentially facing a higher risk of dental health issues due to lower fluoridation rates. To address these disparities, it is crucial to consider tailored policy and public health efforts that promote access to fluoridated water in regions with lower coverage. Additionally, further research could delve into the specific factors influencing these disparities and their potential impacts on dental health outcomes at the state level.

4. Conclusions

This study serves as a foundation for continued exploration of the effectiveness and equity of public health interventions, like CWF, across various US states. The spectral clustering method effectively grouped states based on the percentage of their population served by CWS receiving fluorinated water. It's important to emphasize that CWF remains a crucial public health strategy for preventing tooth decay and promoting dental health, transcending socioeconomic disparities and barriers to dental care access. The success of spectral clustering in analyzing this dataset suggests its potential application in future research to classify and synthesize information at the macro-area level, offering a valuable tool for understanding and addressing health disparities on a broader scale.

Author Contributions: Conceptualization, F.N.; methodology, C.D.N.; validation, C.D.N.; data curation, F.N.; writing—original draft preparation, F.N.; writing—review and editing, C.D.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on this paper.

Conflicts of Interest: The authors declare no conflict of interest.

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