RUWA JURAI: JURNAL KESEHATAN LINGKUNGAN
ISSN (p) 1978-6204 ISSN (e) 2723-6204
https://ejurnal.poltekkes-tjk.ac.id/index.php/JKESLING

Spatial Temporal Analysis of Groundwater Fluoride Concentration and Its Implication to Human Health in Jakarta, Indonesia

Dhandhun Wacano[1*], Minoru Yoneda[2], Prayudhy Yushananta[3]

[1] Department of Environmental Engineering, Universitas Islam Indonesia, Yogyakarta, Indonesia.
[2] Department of Environmental Engineering, Kyoto University, Kyoto, Japan.
[3] Department of Environmental Health, Politeknik Kesehatan Tanjungkarang, Lampung, Indonesia.

ARTICLE HISTORY

Received July 30, 2024
Accepted April 16, 2025
Published May 15, 2025

Keyword:

Groundwater; Fluoride; Dental caries; Jakarta

Kata kunci:

Air tanah; Fluorida; Caries gigi; Jakarta

A B S T R A C T

Groundwater serves as the primary source of potable water globally, including in Indonesia. Unfortunately, the presence of fluoride concentrations in groundwater, whether in ideal, insufficient, or excessive quantities, can have either beneficial or detrimental effects. Presently, the inhabitants of Jakarta persist in relying on groundwater as their primary source of clean water, which presents an escalating peril to public well-being as a result of increased domestic activities. Regarding the situation, this research aims to analyze the temporal trends and spatial distribution of fluoride concentration in groundwater and its potential consequences for public health risks in Jakarta. A total of 1,418 fluoride and temperature data from the Jakarta Environmental Agency was used for spatial-temporal analysis of 2016–2019 trends. We applied Microsoft Excel 2021 and ArcGIS Pro 3.2 for statistical and spatial data analysis. The result indicated that the fluoride concentration in groundwater was 72.14% below the minimum recommended value of 0.5 mg/L, mostly in the southern part of Jakarta. However, the average fluoride concentration for all seasons per year is consistently increasing, specifically in the northern part of Jakarta. Based on this research's findings, we concluded that the deficiency of fluoride concentration in groundwater is the majority problem in Southern Jakarta and could potentially cause dental caries if the groundwater is used as the daily source of clean water. This information is very useful for the government and public health authorities to further mitigate and protect people in Jakarta who still rely on groundwater as the source of clean water.

Air tanah merupakan sumber utama air minum di dunia, termasuk di Indonesia. Sayangnya, keberadaan konsentrasi fluorida dalam air tanah, baik dalam jumlah ideal, tidak mencukupi, atau berlebihan, dapat memberikan dampak yang menguntungkan maupun merugikan. Saat ini, penduduk Jakarta masih mengandalkan air tanah sebagai sumber utama air bersih, yang menimbulkan risiko yang semakin besar bagi kesejahteraan masyarakat akibat meningkatnya aktivitas domestik. Terkait dengan situasi tersebut, penelitian ini bertujuan untuk menganalisis tren temporal dan distribusi spasial konsentrasi fluorida dalam air tanah serta potensi konsekuensinya terhadap risiko kesehatan masyarakat di Jakarta. Sebanyak 1.418 data fluorida dan suhu dari Dinas Lingkungan Hidup Jakarta digunakan untuk analisis spasial-temporal tren 2016–2019. Kami menerapkan Microsoft Excel 2021 dan ArcGIS Pro 3.2 untuk analisis data statistik dan spasial. Hasil penelitian menunjukkan bahwa konsentrasi fluorida dalam air tanah adalah 72,14% di bawah nilai minimum yang direkomendasikan yaitu 0,5 mg/L, sebagian besar di wilayah selatan Jakarta. Namun, rata-rata konsentrasi fluorida untuk semua musim per tahun terus meningkat, khususnya di wilayah utara Jakarta. Berdasarkan temuan penelitian ini, kami menyimpulkan bahwa kekurangan konsentrasi fluorida dalam air tanah merupakan masalah utama di wilayah selatan Jakarta dan berpotensi menyebabkan karies gigi jika air tanah digunakan sebagai sumber air bersih sehari-hari. Informasi ini sangat berguna bagi pemerintah dan otoritas kesehatan masyarakat untuk mencegah dan melindungi masyarakat Jakarta yang masih mengandalkan air tanah sebagai sumber air bersih.

* Corresponding author: Dhandhun Wacano
Department of Environmental Engineering, Universitas Islam Indonesia, Yogyakarta, Indonesia
Email: dhandhunwacano@uii.ac.id

1. Introduction

Fluoride has a significant impact on human health (Yang et al., 2022). Regardless of whether they are present in optimal, deficient, or excessive amounts, each concentration has its own positive or negative effect. The human body requires optimal concentrations of fluoride, which range from 0.5 to 1.0 mg/L, in order to prevent dental caries, promote bone formation, facilitate mineralization, and support tooth enamel development (Jha & Tripathi, 2021; Mukherjee & Singh, 2018; Rasool et al., 2018; Shaji et al., 2024; Yadav et al., 2021). Fluorapatite exhibits lower solubility and greater resistance to acid erosion compared to hydroxyapatite. This property makes it beneficial for reinforcing enamel and safeguarding it against acidic substances derived from food residues in the oral cavity. Nevertheless, this is only beneficial when the levels of fluoride are low. High levels of fluoride can change hydroxyapatite into fluorapatite, which may be more significant than the substitution of hydroxide (Kimambo et al., 2019). In contrast, a lack of fluoride causes dental cavities, enamel failure, and weakened bones (Ayenew, 2008; Edmunds & Smedley, 2013; Kumar et al., 2019). Enamel development and bone mineralization necessitate a daily intake of 0.5 mg/L fluoride (Ahmad et al., 2022; Ali et al., 2016; Gangani et al., 2022; Kumar et al., 2019). Research shows that food choices and insufficient fluoride consumption primarily cause persistent tooth decay, a widespread health issue that affects 350 million adults and 486 million children (World Health Organization, 2002).

Jakarta, a prominent megacity, is currently experiencing a multitude of environmental degradations. Since the early 1970s, Jakarta has experienced rapid urbanization, industrialization, and population growth. As a result, the city has had to extract groundwater to fulfill its municipal and industrial requirements (Maathuis et al., 1996). Jakarta heavily relies on groundwater as a substitute for its inadequate public water supply system (Costa et al., 2016). In 2015, the Regional Environmental Agency conducted a water security assessment, which found that the drinking water company of Jakarta (PAM Jaya) was only able to provide 40% of the population's water needs. Groundwater sources provided the remaining 60% of the water. Unfortunately, 80% of the unconfined aquifer and 85% of the confined aquifer fail to meet the water quality criteria for drinking water regulation (Indonesian Ministry of Health, 2023). Currently, Jakarta's residents continue to depend on groundwater for their drinking water, which poses a growing threat to public health due to increased domestic activities. Hence, the objective of this research is to analyze the temporal trends and spatial distribution of fluoride concentrations in groundwater and their potential consequences on human health risk in Jakarta. This research will also help the authorities develop more effective strategies to reduce the hazards to public health.

2. Methods

Jakarta, the capital of Indonesia, is situated on the northwest coast of Java Island (Figure 1). Jakarta has a total area of 664.01 km^2, with its metropolitan area encompassing 9,957.08 km^2, which includes the satellite cities of Bogor, Depok, Tangerang, South Tangerang, and Bekasi. The Jakarta metropolitan region, often known as Greater Jakarta, is the largest urban area in Indonesia and the second-largest in the world, surpassed only by Tokyo, Japan. Jakarta serves as the hub for the economic, industrial, cultural, and political activities in Indonesia. According to the BPS-Statistics of DKI Jakarta Province (2022), the population of the area was 10,562,088 as of mid-2021.

Data on fluoride in groundwater was compiled from institutional secondary data. Secondary fluoride concentration data from the Jakarta Environmental Agency have been proposed and granted for use in this research. The data consist of 4 years of temporal monitoring of fluoride concentration in groundwater, both in the dry and wet seasons, from 2016–2019. The total of 1,418 fluoride concentration data was used for spatial-temporal analysis to reveal the trends of groundwater fluoride in the research area. Not only fluoride concentration, but the temperature of

groundwater from the same institution was also used to support the occurrence factor analysis. We used Microsoft Excel 2021 software for basic calculations, data preparation, and supporting and descriptive statistical analyses. ArcGIS Pro 3.2 was used to analyze the spatial patterns in the data.

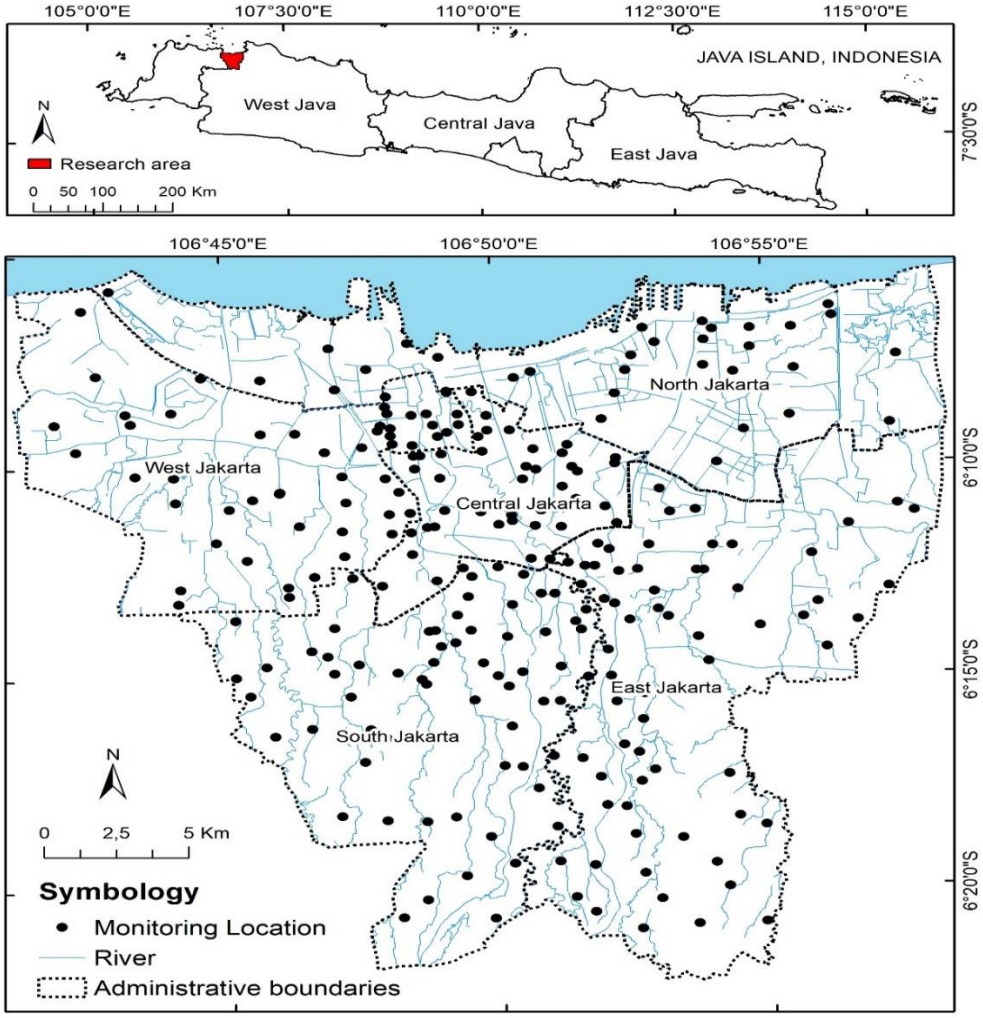

Figure 1. Research area position on Java Island, Indonesia

3. Results

The fluoride concentration in Jakarta varied from 0.05 to 0.81 mg/L (with a mean of 0.20 mg/L) in dry season 2016 (n = 119) and from 0.05 to 0.93 mg/L (with a mean of 0.23 mg/L) in dry season 2016 (n = 45). The same pattern on minimum, maximum, and average concentration is not so far between the dry and wet seasons in the years 2017, 2018, and 2019. As shown in Table 1, the average amount of fluoride in Jakarta's groundwater is mostly low concentrations below 0.5 mg/L. 0.5 mg/L.

Groundwater fluoride concentration analysis from 2016–2019 showed that the fluoride concentration in groundwater was 72.14% below the minimum recommended value of 0.5 mg/L. As shown in Table 2, the amount of fluoride data in Jakarta's groundwater below 0.5 mg/L is mostly between 50.58% and 92.44% for the dry season and 41.67% and 90.76% for the wet season. Conversely, the fluoride concentration above 1.5 mg/L is almost below 1% for all years, except in the wet season of 2018. For the 2018 sample data, the fluoride concentration was slightly higher, about 3.77 mg/L above 1.5 mg/L standard. The remaining optimum range is not significant compared to the low concentration.

Table 1. Statistical summary of temporal fluoride concentration

Season	Year	(n)	Min	Max	Mean	SD
Dry	2016	119	0.05	0.81	0.20	0.16
	2017	259	0.04	1.59	0.31	0.27
	2018	132	0.04	2.00	0.39	0.36
	2019	259	0.10	1.48	0.47	0.26
	Total n	769				
Rainy	2016	119	0.05	0.93	0.23	0.16
	2017	259	0.03	1.54	0.27	0.27
	2018	259	0.04	3.77	0.52	0.54
	2019	12	0.24	1.00	0.65	0.26
	Total n	649				

In the dry season, the minimum average concentration was 0.20, and the maximum was 0.47 mg/L, whereas in the wet season, the minimum average is 0.23, and the maximum average is 0.65. We have observed an interesting pattern in the concentration average, despite the average being very low for almost all samples. Figure 2h shows that the average fluoride concentration for all seasons per year is increasing. Additionally, during the dry season, the average temperature of groundwater for all samples is 23.64 °C, while in the wet season is 23.82 °C.

Table 2. Percentage fluoride concentration classification

Season	Year	n	F< 0.5 mg/L (%)	0.5< F<1.5 mg/L (%)	F >1.5 mg/L (%)	Total (%)
Dry	2016	119	92.44	7.56	0.00	100
	2017	259	77.99	21.62	0.39	100
	2018	132	71.21	28.03	0.76	100
	2019	259	50.58	49.42	0.00	100
Rainy	2016	119	90.76	9.24	0.00	100
	2017	259	81.47	18.15	0.39	100
	2018	259	62.55	33.59	3.86	100
	2019	12	41.67	58.33	0.00	100

The spatial distribution and pattern of fluoride in the groundwater of Jakarta are presented in Figures 2a–f, while mean concentration trend in Figure 2h. The number of samples with high fluoride concentrations is increasing per year, from the dry season of 2016 to the dry season of 2019. Generally, all of the increasing concentration is mostly situated in the northern part of Jakarta, while the eastern and middle parts are also slightly affected. The northern part of Jakarta is located in the coastal area and is associated with land subsidence and tidal flooding. Northern Jakarta is also associated with seawater intrusion, which can also contribute to the enrichment factor of fluoride occurrence in groundwater and needs further evaluation. Not to mention that industrial and harbor activity is dense in this location. Despite the fact that the average is very low for almost all samples, an interesting pattern has been observed in the concentration average. The average fluoride concentration for all seasons per year is increasing, as we can see in Figure 2h.

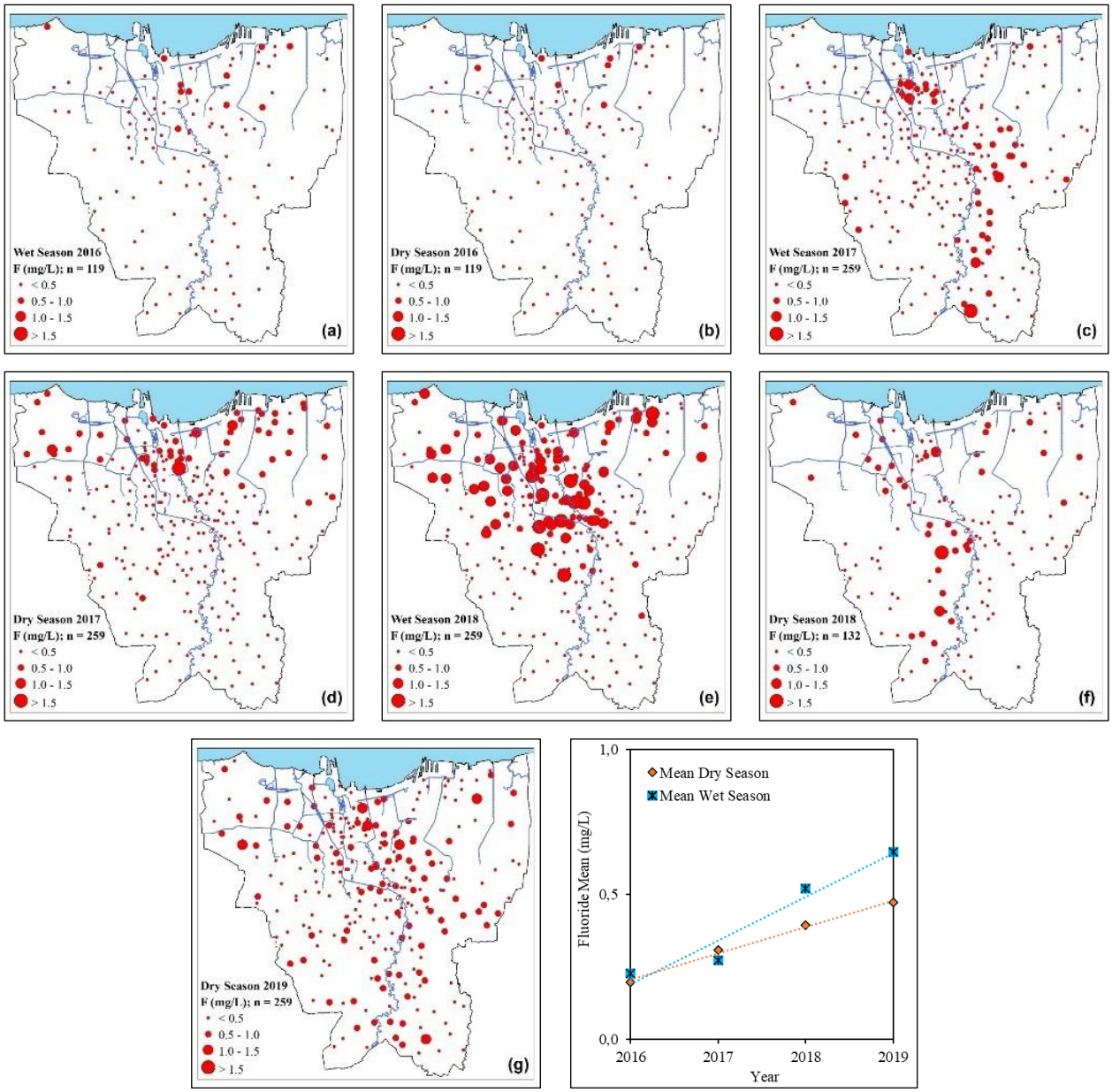

Figure 2. Mean fluoride concentration trends.

4. Discussion

Fluoride is abundant in the Earth's crust and is thermodynamically mobile at higher temperatures (Selinus, 2013). In terms of fluoride occurrence in groundwater, climate is one of the important controlling factors. Indonesia is a tropical country with two seasons, i.e., a dry season (May to October) and a wet season (November to April). Since fluoride is mobile at high temperatures, the differentiation between the dry and wet seasons in Jakarta was discussed. During the dry season, the average temperature of groundwater is 23.64 °C, with an average fluoride concentration of 0.34 mg/L. In the wet season, the average temperature of groundwater is 23.82 °C, with an average fluoride concentration of 0.39 mg/L. Thus, the different seasons in Jakarta did not significantly impact the average temperature of the groundwater. The average temperature of groundwater is nearly the same in both the dry and wet seasons, with the wet season being slightly warmer. Therefore, different seasons in Jakarta did not have a significant impact on the average temperature of groundwater concentration.

In terms of public health, fluoride concentration deficiency in groundwater is the majority problem in Jakarta. Consequently, the risk of deficiency

leading to dental caries is significantly higher than the excessive risk of fluoride causing fluorosis disease. Furthermore, about 32% of the population in Jakarta does not have access to clean water, and only 68% have already received clean water from the Jakarta Clean Water Company (PAM Jaya).

The Statistical Agency of Jakarta for 2018–2019 has reported that South Jakarta is one of the cities that use a large amount of groundwater, with a total of 4.3 million m^3 in 2018 and 3,7 million m^3 in 2019, or 53–56% of the groundwater usage in the entire city. Groundwater usage in East Jakarta and Central Jakarta is still high, at 17% and 13%, respectively. The use of groundwater as the source of domestic activities such as drinking water and cooking can increase the potential for chronic problems caused by fluoride occurrence in groundwater. In these cases, the deficiency is likely to be a significant concern and is more often found in the southern part of Jakarta, according to spatial distribution patterns. Conversely, the northern part of Jakarta exhibits the high concentration of fluoride in groundwater.

The deficiency of fluoride content in drinking water from groundwater in Indonesia will lead to negative impacts such as the development of dental caries, the absence of enamel formation, and bone fragility (Ayenew, 2008; Edmunds & Smedley, 2013; Kumar et al., 2019). The prevalence of dental caries, which remains high and has become a significant issue for the entire nation, may also indirectly correlate with the current situation. The results of the 2018 Basic Health Research study (adjusted to the year that groundwater data was compiled) showed that the prevalence of tooth decay in young children remains extremely high, at approximately 93% (Indonesian Agency of Health Research and Development, 2018). Safe drinking water development and fluoridation will be an option if the dental caries problem is also present in Jakarta.

The result of this research is only to represent the factual temporal data from 2016 to 2019; thus, the updated situation may be changing nowadays and needs to be investigated in future research. However, from the four years of spatial-temporal distribution, we can reveal that the average fluoride concentration in groundwater in Jakarta is increasing, especially in the northern part of Jakarta, and low fluoride concentration is observed in the southern part of Jakarta. This information may be crucial for developing future policies aimed at addressing the fluoride issue in drinking water and improving overall water quality management.

5. Conclusions

Based on our findings, we conclude that the low fluoride concentration (F < 0.5 mg/L) in Jakarta's groundwater is a major concern. The majority of the fluoride concentration in groundwater is below the optimum limit to prevent dental caries. The Jakarta case study may explain Indonesia's high prevalence of dental caries. In general, dental caries is prevalent in the southern part of Jakarta and supported by the very low concentration of fluoride in groundwater, which is below the optimum limit needed for supporting dental health. Furthermore, the mean fluoride concentration is consistently increasing in the northern part of Jakarta and requires further investigation for future public health concerns.

Acknowledgment

The author would like to thank the Jakarta Environmental Agency for supporting this research by sharing groundwater quality data from 2016 to 2019 and granting permission to use it based on PPID-202100568.

References

Ahmad, S., Singh, R., Arfin, T., & Neeti, K. (2022). Fluoride contamination, consequences and removal techniques in water: a review. *Environmental Science: Advances*, *1*(5), 620–661. https://doi.org/10.1039/D1VA00039J

Ali, S., Thakur, S. K., Sarkar, A., & Shekhar, S. (2016). Worldwide contamination of water by fluoride. *Environmental Chemistry Letters*, *14*(3), 291–315. https://doi.org/10.1007/s10311-016-0563-5

Ayenew, T. (2008). The distribution and hydrogeological controls of fluoride in the groundwater of central Ethiopian rift and adjacent highlands. *Environmental Geology*, *54*(6), 1313–1324. https://doi.org/10.1007/s00254-007-0914-4

BPS-Statistics of DKI Jakarta Province. (2022). *DKI Jakarta Province in Figures 2022* (1st ed.). BPS-Statistics of DKI Jakarta Province. https://jakarta.bps.go.id/id/publication/2022/0

2/25/5979600247867d861a1f334c/provinsi-dki-jakarta-dalam-angka-2022.html

Costa, D., Burlando, P., Priadi, C., & Shie-Yui, L. (2016). The nitrogen cycle in highly urbanized tropical regions and the effect of river–aquifer interactions: The case of Jakarta and the Ciliwung River. *Journal of Contaminant Hydrology*, *192*, 87–100. https://doi.org/10.1016/j.jconhyd.2016.06.004

Edmunds, W. M., & Smedley, P. L. (2013). Fluoride in Natural Waters. In *Essentials of Medical Geology* (pp. 311–336). Springer Netherlands. https://doi.org/10.1007/978-94-007-4375-5_13

Gangani, N., Joshi, V. C., Sharma, S., & Bhattacharya, A. (2022). Fluoride contamination in water: Remediation strategies through membranes. *Groundwater for Sustainable Development*, *17*, 100751. https://doi.org/10.1016/j.gsd.2022.100751

Indonesian Agency of Health Research and Development. (2018). *Indonesia Basic Health Research Report*. Indonesian Ministry of Health. https://repository.badankebijakan.kemkes.go.id/id/eprint/3514/1/Laporan Riskesdas 2018 Nasional.pdf

Indonesian Ministry of Health. (2023). *Indonesian Ministry of Health Regulation No. 2 Year 2023*. Indonesian Ministry of Health. https://peraturan.bpk.go.id/Details/245563/permenkes-no-2-tahun-2023

Jha, P. K., & Tripathi, P. (2021). Arsenic and fluoride contamination in groundwater: A review of global scenarios with special reference to India. *Groundwater for Sustainable Development*, *13*, 100576. https://doi.org/10.1016/j.gsd.2021.100576

Kimambo, V., Bhattacharya, P., Mtalo, F., Mtamba, J., & Ahmad, A. (2019). Fluoride occurrence in groundwater systems at global scale and status of defluoridation – State of the art. *Groundwater for Sustainable Development*, *9*, 100223. https://doi.org/10.1016/j.gsd.2019.100223

Kumar, P. S., Suganya, S., Srinivas, S., Priyadharshini, S., Karthika, M., Karishma Sri, R., Swetha, V., Naushad, M., & Lichtfouse, E. (2019). Treatment of fluoride-contaminated water. A review. *Environmental Chemistry Letters*, *17*(4), 1707–1726. https://doi.org/10.1007/s10311-019-00906-9

Maathuis, H., Yong, R. N. Y., Adi, S. B., & Prawiradisastra, S. (1996). *Development of groundwater management strategies in the coastal region of Jakarta, Indonesia: final report*. https://api.semanticscholar.org/CorpusID:127448967

Mukherjee, I., & Singh, U. K. (2018). Groundwater fluoride contamination, probable release, and containment mechanisms: a review on Indian context. *Environmental Geochemistry and Health*, *40*(6), 2259–2301. https://doi.org/10.1007/s10653-018-0096-x

Rasool, A., Farooqi, A., Xiao, T., Ali, W., Noor, S., Abiola, O., Ali, S., & Nasim, W. (2018). A review of global outlook on fluoride contamination in groundwater with prominence on the Pakistan current situation. *Environmental Geochemistry and Health*, *40*(4), 1265–1281. https://doi.org/10.1007/s10653-017-0054-z

Selinus, O. (Ed.). (2013). *Essentials of Medical Geology*. Springer Netherlands. https://doi.org/10.1007/978-94-007-4375-5

Shaji, E., Sarath, K. V., Santosh, M., Krishnaprasad, P. K., Arya, B. K., & Babu, M. S. (2024). Fluoride contamination in groundwater: A global review of the status, processes, challenges, and remedial measures. *Geoscience Frontiers*, *15*(2), 101734. https://doi.org/10.1016/j.gsf.2023.101734

World Health Organization. (2002). *World Health Report 2002: Reducing Risks, Promoting Healthy Life* (1st ed.). https://www.who.int/publications/i/item/9241562072

Yadav, M., Singh, G., & Jadeja, R. N. (2021). Fluoride Contamination in Groundwater, Impacts, and Their Potential Remediation Techniques. In *Groundwater Geochemistry* (pp. 22–41). Wiley. https://doi.org/10.1002/9781119709732.ch2

Yang, F., Jia, C., Yang, X., Yang, H., & Chang, W. (2022). Probabilistic potential health risk quantification, hydrochemistry, driving forces of groundwater nitrate and fluoride in a typical irrigation district, Northern China. *Journal of Environmental Management*, *323*, 116171. https://doi.org/10.1016/j.jenvman.2022.116171