Journal of Applied Sciences

ISSN 1812-5654

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Journal of Applied Sciences 12 (13): 1345-1354, 2012
ISSN 1812-5654 / DOI: 10.3923/jas.2012.1345.1354

Effect of Long-term Pumping on Fluoride Concentration Levels in Groundwater: A Case Study from East of Blue Nile Communities of Sudan

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Abstract: Many studies reported that groundwater constituents are not always stable during long-term pumping. This study conducted to investigate fluoride ion (F^-) trend in some boreholes in the study area. A total of 26 boreholes were analyzed and compared with the Construction Analyses (CA). The data from CA and Study Analysis (SA) were graphed and trends of F^- levels were prepared. The consequent results revealed that, in general, F^- levels decreased in almost all of the investigated boreholes. Only one borehole exhibited of F^- ion concentration level from 0.7-0.9 mg L^{-1} (4.3% increasing rate per year) while another borehole showed a negligible decrease of F^- concentration level, from 2-1.9 mg L^{-1} (0.2% decreasing rate per year). In general, decreasing rates of F^- concentration levels were almost observed in communities with intensive population in the study area. This study attributed the decreasing rate of F^- concentration levels in boreholes of the study area to the continuous withdrawal of groundwater that eventually washing up and depleting F^- content in aquifers. Researchers should be advised to develop and use the "fluoride trend method" used in this study to determine F^- concentration levels previously registered in well water and to properly pinpoint the exact F^- concentration level providing the threshold of dental fluorosis prevalence among schoolchildren.

Key words: Groundwater fluoride trend, dental fluorosis, Blue Nile, Sudan

INTRODUCTION

The quality of groundwater is the result of all the processes and reactions that act on the water from its condensation in the atmosphere until discharging in a well or spring (Naeem *et al*., 2007). The most well-known and documented area associated with volcanic activity reported by Helmut and Redda (1999) that follows the East African Rift System from the Jordan valley down through Sudan, Ethiopia, Uganda, Kenya and Tanzania.

In general, Fawell *et al*. (2006) documented that the F^- concentration levels in groundwater are affected by several factors: availability and solubility of fluoride-containing materials, porosity of the rocks or soil through which water passes, residence time and temperature, the hydrogen ion concentration of the water and the presence of other elements which may complex with F^- ions. Concentrations of F^- in water are limited by F^- solubility, in presence of 40 mg L^{-1} calcium; F^- concentration should be limited to 1-3 mg L^{-1}. The absence of calcium in solution allows higher concentrations to be stable. High F^- concentration levels may, therefore, be expected in groundwater from calcium-poor aquifers and in areas where fluoride-containing minerals are common. Fluoride levels may also increase in groundwater in which cation exchange between sodium and calcium occurs. In general, the deeper groundwater has the higher F^- concentration levels.

It is documented by Shanthakumari *et al*. (2007) that F^- in groundwater has drawn worldwide attention and widely discussed due to its remarkable impact on human physiology and the environment. Fluoride can positively or negatively affects human health. The beneficial effects of F^-, when found at optimal concentrations in drinking water, is the teeth protection against dental caries, but excessive exposure to high F^- concentration in drinking groundwater, or in combination with exposure to F^- from other sources, can elevate the risk to a number of wide range adverse effects (Ekstrand *et al*., 1988; Jawed *et al*., 2006; Goyal *et al*., 2011; Adebayo and Adenuga, 2012). In general, F^- has been described as a double edged sword, because both deficient and excessive consumption of F^- causes completely different results (Shanthakumari and Subramanian, 2007; Al-Omireeni *et al*., 2011). Fluoride can be eliminated from drinking groundwater by: Adsorption, ion exchange, coagulation-precipitation and membrane process (Mahmood *et al*., 2007; Abdellah, 2011).

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In general, Al-Redhaiman and Abdel Magid (2002) and Munday and Andrew (2008) blamed over-exploitation and excessive water pumping among the other factors, for high salinity in groundwater. Increasing levels of TDS, generally, in some groundwater areas are usually caused by the intrusion of high salinity water due to over-exploitation in aquifers adjacent to seawater or by the replacement of low salinity water with high salinity water in evaporated temperate climates (Driscoll, 1986). On the other hand, Abdellah *et al*. (2012) demonstrated the decrease of TDS level by over exploitation in some aquifer located in Al-Butana region of Sudan. No data have been found in the literature concerning solely F^- ion changes in well water during discharge over time. The unique exception is the study by Abdellah (2011), who reported that concentration of naturally occurring F^- can becomes dangerously high as the amount of water dwindles. Therefore, this study was conducted to investigate the changes of F^- ion concentration levels in groundwater during long term excessive pumping in order to help to back-determine the exact F^- ion level being responsible for the threshold of dental fluorosis prevalence.

MATERIALS AND METHODS

Location and topography of the study area: The study area is confined by longitudes 32 45' and 33 45'E and latitudes 14 15' and 16 00 N and is located to the east of the Blue Nile river and its tributary the Al-Rahad river. This area is bounded from the east by upstanding Basement Complex rocks. The slope of the study area is from the northeastern side towards the southwestern one, where the Blue Nile River is situated. The study area contains many 'Khors' and 'Wadies' which drain into the Blue Nile River during the rainy season. It is divided, administratively, into three regions as follows:

- The whole area of the Locality of East of Gezira, Gezira State
- The area of the Western Administrative Unit of the Locality of Umelghura, Gezira State
- The area of the eastern part of Locality of Shark-El-Neel which comprises Umdawanban, Wadtlossona and Abu-Deleig administrative units, Khartoum State. The plan of the study area is presented in Fig. 1

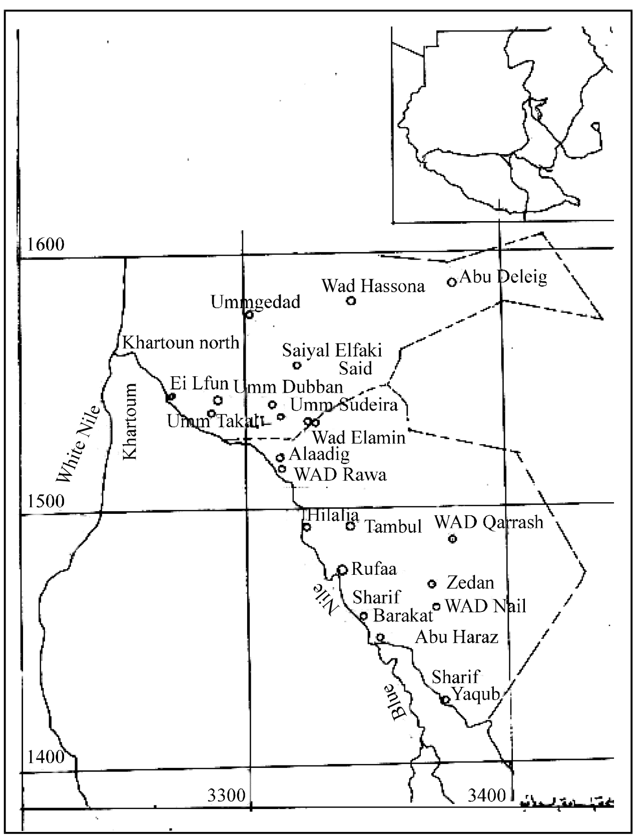

Fig. 1: Location map of the study area, East of Blue Nile River of Sudan (1 cm = 18 km) Source: Sudan National Survey Authority, prepared for the current study

Climatic and geological characteristics of the study area: According to Oliver (1965), the study area is located within the northern part of the poor savannah belt through a semi-desert region, characterized by a short humid rainy climate, hot summer and dry winter. Temperature is generally high and reaches its maximum during the hot season, April to June, when the dry hot north wind is dominant. The maximum mean temperature reached in April and May and reached its minimum in December. Rainfall is associated with the northward and southward movement of the Inter-tropical Convergence Zone (ITCZ). In July and August the ITCZ is situated near its northern limit in the Atbara area (16° 43'N, 34° 00'E). Cool moist air prevails in the south of the ITCZ and is probably derived from the Indian Ocean and the South Atlantic Ocean; however, dry air prevails in the northern zone. The area is characterized by a short wet season in mid-summer and a long dry season throughout the rest of the year. The mean relative humidity varies from a minimum of 16% in winter (April) to a maximum of 60% during the rainy season (August). A secondary peak also occurs in December, the coolest month of the year. The open nature of the area and free movement of the air accelerate evaporation. The mean relative humidity varies from a minimum of 25% in April to a maximum of 65, 74 and 72% during the rainy season (June, August and September), respectively.

The geology of the study area consists of the basement complex in the middle and to the southeast; Nubian Formation in the west and south, the central region is a basement complex with flat surface; with only a few rocky hills breaking the monotony of flatness. The central part is plain clay with numerous water courses. Most of these watercourses form their own deltas and do not drain into nearby rivers. At the deltas of these watercourses or ‘Khors’, people usually cultivate sorghum crops (El-Hassan, 1981).

Soil and vegetation characteristics of the study area: The variation in the rainfall, together with variations in relief, drainage and parent materials produces clear local differences in the soil of the study area. The top soil is mid-brown gray friable clay with round quartz pebbles and stone fragments. Cracks are not large but medium in size and more abundant in the soil under grass. The soil is a medium to fine textured tight clay, sandy clay or silt clay which contains more than 40% expanding clay. Recent alluvium provides bases for productive agriculture in the narrow Nile Valley and elsewhere soils are sandy with little agricultural potential (Khalil, 1986). In general, the description of the dense vegetation life in the past and partially scattered in recent decades, can be summarized as follows: (*Acacia mellifera)* ‘Kittir’, (*Acacia seyal*) ‘Taleh’, (*Acacia nubica)* ‘Lota’, (*Faidherbia albida)* ‘Haraz’, (*Acacia tortilis*) ‘Seyal’, (*Acacia nilotica*) ‘Sunt’, (*Balanites aegyptiaca)* ‘Hegleig’ and (*Cymbopogon proximus*) 'Maharaib' (Harrison, 1955).

Economic activities and population in the study area: In past centuries, agricultural activities were limited and confined to small areas nearby the Blue Nile River. In the rainy season, far from the river, some of the inhabitants used to herd animals and to grow durra for their own supply and subsequently, communities were established. In recent decades, agricultural schemes were introduced and the communities were enlarged.

According to the 1993 census, the population is about 69827 people in the whole study area. In the last census (2008), the population has increased to 414437 (33% per year). As consequent, there has been a great increase in demand for drinking groundwater. The expansion of population in the study area depends very much on the availability of adequate palatable and safe supplies of drinking groundwater.

Water supply in the study area: In the past, the communities in the study area were having their own water supplies from hand-dug wells. The depth to groundwater varies for each well, increasing according to its distance to the Blue Nile River until completely disappearing in the extreme north of the study area, where ‘Hafirs’ pools are constructed to solve the problem of lack of groundwater. Deep boreholes were introduced in the study area during the 1960s and spread throughout the study area for few years later. Groundwater availability is greatly dependent on both the distance from the Blue Nile and the hydrogeological characteristics of aquifers (Abdellah, 2011).

Samples and data collection: A total of 26 samples were collected from water wells of well-known documented data using 250 mL plastic bottles, each bottle was rinsed with the same water 3-4 times before filling. Samples were collected directly from the outlet point of the well, if possible. Otherwise, samples were collected from reservoir or from the nearest water-tap to groundwater source. The computerized hydro-geological information and the CA of boreholes were obtained from the archives in the Information Center of Groundwater Directorate in Khartoum, the National Institute for Drilling at Wad-Medani and the Water Corporation of East Gezira; Rufaa’ Town.

Chemical analyses of fluoride concentration: The analyses were carried out according to the Standard Methods for the Examination of Water and Waste Water (Eaton *et al.*, 1998). In this method fluoride concentration in groundwater samples is determined by Alizarin Visual method. This method is based on the reaction between F^- and a zirconium-dye lake. Fluoride reacts to Dye Lake, dissociating a portion into a colorless complex anion $(ZrF_6)^{2-}$ and the dye. As the amount of F^- increases, the color produced becomes progressively lighter in comparison with control samples containing different fluoride concentrations.

RESULTS AND DISCUSSION

It has been reported by Bell *et al.* (1970) that the F^- concentration levels in groundwater is widely dependent on the availability and solubility of the parent F^- minerals with which groundwater is in contact, the porosity of rocks through which the water flows, the hydrogen ion concentration of groundwater, the temperature of the interaction between rock and groundwater and the concentration of calcium ions in the groundwater. Furthermore, the daily pumping rate of groundwater can also contribute to F^- levels of the well water. Table 1 shows that comparison between F^- concentration levels in the SA data with those in the CA data of the same well water samples showing that the daily pumping rate decreases F^- concentration levels in groundwater of the study area. According to Table 1, it is clear the groundwater F^- concentration level decreases as the groundwater pumping rate increases.

Comparison of the mean value of the CA data (1.4 mg L^{-1}) with that of the SA data (0.6 mg L^{-1}) (Table 1) demonstrates the general decrease of F^- level in the investigated boreholes in the study area. Continuous pumping of groundwater may wash the F^- ion from aquifer rock formation. Furthermore, underground seepage from the Blue Nile may contribute to the dilution of the groundwater F^- concentration levels in the study area. On the other hand, low water pumping may increase the contact time between groundwater and hosted rock and thus creating more chances to dissolve F^- into the groundwater.

To study, precisely, the trends of F- concentration levels in a particular well water after long-term pumping-time, the drilling analytical data and subsequent periodical analyses of the well water are necessary and required. Due to lack of periodical analyses of boreholes in the study area, we only used the previous CA data and

Table 1: The tendency of groundwater F^- levels during discharge time in some boreholes in the study area (n = 26)

Name of village	Date of drilling (CA)	F^- level in CA (mg L^{-1})	F^- level in SA (2008) (mg L^{-1})	F^- total decrease (mg L^{-1})	F^- mean decrease per year (mg L^{-1})
Gozelahamda	3,2,1976	0.3	0.1	0.2	0.01 (3.3%)**
Sayal-Attay	13,6,1988	0.5	0.4	0.1	0.01 (1%)
Wadennour	8,7,1971	0.4	0.3	0.1	0.003 (0.8%)
Damgadkrem	25,4,1972	0.7	0.6	0.2	0.004 (0.8%)
Elteragma	9,10,1971	1.0	0.3	0.8	0.02 (2%)
Abugalfa	9,2,1978	0.4	0.3	0.2	0.01 (1.3%)
Sharafa-brkat	4,4,1987	0.3	0.2	0.1	0.01 (1.7%)
Umhiryzat	1,7,1971	1.0	0.5	0.6	0.014 (1.4%)
Almegareet-1	29,5,1972	1.8	1.0	0.8	0.022 (1.2%)
Tamboul-1	30,1,1978	0.9	0.8	0.1	0.003 (0.3%)
Banat	30,1,1978	0.7	0.2	0.6	0.02 (2.6%)
Aidaj	12,1,1978	2.0	1.9	0.1	0.003 (0.2)
Fadniabyoda*	16.1.2001*	0.7*	0.9*	0.2*	0.03 (4.3%)*
Sialesawra	1.8.1990	1.4	0.6	0.8	0.04 (2.9%)
Altikalat	11,1,1986	1.4	0.5	0.9	0.04 (2.9%)
Amara-Ali	18,6,1971	1.0	0.6	0.5	0.01 (1.2%)
Gurra-tay	5,4,1993	0.8	0.1	0.7	0.1 (5.9%)
Hillat-Idrees	3,1,2001	1.0	0.6	0.5	0.06 (6.4%)
Doma-Isalat	20.11.2001	0.8	0.5	0.3	0.04 (5%)
Alwan Ibrahim	21.9.1999	0.9	0.4	0.5	0.06 (6.7%)
Mstfa-Fadni	26.12.1973	1.1	0.5	0.6	0.02 (1.8%)
Alfadnia-North	22.8.1998	1.5	1.2	0.3	0.03 (2%)
Umdwanban	8,10,1970	1.6	1.1	0.5	0.01 (0.8%)
Umdwanban	27,10,1978	1.4	1.1	0.3	0.03 (2.1%)
Rufaa-2	11,10,1986	0.2	0.0	0.2	0.01 (4.5%)
Rufaa-3	9,10,1986	6.0	0.6	5.4	0.3 (4.1%)
Ahamda-fresh	16,10,1999	7.0	2.5	4.5	0.5 (7.1%)
Mean	1983	1.4	0.6	0.8	0.1 (2.5%)
Range	1970-2001	0.2-7	0.0-2.5	0.1-5.4	0.003-0.5 (0.2%-7.1%)
SD	11	1.7	0.6	1.1	0.01 (1.95%)

* In this borehole F^- level in SA is greater than in CA. ** Percentages in parenthesis indicate total decrease per year

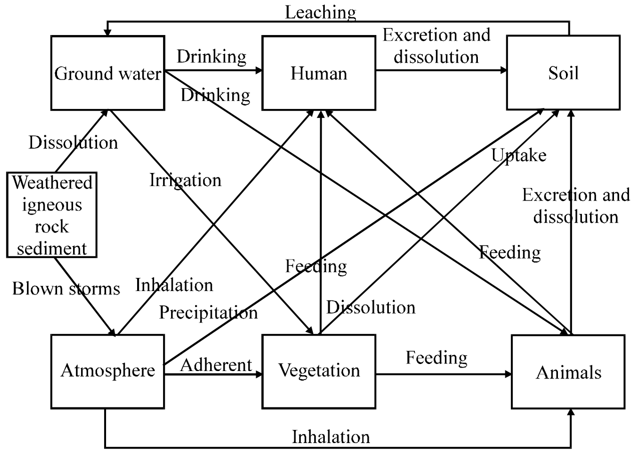

Fig. 2: The F^- route in the study area, East of Blue Nile of Central Sudan, as visualized in this study

compared with SA in order to pinpoint the backdated history of F^- concentration levels. Therefore, the F^- trends during pumping time are obtained as a straight line. The behavior of this line beyond the SA point is, by far; depend on the sustainability of the F^- source and pumping rate of the withdrawal water.

Fluoride trends in Alteragma, Umhiryzat and Amara Ali villages: The three boreholes drilled in the villages of Alteragma, Umhiryzat and Amara Ali was selected for studying the F^- trend. These boreholes were drilled in the same year of 1971 and have the same F^- concentration level of 1.0 mg L^{-1} in the previous CA data. In the current SA, the F^- concentration level for each of the three boreholes decreased during pumping time. The decreasing rate of F^- concentration level varies for each borehole (Fig. 3). The borehole drilled in Alteragma village exhibited a drastic decline of Depletion Rate (DR) of F^- during pumping time and F^- decreased from 1.0 mg L^{-1} (CA) to only 0.25 mg F^- L^{-1} at the time of the current SA. Accordingly, the F^- concentration in this borehole may reach zero F^- concentration level at the expected Depletion Date (DD) in the year 2020 (assuming that pumping rate and other effective factors are constant). Comparatively, the borehole drilled in Umhiryzat village exhibited a moderate decline of DR of groundwater F^- levels and the F^- levels decreased from 1.0-0.45 mg L^{-1}. The expected DD of F^- level is probably during the year 2039. A mild decline of F^- concentration can be observed in the borehole situated in Amara Ali, the F^- levels decreased from 1.0-0.55 mg L^{-1} in drinking groundwater in the current study. The expected DD of this borehole may be during the year 2055.

Fluoride trends in Mustafa-Fadni and Doma-Isalat villages: Figure 4 represents two different types of F^- trends of two boreholes. The Borehole situated in Mustafa-Fadni was drilled in 1973 and has previously registered F^- concentration levels of 1.1 mg L^{-1} and recently registered concentration levels of 0.5 mg L^{-1}. The F^- DD of this borehole is expected to be during the year 2041. Comparatively, more drastic DR has been observed in borehole located in Al-Doma-Isalat which has been drilled in 2001. Groundwater F^- levels of this borehole were declined from 0.8 mg L^{-1} in CA to 0.5 mg L^{-1} in SA. The borehole situated in Al-Doma-Isalat village exhibited a drastic decline of F^- concentration levels in comparison with the borehole in Mustafa-Fadni. The DD of the borehole situated in Doma-Isalat may be within the year of 2020.

Fluoride trends in Rufaa' and Umdwanban towns: The most drastic drop in groundwater F^- concentration levels were observed in Fig. 5 which represents the F^- trend of the borehole drilled in Rufaa' Town in 1986. Previous construction analysis of this borehole registered 6.0 mg L^{-1} in drinking groundwater while in SA the F^- concentration in this borehole registered only 0.57 mg F^- L^{-1}. The expected DD for this borehole is expected to be already ended during the year 2010. This drastic decrease in groundwater F^- concentration may be attributed to geological factors related to the aquifer formation (low solubility of fluoride parent-rock) or/and may be washing out by the high pumping rate which accelerates washing-off fluoride formation source in this type of aquifer or probably the two factors acting together. On the contrary, very mild decrease in

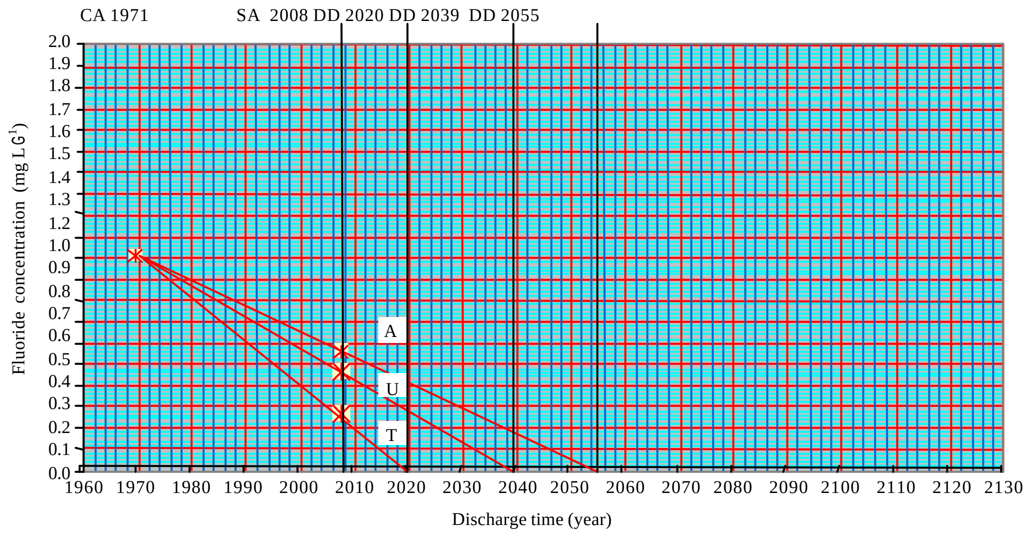

Fig. 3: Fluoride trends of the boreholes drilled in Alteragma, Umhiryzat and Amara Ali villages, CA: Construction analysis, SA: Study analysis, T: Alteragma village, U: Umhiryzat village, A: Amara-Ali village, DD: Depletion date of fluoride

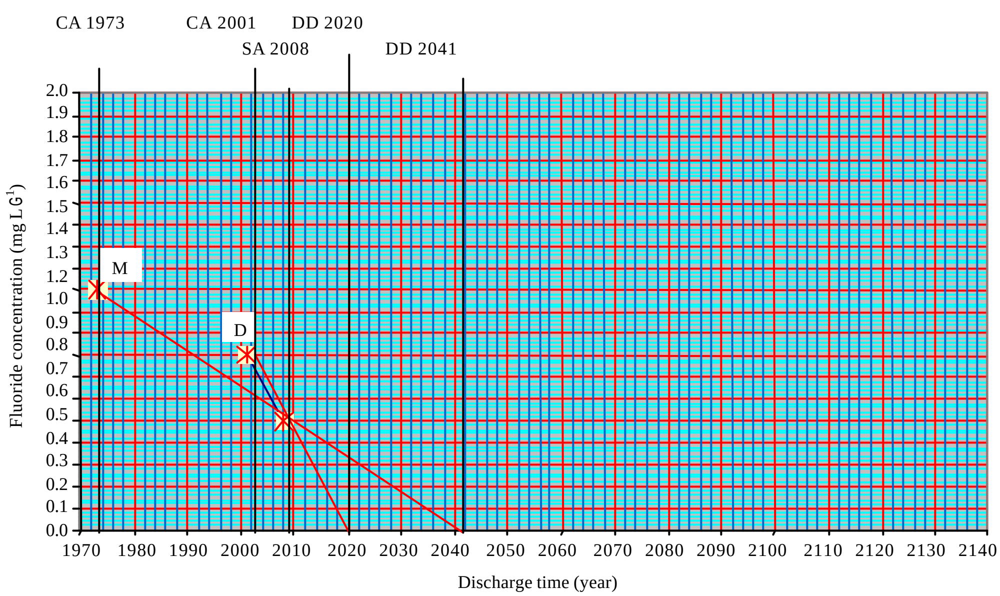

Fig. 4: Fluoride trends of the boreholes drilled in Mustafa-Fadni and Doma-Isailat, CA: Construction analysis, SA: Study analysis, M: Mustafa-Fadni, D: Doma Al-Isalat, DD: Depletion date

groundwater F^- levels can be observed in the borehole situated in Umdwanban Town which exhibited 1.1 mg L^{-1} in SA while the CA of this borehole was 1.4 mg L^{-1}. The DD pointed to some year beyond the scope of this diagram. Slight decrease of F^- level in this borehole may be attributed to rich-fluoride formation source in the aquifer where the borehole was drilled.

Fluoride trends in Magareet and Fadnia north villages: Comparatively, in Fig. 6, moderate decline of F^- concentration level in drinking groundwater is observed in boreholes situated in Magareet village that was drilled in 1972 and Fadnia North which was drilled in 1998. Previous CA of Magareet borehole was registered 1.8 mg L^{-1} and recent SA has registered 1.0 mg L^{-1} while the Fadnia North borehole registered 1.5 mg L^{-1} previous

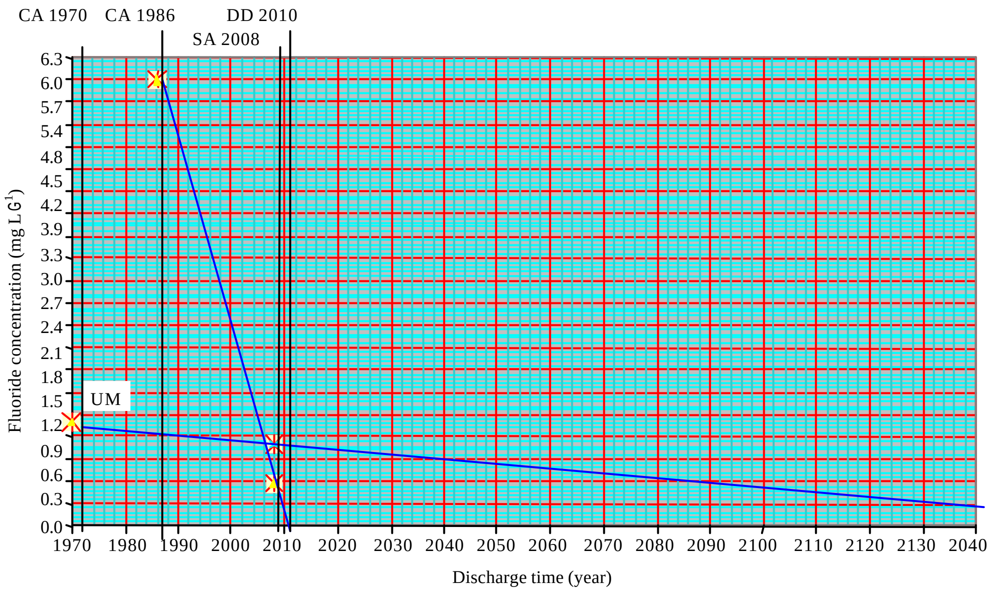

Fig. 5: Fluoride trends of the boreholes drilled at Umdawanban village and Rufaa' Town, CA: Construction analysis, SA: Study analysis, UM: Umdwanban, RF: Rufaa town, DD: Depletion date of fluoride

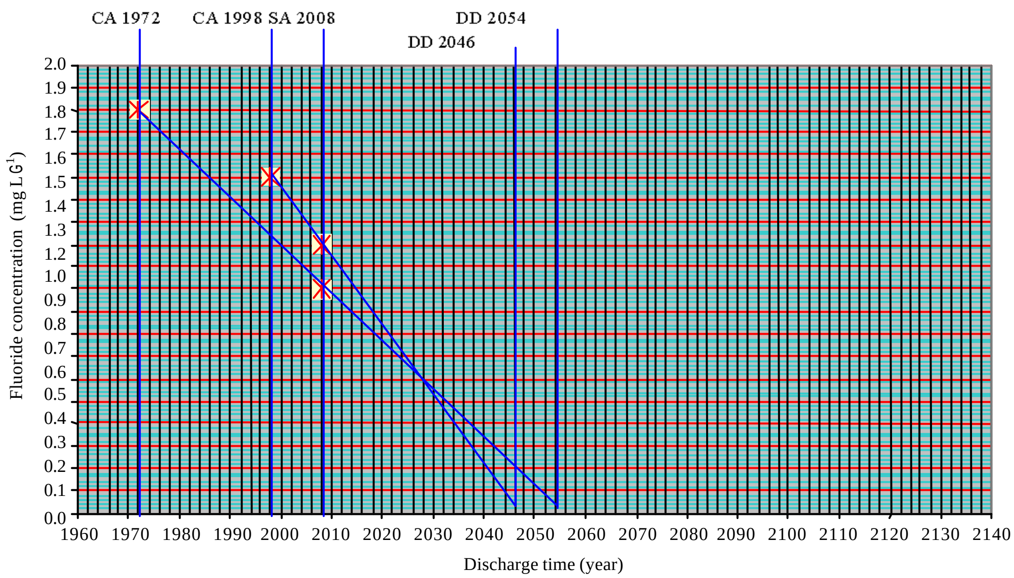

Fig. 6: Fluoride trends of the boreholes drilled in Magareet and Fadnia North villages, CA: Construction analysis, SA: Study analysis, MG: Magareet village, FN: Fadnia North

CA and 1.2 mg L^{-1} in recent SA. The trends performed for F^- DDs have pointed to 2054 and 2046 for these boreholes, respectively.

Fluoride trends in Aidaj village: A very-hard-detectable decrease of F^- in groundwater is observed in Fig. 7 which revealed a negligible decrease in the groundwater F^- concentration in the borehole takes water supply from the aquifer beneath Aidaj village. The previous CA of this borehole was registered 2.0 mg L^{-1} while the recent SA has registered 1.9 mg L^{-1}. The DD of F^- in this borehole is out of the scope of this diagram.

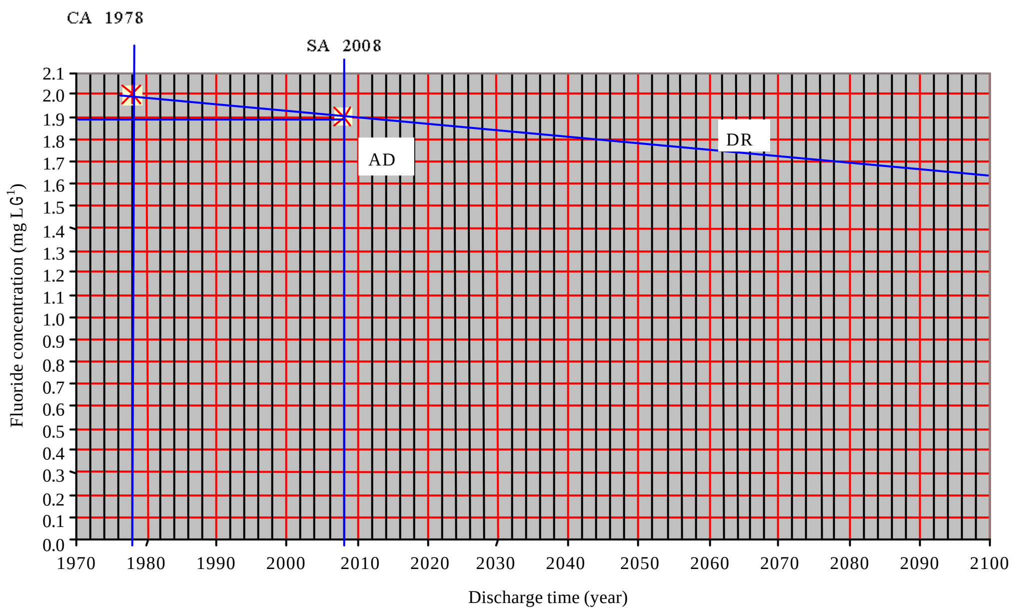

Fig. 7: Fluoride trend of the borehole drilled in Aidaj village, CA: Construction analysis, SA: Current study analysis, AD: Aidaj village, DR: Depletion rate of fluoride

Fluoride trends in Fadniabyoda village: Figure 8 showed an abnormal F^- trend that was observed in a borehole situated in Fadniabyoda village. This borehole was drilled in 2001 and the previous CA for F^- was registered to be 0.7 mg L^{-1} while the current SA figure for F^- concentration level is 0.9 mg L^{-1}. This result may be justified as follows: The low pumping rate in this small village may have created more chances for F^- to be dissolved into groundwater or maybe there is an active F^- geological formation source which accelerated F^- solubility into the groundwater underlying this village. In general, F^- trend for borehole in Fadniabyoda village needs further investigation in the future to confirm this contradictory result.

The ‘fluoride trends method’ has not been reported in the literature before, either locally or internationally, in spite of its importance in the determination of F^- concentration trend in term of time. The diagrams of fluoride trend can help to determine the exact backdated F^- level in a particular groundwater well in a community. Representative fluoride-trends lead to the real groundwater F^- concentration that may actually mark the threshold of dental fluorosis prevalence in a definite particular community. Some researchers might have mistaken, when investigating dental fluorosis prevalence among school children, by accepting the recent F^- concentration in groundwater supply without referring to the previous periodical analyses of F^- concentration. The concentration of naturally occurring ions (e.g., fluoride) can become dangerously high as the amount of water dwindles (Abdellah, 2011). In contrast, as cited previously in this study, F^- concentration in a particular well is not always constant; it generally decreases during discharge time. Therefore, recent F^- concentration in a particular well does not mean that this is the same concentration of the previous year or years. For example, when we investigate dental fluorosis among 12 years old children, we must refer to 3-4 years earlier (the time when the teeth were erupting) and point out, from fluoride trend diagram, the exact F^- concentration that corresponds to the year when the participant ingested fluoride. The fluoride trend method helps to determine the maximum F^- level in drinking groundwater that is responsible for the threshold of dental fluorosis prevalence. For example, in this study, by referring to Fig. 8 and Plate 1, the real F^- concentration that caused dental fluorosis to this child was 0.57 mg L^{-1} which corresponds to the year 2001 when the child was 8 years old. Noteworthy that El-Nadeef and Honkala (1998) attributed the high prevalence of dental fluorosis in Nigerian children to factors other than the F^- levels in water. In addition, Mahvi *et al.* (2006) recommended that other sources of fluoride should be considered when planning programs in public health dentistry. Therefore, when determining the safe limits of fluoride concentration levels, any other sources of fluoride should be considered. The probability of F^-

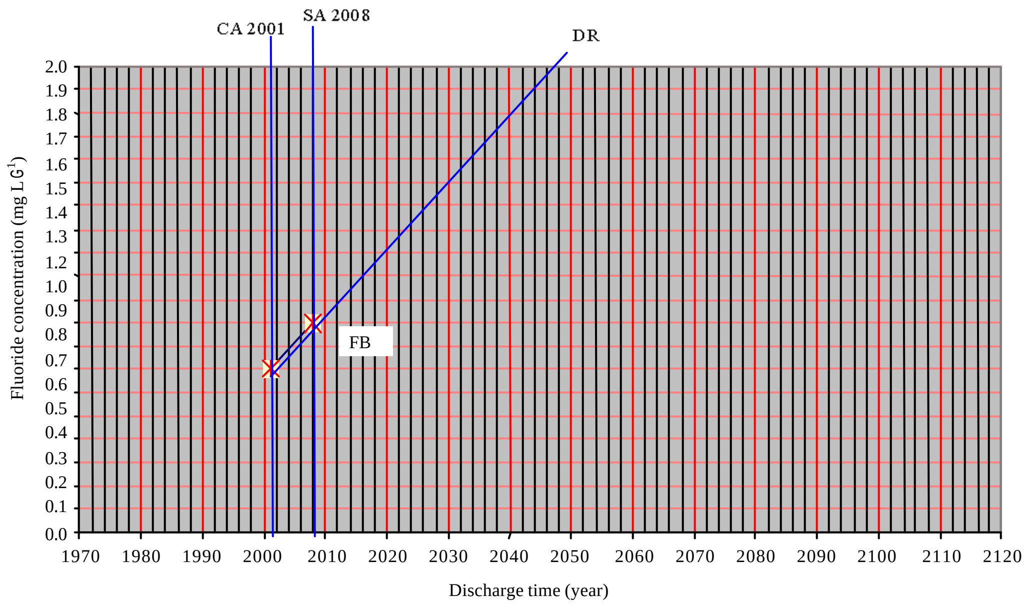

Fig. 8: Fluoride trend of the borehole drilled in Fadniabyoda village, CA: Construction analysis, SA: Study analysis, FB: Fadniabyoda village, DR: Dissolution rate of fluoride

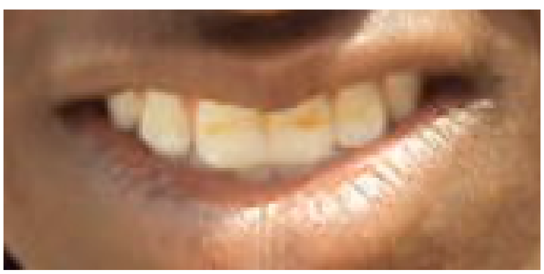

Plate 1: Mottled teeth of a child aged 15 years permanent resident in Umhiryzat village (Fig. 3) consuming well water containing 0.45 mg L^{-1} fluoride (2008) with previous construction analysis (1971) of 1 mg L^{-1} fluoride

sources other than groundwater that may probably contribute to dental fluorosis prevalence in the study area can be summarized in the following two points:

- Consumption of F^- that had already accumulated into crops and vegetables tissues. It has been demonstrated that various vegetable plants accumulate F^- in roots and tissues (Elhadi, 2004), especially in vegetables that are usually grown in soils of high F^- content or irrigated with water containing high F^- levels
- Ingestion of F^- via high consumption of tea and feeding on animal meat. Tea and animal meat are considered another potential F^- sources that largely contribute to the overall ingested F^- by human body (Adler *et al*., 1970)

In general, in this study, we summarized the relationship between human and the probable F^- sources that may affect dental fluorosis prevalence (Fig. 2).

Conclusions and Recommendations: Fluoride concentration levels of the investigated boreholes in the study area are continuously decreasing during discharge time. Trends in some boreholes showed drastic Depletion Rate (DR) while in others, the fluoride trend showed a relatively moderate DR. Researchers are advised to use "fluoride trend method" in determining the allowable (permissible) maximum level of fluoride concentration in drinking water that marks the threshold of dental fluorosis prevalence among school children. Noteworthy that the availability of other sources of fluoride must be considered while determining optimal fluoride levels.

ACKNOWLEDGMENTS

The authors acknowledge the assistance of the staff members of the Groundwater Directorate. We are gratefully indebted to the Head of the Department of

Water and Food Chemistry of the National Laboratory Dr. Adam Ali and his staff members for their kind welcome and the unlimited help that has been given during laboratory analysis.

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