Open Access Library Journal
2024, Volume 11, e11961
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Modelling Spatial Variation, Distribution, and Prediction of Fluoride Levels in Groundwater in the Njoro River Catchment, Kenya

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How to cite this paper: Ontumbi, G.M., Jepkirui, M. (2024) Modelling Spatial Variation, Distribution, and Prediction of Fluoride Levels in Groundwater in the Njoro River Catchment, Kenya. *Open Access Library Journal*, **11**: e11961.
https://doi.org/10.4236/oalib.1111961

Received: July 17, 2024
Accepted: August 27, 2024
Published: August 30, 2024

Abstract

Fluoride, whose levels are higher than the World Health Organization (WHO) recommended level of 1.5 mg/l, results in health issues. Therefore, fluoride contamination is a matter that calls for concern by all people and governments, especially in countries where volcanicity has been experienced. This study sought to model spatial variation, distribution, and prediction of fluoride levels in groundwater in the river Njoro catchment. This study aimed to observe the levels of fluoride and give recommendations for identifying and delineating potential sites for safe groundwater for use by the local population and advice on the water treatment and de-fluoridation methods. In this study, borehole water samples were collected for laboratory analysis of fluoride levels. The study adopted descriptive and correlation statistical analysis. The sources of data included: field surveys where data on fluoride levels were collected, remotely sensed data, GIS, and geostatistically interpolated data. The results through geostatistical interpolation observed varied distribution and variations of fluoride levels in the River Njoro catchment.

Subject Areas

Geology

Keywords

Contamination, Delineation, Volcanicity, Spatial Variation, Geostatistical

1. Introduction

According to [1], water is the basic need that determines the quality of life on earth. Consequently, water is essential to man, animals, and plants, without which life on earth would not exist. Good and quality water maintains healthy ecosystems by resulting in improved human welfare. Therefore, safe water free from injurious chemicals and pathogens causing diseases is a requisite for a healthy nation. As stipulated in the Sustainable Development Goals (SDG), access to safe drinking water at national, regional, and local levels is an important health and development-related concern.

Water occupies 70% of the earth's surface, with 96.5% available in oceans and 1.74% in the frozen state. Nonetheless, a large portion of the worldwide water requirements is supplied by rivers and boreholes. However, borehole water use is comparatively fresh and widely distributed instead of the river and spring water. Moreover, the increasing population and their needs pose serious threats to the water sources. [2] observed that globally sufficient freshwater supplies are the foundations upon which all Sustainable Development Goals are based. Therefore, there is a need to ensure safe water for the citizens of a country. Most people living in developing countries have no access to quality drinking water [3] as per the permissible fluoride levels.

Surface and groundwater quality would be linked and affected by the type of aquifer where the river's source is located, as observed by [4]. Naturally, the chemicals present in groundwater originate from the rocks and soil facilitated by the processes of percolation and infiltration. The hydrological processes of percolation and infiltration, therefore, have the potential to cause contamination and thereby affecting both the surface and groundwater quality. Water for drinking should be free from pathogenic organisms and compounds with adverse immediate and long-term impacts on human health [5].

Fluoride occurrence in groundwater would be attributed to geologically related contamination [6] however, the source cannot be precisely identified. Generally, contamination of groundwater associated with geogenic processes is dependent on the geological formations of specific areas. The contamination is justified when rainwater penetrates through the soil and comes in contact with the water table, thereby dissolving some bedrock minerals. Consequently, the fluoride content of groundwater is a result of the dissolution of the bedrock that is rich in fluorine-bearing minerals. According to [7] the minerals forming the bedrock generally are a principal factor responsible for fluoride variations in fluoride levels in boreholes. The elevated fluoride levels in groundwater can be attributed to natural and anthropogenic processes. Moreover, the natural causes are more responsible for the degradation of groundwater through geological conditions.

Fluoride contamination associated with surface and groundwater is related to availability and dissolubility of minerals bearing fluorine, temperature, acidity or alkalinity, concentration levels of calcium and bicarbonate ions dissolved in water. Over 95% of the world's available fresh water has aquifers in groundwater. According to [8], groundwater water is the main source of drinking water for a large percentage of the world's population. Groundwater is found in most environments; however, geology, geomorphology, land use, and climatic variations determine its quantity, quality, accessibility, and recharge. Rock types and geomorphology play a significant role in the storage, transportation and nature of borehole water. [9] observe that a place's geomorphological and geological attributes contribute to the recharge of 10 - 50 mm of fluoride levels in areas whose annual precipitation is less than 500 mm.

[10] observes that in parts of India, Pakistan, West Africa, Thailand, China, Sri Lanka, and Southern Africa, high groundwater fluoride concentrations are associated with rocks with volcanic and metamorphic rocks. Further, [11] observe that in the 28 provinces of China, rampant cases of elevated fluoride levels have been reported in groundwater sources. However, comparatively shallow borehole sources had fewer concentrations than deeper groundwater which recorded higher fluoride concentrations. Similarly, the nature of rocks in Kenya makes it one of the countries in the world with extraordinarily high concentrations of fluoride levels in rocks and soil, surface, and groundwater. Maximum fluoride concentrations in water sources in Kenya have been observed in some river sources, groundwater, and lakes in the Rift Valley [11]. The documented places that experienced magmatic activities are located in the East African Rift Valley system.

The majority of rocks in places where the phenomena of volcanicity were experienced have fluoride, but the concentration levels are different relative to the locations of the rock. Conversely, the quantity of fluoride in the water depends on the saturation of the chemical compound in the rock or layer. Fluoride is regarded as an essential element for the formation of healthy bones and teeth; however, levels above 1.5 mg/l in drinking water have been associated with high incidences of dental fluorosis [12]. In a study by [13], in Njoro Division, in the then Nakuru District, the groundwater used for cooking and drinking was obtained from boreholes and wells and had fluoride levels much higher than those obtained from boreholes and wells the World Health Organisation recommended level of 1.5 mg/l.

The occurrence of elevated and concentrations of fluoride levels in subsurface and surface water has attracted attention worldwide because of the repercussions associated with human health. The geology of the Rift Valley with the associated phenomena of volcanicity makes it one of the worldwide regions vulnerable to the outcomes of elevated fluoride levels in mineral rocks, soil, surface, and groundwater. Fluoride fluctuates in different water sources, with increased concentration levels observed within groundwater sources. This study sought to model spatial variation, distribution, and prediction of fluoride levels in groundwater in the river Njoro catchment.

2. Literature Review

2.1. Factors Influencing Fluoride Levels

In groundwater, the natural concentration is determined by rock types, aquifer characteristics (chemical and physical), and the porosity and acidity of the soil and rocks. Additionally, as [14] observed, quantities of temperature and chemical reaction of elements contribute to more fluoride. Conversely, fluoride concentration within surface water has a relationship with the hotness or coldness of the water, acidity or alkalinity, availability of precipitating ions and colloids, and the nature of solubility minerals bearing fluorine. Additionally, fluoride levels are associated with the anion exchangeability of the materials making the water sources, the nature and size of rock formations crisscrossed by water, and residence time during which water takes within the particular formation of rocks [15].

2.2. Fluoride Occurrence in the World

In Africa, groundwater contains fluoride higher than WHO upper limits than surface water. As observed by [16], past studies in East Africa concluded that East African Rift Valley is considered a region with high fluoride levels. The East African Rift Valley region traverses from Jordan Valley to Tanzania through various countries. Incidences of high fluoride countries are witnessed in Malawi and The Republic of South Africa. In Tanzania, a fluoride survey in groundwater showed that 30% of the water used for drinking had fluoride levels exceeding 1.5 mg/l. According to [16], a survey of fluoride in borehole water asserts that the occurrence of dental fluorosis in Malawi and the Republic of South Africa has been associated with fluoride levels beyond 1.5 mg/l. High sodium and bicarbonate concentrations and high pH in the water are proxy indicators of high fluoride levels in groundwater. In addition to countries traversed by the Great East African Rift Valley's high fluoride levels in Africa, there are elevated fluoride levels in Ghana, Malawi, Nigeria, Algeria, and South Africa [17] [18]. Other countries of the world that are experiencing the phenomena of elevated fluoride levels in the world include: India, Türkiye, Saudi Arabia, and Sri Lanka [18]-[20].

2.3. The Geostatistical Process

The Geostatistical technique quantified the spatial autocorrelation of fluoride levels in the borehole sampling points and accounted for the spatial alignment of the sample points around the prediction areas. Kriging is a stochastic interpolation method useful in predicting phenomena on the spatial surface. Kriging is flexible and allows the investigation of spatial autocorrelation of the data by using statistical models. In Kriging, the basic assumption is that the data for modeling comes from a static stochastic process, and the data should be normally distributed, as observed by [21].

Using Kriging Interpolation in this study, the fluoride levels in the borehole data were quantified and later used to produce a predicted fluoride distribution surface map in the River Njoro catchment. To predict the unknown fluoride values neighboring the sampled boreholes, Kriging was used to fit the model from the values of fluoride from the measured sample points around the prediction areas. Kriging uses statistical models, and therefore this study allowed the production of a borehole fluoride distribution prediction map in the River Njoro catchment. GIS provided a platform for multiple layers of topographical, geological, and hydrological maps of the River Njoro catchment, where analyses were done to locate the spatial locations of the boreholes. The topographical map of Njoro (Topographical Sheet Number 118 1:50,000) was used to digitalize the River Njoro catchment using ArcGIS. The selection of training samples was based on information from available past maps of the River Njoro catchment, Google Earth images, and field surveys that were carried out between January 2017 and April 2017.

The truthing ground survey was undertaken in the area of study to confirm the sampling boreholes' location. Finally, to validate the fluoride distribution as projected by Kirging modeling, six neighboring boreholes in the study are presented in Figure 2, with their relative locations identified for statistical interpolation purposes. The six neighboring boreholes were selected purposely with two boreholes in each case representing upstream (Ogiek Primary and Bontana flowers boreholes), midstream Tumaini Schools, and Egerton University boreholes) and downstream (Mustard seed and Rift Valley Institute of Science and Technology-RVIST boreholes) of the River Njoro catchment. The secondary data on the predictor boreholes were collected from WRA offices in Nakuru.

2.4. Geostatistical Modeling and Mapping

The interpolation technique by Kriging provides the "best" impartial, linear estimate of a regionalized variable in a location that was not sampled. In this scenario, "best" refers to a least-squares sense. The emphasis in Kriging interpolation is set on local accuracy, with the actual being close to the estimated value without any regard to the global statistical characteristics of the estimates. Geostatistics in this study provided a set of statistical tools that analyzed the spatial variability and spatial interpolation of fluoride in groundwater in the River Njoro catchment. A geostatistical analysis tool was employed in establishing groundwater and surface fluoride spatial variation.

2.5. GIS and Interpolation

The first step in geostatistical analysis, involves exploratory data analysis by using histogram, normality, the trend of data, semi-variogram cloud, and cross-covariance cloud of the observed raw data. The data on the water samples in this study had normal distribution in the upper, middle, and downstream of the Njoro catchment, which was sampled covering the wet and dry seasons and resulting in the adoption of the Kriging technique. The transformation was used to make the data normally distributed to confirm similarity for the borehole fluoride data. The histogram was used in ArcGIS Geostatistical Analyst to see the need for transformations, subsequently making the data more normally distributed. Prediction performances were assessed by cross-validation of the secondary borehole data from the neighboring boreholes.

3. Methodology

A purposive longitudinal survey design was adopted for this study, with the study area purposefully categorized into upstream, midstream, and downstream in identifying the water sampling points. The borehole water sampling was done during the rainy and sunny seasons to capture the seasonal variations during the study period. This study involved collecting borehole water samples from selected boreholes for laboratory analysis of fluoride levels. Analysis of Geostatistical data and geological interpretation of the study area was done at the GIS laboratory of the University of Eldoret.

Water sampling from the boreholes whose GPS locations, depths, and altitudes are presented in Table 1.

Table 1. Location of sampled boreholes.

S/NO	GPS LOCATION	ALTITUDE	NAME	DEPTH
1	−0.362, 35.907	2450	Beeston-Rurii	130 m
2	−0.3866, 35.888	2485	Nesuit sec school	180 m
3	−0.397, 35.945	2307	Egerton Sunrise	172 m
4	−0.362, 35.987	2142	Kikapu community	114 m
5	−0.367, 35.942	2160	Njoro canning	230 m
6	−0.367, 35.992	2156	Kwa Annah	207 m
7	−0.305, 35.988	2043	Ngata Ndaruk	127 m
8	−0.304, 36.033	1860	Ainabtich community	130 m
9	−0.270, 36.037	1947	Kiamunyi	212 m
10	−0.302, 36.062	1819	Pistis	180 m
11	−0.304, 36.050	1794	Mother Kelvin	110 m
12	−0.320, 36.022	1935	Mogon Community	140 m

3.1. Catchment Delineation

A Digital Elevation Model (DEM) with a 90 m resolution was obtained by the Shuttle Radar Topography Mission (SRTM) and downloaded from the Global Land Cover Facility (GLCF). A DEM represents the continuous spatial variation of relief that assists in assessing landscape characteristics along with topography and has a wide application in hydrological modeling. The Hydrology Tools of ArcGIS software was used to delineate the River Njoro catchment. After that, the process of catchment delineation in ArcGis involved filling the sinks, determining the flow direction, accumulation, and creating the stream links. The point at which River Njoro enters into the Nakuru National Park, a protected area, was used as the end of River Njoro and helped delineate the watershed.

3.2. Geostatistics Data Collection and Analysis

In this study, Geostatistical data included: GPS locations of the boreholes, fluoride levels, and depths of the sampled boreholes. The main elements of the geostatistics data collecting and analysis included: data input, data pre-processing, and distance estimation between boreholes to depict spatial variability between the sampled boreholes. The other elements included average fluoride levels of the sampled and neighboring boreholes scenario analysis at the diagnostic stage. If the scenario analysis depicts the picture of fluoride distribution in the River Njoro catchment, then fluoride prediction will be represented by a fluoride spatial distribution map. The procedure of geostatistics data collecting and analysis is represented in Figure 1.

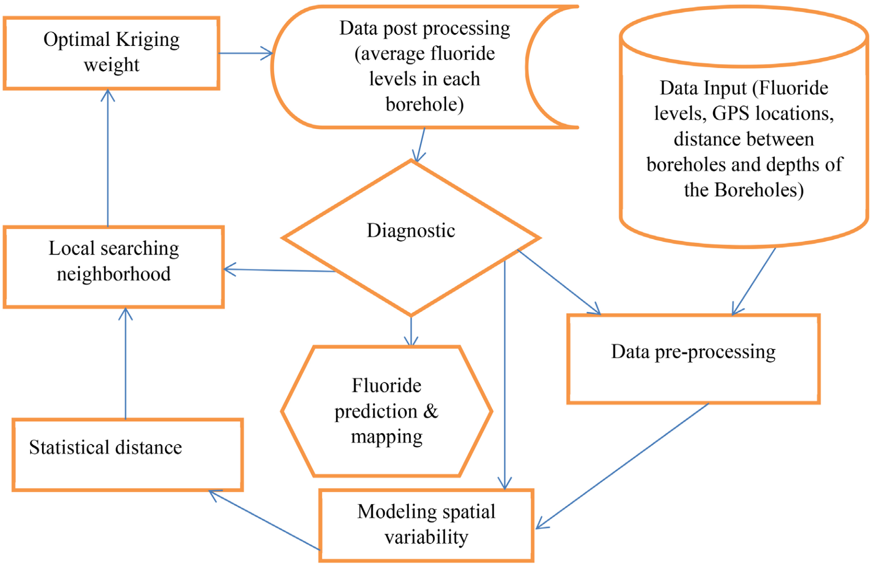

Figure 1. Geostatistics data collecting and analysis. Source: Author.

The GPS locations and elevations of the 12 upstream, midstream, and downstream boreholes were obtained using a handheld Germin (model GTN 635) Global Positioning System (GPS) receiver.

After that, ArcGIS 10.1 GIS software packages and ArcGIS Geostatistical Analyst extension were adopted to derive the ordinary Kriging projections. Kriging is a geostatistical term depicting optimal linear prediction of spatial processes. Kriging interpolates spatial data in geology, hydrology, and environmental monitoring. Interpolation procedures simplify mathematical models by taking the form of inverse distance weighting, trend surface analysis, and Thiessen polygon [22]. In this study Kriging Geostatistical interpolation technique utilized both the mathematical and the statistical properties of the fluoride levels in the sampled boreholes to project fluoride distribution in the boreholes in the River Njoro catchment.

3.3. Assumptions for the Model

Assumptions were user-defined parameters used in the Kirging model's development in the production of the fluoride distribution map. The use of assumptions was important because the model was adopted in a catchment with near similar characteristics in geology coverage, and the depths of the sampled and neighboring boreholes ranged between 130 M and 200 M. The interpolation and mapping of the final prediction fluoride spatial distribution map was based on the following assumptions:

1) The stratigraphy in most of the boreholes in the Njoro catchment displays almost a similar matrix.

2) The rock types in the River Njoro catchment area are of the same nature and type.

3) There was equal variability for the borehole fluoride data.

4) The distribution of fluoride levels Upstream, Downstream, and Midstream boreholes did not show great variation in each segment.

3.4. Geostatistical Model Calibration and Validation

Calibration of the geostatistically interpolated results of the Kriging model was done by using the data for the current scenario and comparing the Kirging output to the recorded fluoride levels in the boreholes. Proper model calibration is in modeling because it helps in minimizing model simulation uncertainty. In this study, fluoride levels measured in sampled boreholes in the River Njoro catchment were compared with the fluoride levels in the neighboring boreholes with equal depths to generate the fluoride prediction of the catchment.

Therefore, the calibration process helped minimize the difference between predicted and measured fluoride levels. However, variations between the model and observed data are always anticipated in all the model projections.

The greatest limitation of this study was the availability of continuous current fluoride data from the boreholes. Much of the data on fluoride levels were measured after drilling, and therefore fluoride levels after operation of the boreholes were not available. The unavailability and incompleteness of fluoride levels were addressed by spatial interpolation and extrapolation. In this study, Cross-validation was used for testing “moving neighborhood.” Therefore, the predicted fluoride distribution was validated in the groundwater map of the River Njoro catchment by comparing the fluoride levels of sampled boreholes with the neighboring boreholes. After the prediction by Kriging, the study compared fluoride data available at the WRA Nakuru office of the neighboring boreholes with almost similar characteristics of borehole depths and elevations. The average mean variation between the fluoride levels of the sampled and predictor boreholes was calculated to assist in geostatistical modeling and mapping.

Geostatistical estimation consist of two stages. The first stage consisted of identifying and modeling the spatial structure of fluoride that was being investigated by semi-variogram analysis, while the second phase was the estimation and interpolation of data using the Kriging method. Using Geostatistical methods was stationarity tested using semi-variogram and independence and stationarity tests. Secondly, the distribution of the fluoride data from the boreholes was close to a normal distribution. The Kriging model was used to interpolate the fluoride concentration of the sampled wells in the study area. The fluoride data from the boreholes helped build a valid Kriging model by sub-setting and simulating the observed data. The predictions and their respective standard errors were generated during this process at unsampled neighboring boreholes. Finally, these repeated processes from each sampling station created a semi-variogram spectrum to generate the model for the prediction of fluoride distribution.

The boreholes used to validate the Kriging model included: Rift Valley Institute of Science and Technology (downstream), Ogiek Primary School and Bontana Flowers, and Tumaini School and Egerton University boreholes to represent downstream boreholes as represented in Figure 2. The data of these boreholes were used as predictor boreholes to validate the predicted fluoride distribution in the Njoro catchment. Therefore, each unknown value on fluoride levels was validated from fluoride level data of the surrounding boreholes. ArcGIS was used to draw and overlay the predicted fluoride distribution map on the digitized map of the River Njoro catchment. Fluoride concentration and distribution mapping were done by graduated symbols proportional to values using ArcMap version 10.1. The fluoride concentration ranges in borehole water were grouped based on WHO (0.0 - 1.5 mg/l) standards to assess the status of the borehole water according to WHO requirements.

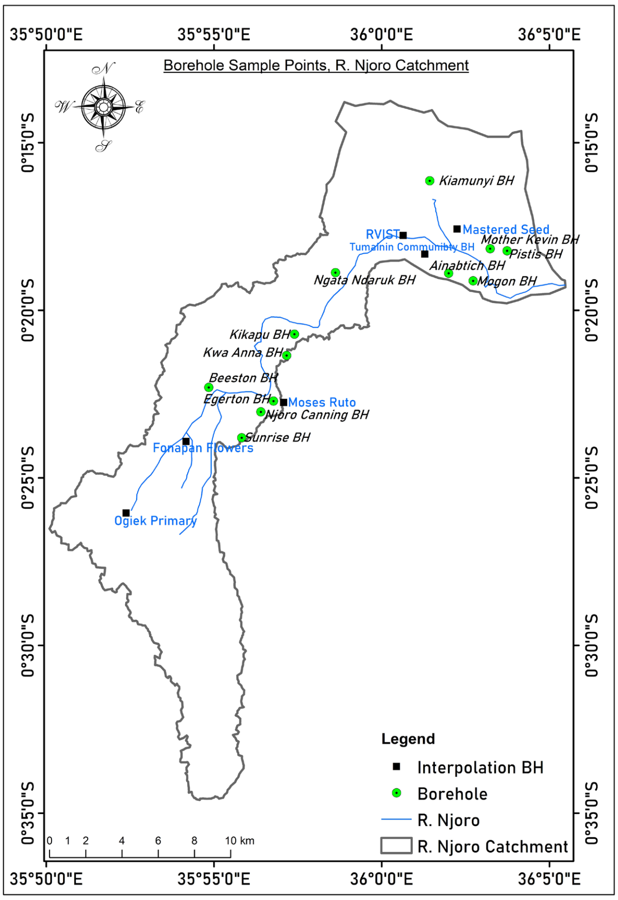

Figure 2. Sampled and predictor boreholes. Source: Author.

4. Results

The neighboring boreholes used as predictor boreholes included: Rift Valley Technical Institute of Science and Technology, Mustard Seed boreholes downstream, Ogiek Primary School, and Bontana flowers upstream of the study area. The other boreholes were: Tumaini School and Egerton University boreholes at midstream. The analysis helped predict the contribution of: surface geology, borehole stratigraphy, and physical parameters of water quality on the fluoride levels in the groundwater of River Njoro Catchment based on the analysis of the fluoride levels of the sampled boreholes.

The average fluoride levels for the sampled and predictor boreholes upstream, midstream, and downstream of the catchment are presented in **Table 2**. The concentration of fluoride in the study area varied from 1.7 mg/l at the Ngata Mbaruk borehole to 18.6 mg/l at the Kiamunyi borehole. The area upstream of the River Njoro catchment around Nesuit Primary is predicted to have fluoride level ranges of between 0 - 1.5 mg/l and 1.6 - 3.0 mg/l. These are areas or zones of low fluoride concentrations. On the other hand, areas midstream of the study area has fluoride ranges between 1.6 - 3.0 mg/l and 3.1 - 4.5 mg/l. This is the area around Njoro Township and its environment. Finally, higher levels are predicted to occur in the boreholes downstream of the study area and its environment. Kiamunyi area, Pistis, located extremely downstream, and Mogon areas are some of the predicted high fluoride areas.

Table 2. Average fluoride levels for the sampled and predictor boreholes.

Borehole name	Type of Borehole	Average F (mg/l)
	Downstream catchment	
Mogon Community	Sampled	8.798
Pistis School	Sampled	19.369
Mother Kelvin	Sampled	3.72
Ainabtich	Sampled	5.533
Mustard Seed	**Predictor**	**7.732**
RVIST	**Predictor**	**8.000**
	Midstream catchment	
Kiamunyi Estate	Sampled	18.591
Ngata Mbaruk	Sampled	1.737
Umoja Kikapu	Sampled	2.907
Kwa Annah	Sampled	3.315
Tumaini Schools	**Predictor**	**4.672**
Egerton University	**Predictor**	**3.820**

Continued

	Upstream catchment	
Egerton Sunrise	Sampled	4.000
Njoro Canning	Sampled	5.896
Beston	Sampled	3.414
Nesuit Pri School	Sampled	3.000
Bontana Flowers	**Predictor**	**4.100**
Ogiek Primary Sch.	**Predictor**	**3.210**

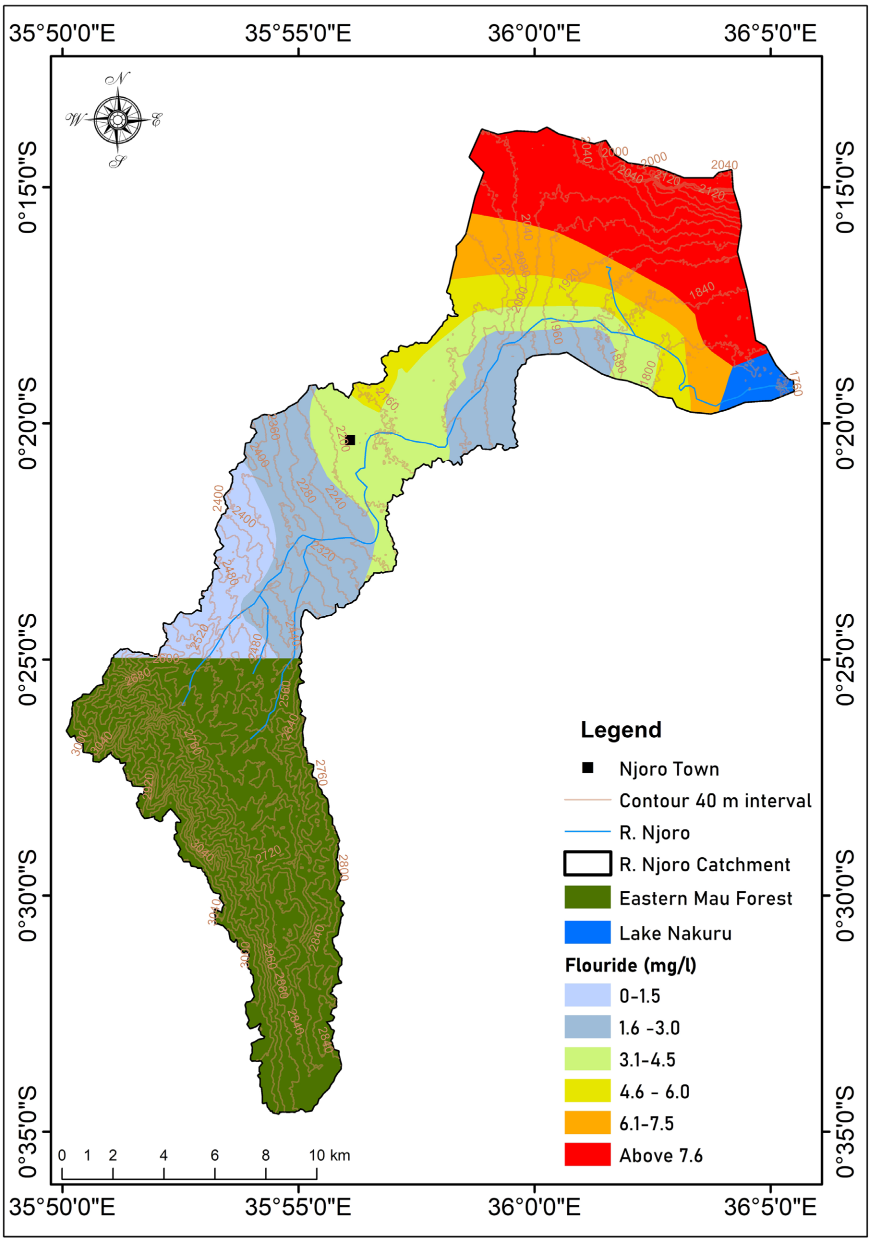

Figure 3. Groundwater fluoride prediction map of river Njoro catchment. Source: Author.

The fluoride levels along River Njoro sampling points showed that Kwa Rhodah, KERMA, and Tumaini Bridge points showed the highest fluoride levels while the upstream points at Ndarogo, Sigaoni, and Kwa Maisori, to the contrary, showed low levels of fluorides in the water. Generally, most of the sampling points within the River Njoro had fluoride levels in the range of 0 - 1.5 mg/l. On the other hand, boreholes with high fluoride levels of the 9.5 mg/l and above were recorded at Kiamunyi and Pistis boreholes. In comparison, average fluoride levels in the classes between 3.00 mg/l and 9.5 mg/l were recorded at Beston, Mogon, Njoro Canning, Njoro Sunrise, Kwa Annah, Mother Kelvin, and Ainabtich Mogon boreholes. Finally, low levels of below 3 mg/l were recorded at Ngata Mbaruk, Nesuit Primary, and Umoja Kikapu. Finally, the validation by the Kriging model on fluoride distribution confirmed that the fluoride levels from the neighboring boreholes were within the ranges of the model prediction. Compared to the average fluoride levels in sampled boreholes and the average recorded fluoride levels in the predictor boreholes, a mean variation of 0.382 mg/l, −0.401 mg/l, and 0.395 mg/l in the downstream, midstream upstream catchments, respectively.

The average fluoride levels of both the predictor and sampled boreholes located downstream were 8.859 mg/l, while the average midstream was 5.851 mg/l and upstream catchment recorded 3.936 mg/l. The average fluoride level results for both boreholes were used in geostatistical analysis and prediction of spatial fluoride distribution. The results of the Geostatistical analysis helped produce the groundwater fluoride prediction map of the River Njoro Catchment presented in Figure 3. The simulation of spatial fluoride distribution data of the sampled and predictor boreholes in the River Njoro catchment using the Kriging model achieved 79.2% similarity. Therefore, there was no great variation in the mean and the covariance of the predictor and sampled boreholes.

5. Discussion

Despite water sampling for fluoride analysis in this study being done during the rainy and dry periods as guided by the study design, fluoride levels in the boreholes remained higher beyond the WHO recommended levels. In the River Njoro catchment, this study observed that the spatial distribution of fluoride concentrations showed high fluoride levels of 19.369 mg/l at Pistitis and its environment, located downstream of the River Njoro catchment. Fluoride distribution in this study helped identify and delineate areas with fewer fluoride levels as per the WHO standards. Elevated fluoride levels beyond the WHO limits in the catchment of River Njoro catchment would be attributed to the presence of basaltic rock formations and volcanic materials containing high fluoride concentrations. Volcanic ash is one of the fluoride-rich rocks that emanate from the Menengai crater's eruption in the neighborhood of the study area. The released volcanic rocks from the crater contaminated groundwater in the Njoro catchment with elevated fluoride levels.

Findings from this study pointed the high levels of fluoride could be attributed to weathering and percolating of minerals whose origin would be traced to rocks whose origin is volcanic in nature with high fluoride concentrations. The Rift Valley floor is where most of the boreholes recorded high fluoride levels are regions experiencing active volcanism. The high levels of fluoride in the boreholes would be associated with the contact of the water with high fluoride volcanic bearing rocks. The main rocks that formed the aquifer of the sampled boreholes in the River Njoro catchment with high fluoride levels included: volcanic soils, tuff, and trachyte. These sentiments are supported by [16], who asserts that the majority of the world zones associated with fluoride contamination occur in granite-dominated terrains or fluoride-dominated sedimentary aquifers.

Like in the scenario in the River Njoro catchment [23], in their study in Tanzania, observed that the spatial variation of fluoride in river catchments is varied. The distribution is a function of levels of fluoride underlying the river channels and several other chemical reactions that result in alterations in the pH in the environment. Further, [24] asserts that groundwater interaction with surface water patterns and external inputs such as surface runoff, salinity, and climate change also determine fluoride levels. Additionally, studies on surface water reported fluoride levels of 12 - 13 mg/l in Maji ya Chai and 690 mg/l in Engare Nanyuki Rivers [25].

The study by [24] justifies the various distribution of fluoride levels in the environment. [26] observe that high pH, varying levels of calcium, groundwater having high temperatures, and desert-like climatic conditions of an area increase make fluoride-bearing rocks dissolve, resulting in high fluoride concentrations. In this study, water samples from areas having minerals bearing elevated fluoride levels had high levels of fluoride. The results have similarities with past studies; [27] observed that areas dominated by: fluorapatite, fluorite, topaz, phlogopite, and lepidolite minerals dominate places with fluoride-contaminated water. These minerals are water-insoluble, making them discharge fluoride ions to the river and borehole water sources depending on variations in temperature and alkalinity, which contribute to their solubility [27].

Ethical Compliance

Procedures performed in this study did not involve or have human participant; Moreover, sampling of the water was done without contamination of the boreholes as per the set-out sampling protocol.

Conflicts of Interest

The author declares that he has NO affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

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