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Impact of wastewaters on groundwater quality of Bani Al-Hareth and Arhab areas in northern Sana’a city, Yemen

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ABSTRACT

The purpose of this research is to determine the impacts of wastewater effluents on groundwater quality of the northern suburbs of Sana’a city. Fourteen duplicate groundwater and wastewater samples were collected from the study area and analyzed. The groundwater samples were analyzed for major elements, and anionic and cationic groups using Atomic Absorption Spectrophotometer (AAS). The wastewater samples were analyzed for Total Coliform (TC), Fecal Coliform (FC), and oxygen demands. For characterizing the groundwater and wastewater qualities of the study area, analysis results were tabulated, statistically treated, and elements and ionic groups were graphically plotted on diagrams and on the Piper well known diagram. The analysis results had shown that some groundwater samples were chemically and biologically contaminated. Moreover, the effluent wastewater samples had shown that all samples contain greater Fecal Coliform (FC) bacteria count and high ammonia content. In addition, the effluent wastewaters are featured with high COD and BOD, reflecting low quality wastewater effluent for the WWTP. Sludge and wastewaters used by farmers, containing high pathogens and parasites, have created or will create significant environmental and health hazards. Similarly, land resources, infrastructure and groundwater quality of the areas are highly, if not already, jeopardized or polluted. Such findings require further detailed studies for monitoring development of pollution in the area.

CONTENTS

1. **Introduction:**

Large volumes of rainwater runoffs mixed with wastewaters were repeatedly diverted away from Sana’a Wastewater Treatment Plant (WWTP) inflow gates due to the high volume and undesired quality of the mixed load, causing a potential damage to the plant. Consequently, the mixed loads had covered an open land strip and runoff channels, extending several kilometers downstream from the location of the WWTP, within Bani Al-Hareth and Arhab areas, in Sana'a Basin.

The purpose of this research is to determine the impacts of wastewater effluents on land and groundwater quality of the northern suburbs of Sana’a city, a region located just north of WWTP. The study region has an area of about 20 km^2, which includes Bani Al-Hareth area and parts of Arhab District, as shown in satellite imagery (Figure. 1), and relative topography with elevations, shown in Figure 2. Over the past few decades, such areas were found to be rapidly expanding in developed infrastructure, mainly homes, buildings, roads and others.

As part of Sana’a Basin, Sana'a city area, including the current study area, were subjected to accelerated anthropogenic, economic and social developments, especially during the past three decades. As a result, high rate of population growth (7% per annum), uncontrolled population movement into the area and expansion of infrastructure and industrial activities were observed. Thus, the demand for water has remarkably increased during the past 30 years (WEC, 2004). The increasing demands, however, meet limited resources. To satisfy the increased need for water, new groundwater wells have been drilled at various locations in the basin, and the abstraction from all groundwater sources has increased beyond the perennial yield of the Sana’a basin which led to a rapid drop of the groundwater level, ranging between 4 and 5 m/year (WEC, 2001). This problem seems even more serious when taking into account the gradual degradation of the water quality and marked drought events recorded in the country within the last few years. The overexploitation of the groundwater in the basin bears the risk of wells falling dry, a degradation of the water quality due to infiltration of sewage water, particularly in the shallow alluvium aquifer below and near the urban areas and in the deeper sandstone aquifer at the northern part of the basin, combined with increasing salinities due to intensive groundwater pumping. Furthermore, groundwater in the agricultural areas could be contaminated by the increased and uncontrolled application of fertilizers and pesticides. In a rather recent evaluation study of water resources in the country, Foppen (2002) predicted that the Sana’a basin would not only enter a phase of water deficit in the near future, but also attested that, if no remedial and immediate solution actions were undertaken to correct the deficit, water shortage in the basin could become a critical problem.

This study was conducted as per request of the Committee of Water and Environment, Yemen’s Parliament, to evaluate the potential extent of pollution on land and groundwater aquifer of Bani Al-Hareth and Arhab areas, as a result of repeated malfunctioning of WWTP, during heavy rain storm runoff flows during the year of 2004.

2. Geologic setting

At the beginning of the Jurassic period the sea transgressed towards the land of southern Arabia (Yemen), causing the deposition of Amran limestone rocks in a beach environment, supported by the presence of fossils in such rocks. Later, towards the end of the Jurassic period, the area was exposed to certain tectonic activities that eventually led to the emergence of Jabal Alsama and surrounding high hills in Arhab area, and consequently producing a descending area with it by forming a Graben fault, through which basaltic dikes and small faults are formed. At such period, the Khared valley, located further north, was probably formed, mainly as a result of deep erosion due to rain and stream waters. At later times, during Cretaceous, Tertiary and Quaternary periods, Tawilah Sandstone, stratified volcanics and erupted volcanoes were formed, respectively, within and nearby the study area (**Al-Subbary, 1990)**. Stratigraphically, the study area, as part of Sana’a Basin, is generally composed of Precambrian, Jurassic, Cretaceous, Tertiary and Quaternary rocks. The Precambrian metamorphic formations make the crystalline base, overlapped by a thick sequence of sedimentary and volcanic younger rocks (sandstone, limestone and basalts).

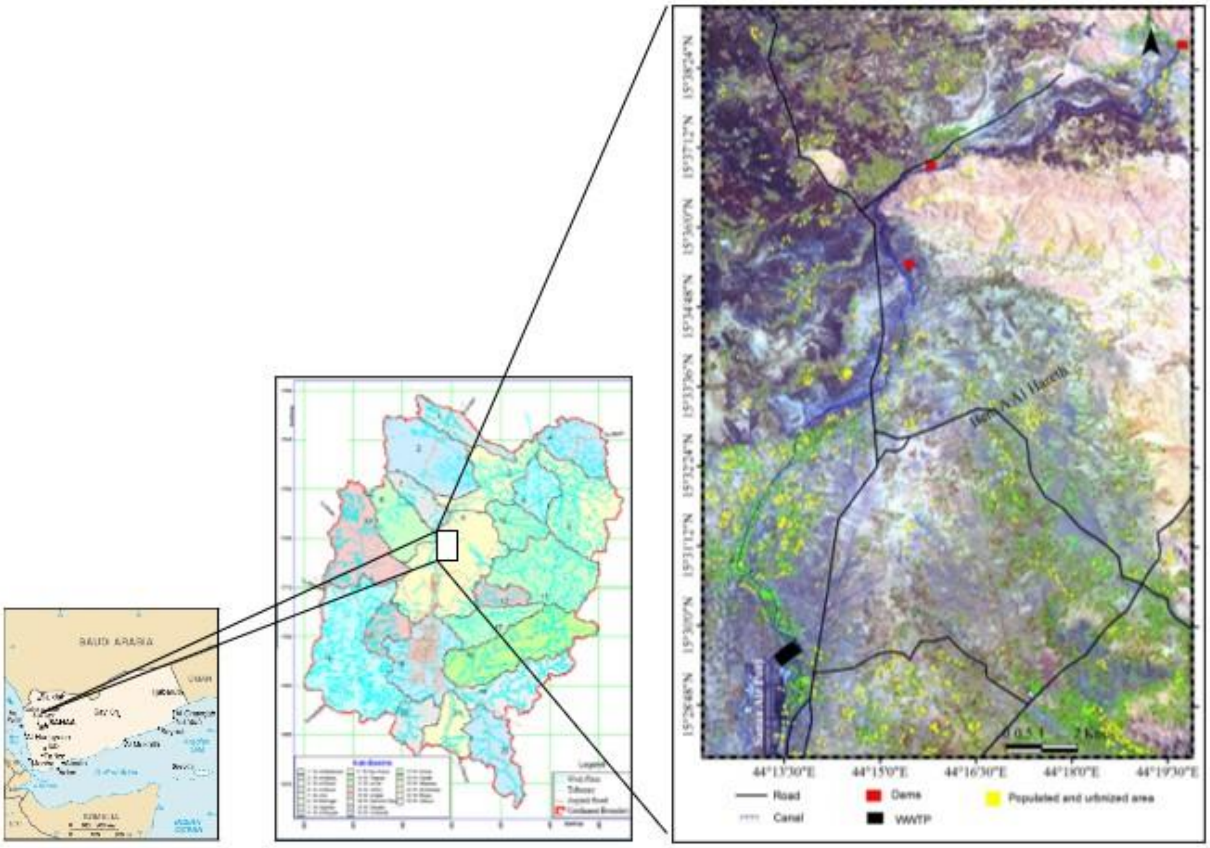

Figure. 1: Satellite imagery of the study area as a subset within Bani-Hawat sub-basin of Sana'a Basin.

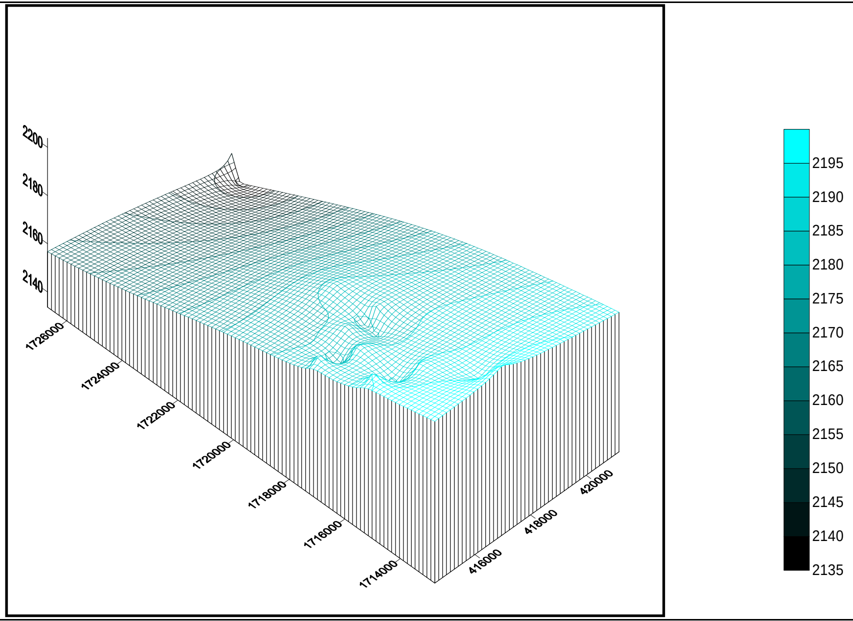

Figure. 2: Relative elevations above sea level (a.m.s.l) of the study area location and vicinity.

The oldest sedimentary formation in the region of Sana'a is the Amran Series (Middle to Upper Jurassic) which comprises limestone, marl and shaly limestone, approximately 350 to 1000 m thick. The Amran outcrops in the northern part of the Basin, covering about 15% of the Basin area. It occurs at depth beneath the Sana'a plain; at the airport the top of the Amran is approximately 350 m deep; at Ar Rawdah 500 m and further south near Sana'a city it is about 900 m or more.

The Tawilah Sandstone (Cretaceous to Tertiary) is exposed in many areas near Sana'a city, for example, at the northern, northwestern and northeastern suburbs of the city. It outcrops over about 15% of the Basin area in the northern part of the Basin It comprises a series of continental cross bedded sandstones generally medium to coarse grained with interblended mudstones, siltstones and occasional silty-sandstones. The overlying Medj Zir Formation is finer grained sandstone with a higher proportion of siltstones and clays. It also contains decomposed volcanic tuffs and "soapy clay beds" associated with the start of regional volcanic activity. It is thought to reach a thickness of 400 to 500 m in areas where it has been protected from erosion by the overlying Tertiary Volcanics (Beydoun et al., 1998).

The Tertiary Volcanics (formerly called the Trap Series) outcrop over some 35% of the area of Sana'a Basin. They form high plateaus to the south, west and east of Sana'a plain and underlie the Quaternary deposits in the southern parts of the Basin. The sequence is divided into two groups. The lowest group is the "Stratoid Volcanics" which include the basal Basalt (a dense homogenous basalt flow with columnar jointing), basalt, tuffs and pyroclastics interblended with fluvio-lacustrine deposits. The upper "Chaotic Volcanics" comprise mixed basaltic flows and rhyolite lavas. The total thickness of Tertiary Volcanics is variable, reaching an estimated maximum of 700 to 900 m.

Unconsolidated Quaternary deposits cover about 15% of the Basin area. They are confined to wadi beds and low areas that form the Sana'a plain. Deposition appears to have been of fluvio-lacostrine nature which led to the accumulation of clays and silts in Basins 100 to 300 m deep. Coarse grained colluvium and alluvium occurs in the wadi beds at the foot of hills. The underlying sedimentary sequence is block faulted and gently folded. The regional dip is southwest under cover of the Tertiary Volcanics (Beydoun *et al*., 1998).

The morphological features of the whole country, including the study area, formed largely as a result of the tectonic and volcanic activities during the Tertiary, and modified to some extent during the Quaternary period. Drainage systems developed; river terraces, alluvial plains and coastal plains were formed (Van der Gun *et al*., 1995).

3. Methods

It is worth mentioning here that some preliminary data, information and perplexing analysis results of groundwater samples from wells in the area were made available to the author for carrying out more synthesis and interpretation, in order to confirm or disconfirm such results we collecting samples analyses of samples and material from the same sites in the area and from additional sites for comparative purposes.

For handling the current research, and based on the scientific methods of research, the author was compelled to test the available data in hand through conducting more research and field work, thereby, collecting more groundwater samples from the same sites in the area and conducting analyses in more than one facility to be able to reach to a sound decision and satisfactory results. Therefore, the following were followed:

- Previous reports submitted by the parliament's Water and Environment Committee were reviewed and analyzed.
- Fourteen groundwater and wastewater samples were collected from the study area (Table 1 and Figure. 3) and analysis for major elements were conducted by Atomic Absorption Spectrophotometer and other

instruments available in two facilities, *i.e.*, the Local Water and Sewage Authority (LWSA), and the Yemen Standardization, Metrology and Quality Control Organization, and the Local Authority (SMA).

- Evaluating Sana’a Wastewater Treatment Plant, the effluent channels and the two dams located downstream from the plant (Bab Al-Rawdah and Al-Masham).
- Studied results of analysis through plotting data on Piper diagram.
- Results were interpreted and compared with those of similar studies.
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Table 1: Locations of groundwater samples (a) and dam wastewater samples (b) collected from the study area; analysis results of wastewaters of dams and channels are shown in (c).

(a)

Well No.	**Lat.**	**Long.**	**Notes**
1	15^{o} 35$^{\backslash}$ 25. 09	44^{o} 14$^{\backslash}$ 42. 54	
2	15^{o} 35$^{\backslash}$ 0. 93	44^{o} 14$^{\backslash}$ 32. 51	
3	15^{o} 38$^{\backslash}$ 43. 33	44^{o} 17$^{\backslash}$ 54. 07	
4	15^{o} 39$^{\backslash}$ 0. 75	44^{o} 18$^{\backslash}$ 16. 58	
5	15^{o} 36$^{\backslash}$ 5. 92	44^{o} 15$^{\backslash}$ 11. 18	
6	15 35$^{\backslash}$ 51. 65	44^{o} 17$^{\backslash}$ 47. 00	
7	15^{o} 38$^{\backslash}$ 59. 15	44^{o} 15$^{\backslash}$ 27. 58	
8	15^{o} 30$^{\backslash}$ 39. 69	44^{o} 13$^{\backslash}$ 14. 12	
9	15^{o} 30$^{\backslash}$ 53. 18	44^{o} 12$^{\backslash}$ 49. 18	
10	15^{o} 32$^{\backslash}$ 9. 54	44^{o} 13$^{\backslash}$ 41. 00	
11	15^{o} 32$^{\backslash}$ 56. 31	44^{o} 13$^{\backslash}$ 43. 95	

(b)

Dam No.	**Lat.**	**Long.**	**Notes**
1	15^{o} 35$^{\backslash}$ 29. 77	44^{o} 15$^{\backslash}$ 25. 32	marked in numbers in the study location map
2	15^{o} 36$^{\backslash}$ 59. 00	44^{o} 15$^{\backslash}$ 45. 23	
3	15^{o} 38$^{\backslash}$ 48. 95	44^{o} 19$^{\backslash}$ 42. 24	

(c)

Parameters	**Unit**	**Dams**		**Surface Channels**			**WWTP Waters**
		Al-Rawdah[1]	Al-Masham[2]	Beit Al-Uthary	Beit Al Shatawy	Beit Al-Awzary	
EC	uS/cm	2620	2410	2510	3100	1992	1881
pH		8.125	8.135	7.95	7.4	7.6	8.22
NH_4	mg/L	129	38.175	86	225.7	51.4	39
NO_3	mg/L	9.1	5	11	3.1	19	12
COD	mg/L	512	124	NA	252	NA	NA
BOD	mg/L	236.5	50	252	93	688	22
TSS	mg/L	60	64		888	NA	NA
Total Coliforms	MPN/ 100 ml	>1600	820	NA*	NA	>16	>16
Fecal Coliforms	MPN/ 100 ml	>1600	>2400	>2400	NA	>16	>16

[1] and [2] denote the dams' numbers 1 and 2, respectively in table (b) (above), while data for dam No. 3 are not available.

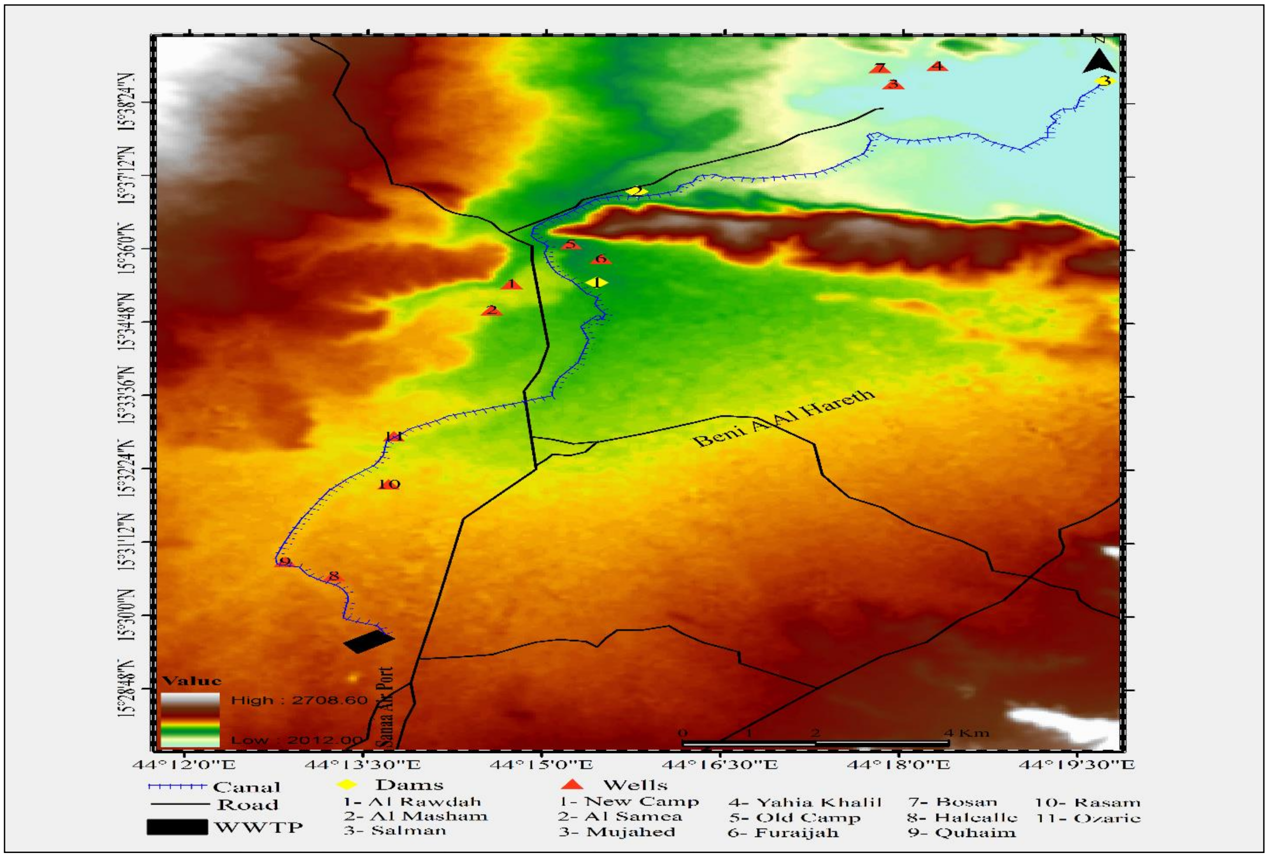

Figure. 3: Digital elevation model of the study area, with locations of groundwater and wastewater samples indicated.

4. Previous Work:

Regarding study area, in particular, there were no previous studies that have dealt in depth and specifically with groundwater pollution and wastewater treatment effluents produced from Sana'a WWTP. However, historically, (Italconsult, 1973) and (Moscow State, 1986) consultants have evaluated Sana'a Basin for the purpose of groundwater potential and availability, away from the pollution issue at such times, although, traditional cesspits, containing wastewater, have been existing in Sana'a city for perhaps centuries and not just decades. It was (Al- Eryani *et al.*, 1991), (Al-Hamdi, 1994) and (Al Hakimi and Almikhlafi, 2005) studies that have seriously started investigating Sana'a Basin from the pollution point of view, due to the remarkable increase in the number of groundwater wells drilled in the basin, including Sana'a city area, and the fear of possible contamination from the increasing number of cesspits in the area, as well.

Al- Eryani *et al.* (1991) had studied domestic wastewater collected in open natural ponds, called stabilization ponds, in Alrawdah and near airport areas, and had found that wastewater produced critical changes in the quality of groundwater in such areas, especially when population started to increase dramatically. Few years later, (Al Hamdi, 1994) had found that the Quality of groundwater in Sana'a city and surroundings are divided into the 3 zones, the northern, middle and southern. The middle zone, was a site of wastewater disposal, and was found to contain more nitrate and chloride than other zones. The middle zone, therefore, had a negative effect on the quality of groundwater.

About a decade later, (Foppen, 2002) made use of a major groundwater well inventory in Sana'a Basin, which was completed in 1995, and in

2000, he made chemical analysis of water in a subset of wells. The result, then, indicated that groundwater in urban area has high content of almost all major cations and anions. The dominant water type, then, was described as being enriched in $CaCl_2$. He concluded that cation exchange process must has taken place, where Ca^{2+} in groundwater had been enriched, while Na^+, K^+ and NH^{4+} were relatively depleted. (Foppen, 2002) then speculated that infiltration of wastewaters into aquifers via cesspits must have taken place.

The current study is a detailed account of an abstract published by Al Hakimi and Almikhlafi (2005) in a symposium held in Taiz, on water issues. They concluded that all wells near WWTP are chemically and biologically polluted beyond the WHO limits. Wells downstream from the WWTP have Total Coliform and Fecal Coliform bacteria counts beyond WHO limits.

Interestingly, the current authors noticed that recent studies that were conducted by Alsubai and Al-Mikhlafi (2008) and Al-Aswadi (2010) have repeatedly focused on the same areas studied earlier by Al Hakimi and Almikhlafi (2005) and documented in the aforementioned abstract. Regardless, the general findings for all investigators were ultimately the same, with slight differences.

For example, Alsubai and Al-Mikhlafi (2008) studied the groundwater characteristics at the northern part of Sana'a Basin, and found that some wells were contaminated and the natural fresh water types ($Na-CO_3$) has changed into a mixture of cations and anions, due to infiltration of wastewaters into deeper layers. The groundwater contamination was recognized by high concentration of wastewater indicators, such as, TDS, NO_3, $Cl^{-1}$and SO_4^{-2}, in addition to microorganisms.

Similarly, Al-Aswadi (2010) has indicated contamination of groundwater at locations that are comparable to locations reported by previous studies **(Al Hakimi** and **Almikhlafi, 2005; Alsubai and Al-Mikhlafi, 2008).** High levels of Cl_2, NO_3, TDS, K, Na and HCO_3 were also reported. Total Coliform (TC) and Fecal Coliform (FC) were also found in in the groundwater samples.

5. Results

Laboratory results of analysis of groundwater samples from the study are shown in Table 2, and Figures. 4 through 11 in Plate 1, and the results conducting correlation statistical tests for the increases in concentrations of different chemical elements or components are shown in Table 3 and Figures. 12 through 16 in Plate 2.

For describing the groundwater quality of the study area, analysis results were plotted on a Piper diagram and are displayed in Figure. 17. Wastewater sample analyses were also plotted on the same Piper Diagram and are shown within the same figure.

6. Discussion

Laboratory results of analysis of groundwater samples from the study area indicated a significant increase in the concentration of dissolved chemical elements compared to normal values (Table 2, and Figures. 4 through 11 in Plate 1). Such increase is clearly evidenced by the electrical conductivity ratio (EC), amount of total dissolved solids (TDS), chloride (Cl^-), nitrate ($NO3^-$), sodium (Na^+), potassium (K^+) and bicarbonate (HCO_3^-) concentrations. The presence of such a large proportion of such elements in concentrations above values of their natural sources in underground reservoirs indicates a presence of some sources that are not natural (Frengstad *et al.*, 2000). The suspected sources are thought to be derived from the wastewater spills or overflows of the Wastewater Treatment Plant existing upstream from the location of the study area, as well as, from the contaminated drainage channels existing near sampled wells. In addition, the use of manure or natural fertilizers may constitute an additional source Helmer and Hespanhol, 1997). Given the hydrology of groundwater in this region, we find that the reservoirs are found in the sediments of Quaternary period, or in the volcanic rocks underlying such sediments and water components of such reservoirs do not normally give such high concentrations of pollutants that exceed the standards set by the World Health Organization (WHO, 1993).

Therefore, the presence of non-natural sources may have led to an increase in the concentration of polluting elements. Consequently, the polluting elements may be derived from a source of sewage and industrial type. Also, as evidence for the existence of industrial pollution is the high concentration of chlorine (from 30 to 403.8 mg/ L) in the absence of a natural source for such element, such as, proximity to a sea, or presence of evaporite rocks, as reservoir rocks, or near them. Chlorine element is present in many sewage and industrial detergents wastes (Hem, 1992). Moreover, the concentration of nitrates at high rates (3.6-93.7 mg/l) is in favor of such pollution, which exceeded the recommended max limit (10 mg/l) set by the WHO (1993), and as reported by Foppen (2002).

When conducting correlation tests (Table 3, and Figures. 12 through 16 in Plate 2) for the increases in concentrations of chemical elements and components, starting with chlorine and nitrate, it is noted that chlorine and nitrates are highly correlated, with a correlation coefficient of 0.78, and such results are in agreement with those reported by Townsend and Whittemore (2005). Moreover, the results for Chlorine and Magnesium are well correlated with a coefficient of 0.88, where Chlorine increases with the increase of Magnesium, as noted by Arveti NAGARAJU (2005). It was further noted that the electrical conductivity (EC) of the sampled water and Chlorine concentration are highly correlated, with a coefficient reaching 0.82, meaning that the water is contaminated, and the increase in electrical conductivity is potentially due to the existence of human waste, as noted previously by researchers; *i.e.*, Italconsult (1973), Arveti (2005), and Autman and Ammar (2004).

From Figures. 12 and 13, in Plate 2, it is found that the data points are generally distributed in a linear trend, which potentially suggest a mixing process of groundwater with another source, as reported by State Department of Agriculture (1999).

The data points plot displayed in Figure. 17 (Piper Plot) describes the groundwater quality of the study area represented by its main constituents. The groundwater quality of the study area was found to be of two types, A and B, where type B is a mixture of the constituents Mg^{2+},Cl^{-}, Ca^{2+}, SO_4^{2-} and Na^{+}, which is fairly high in hardness compared to type A that have the constituents, Mg^{2+}, Cl^{-}, Ca^{2+}, HCO_3^{-}, SO_4^{2-} and Na^{+}, which is less in hardness due to the presence of high concentrations of sodium bicarbonate and medium levels of calcium, chlorine and sulphate, and this was attributed to the diversity of sewage sources, being rich in industrial detergents, that have high contents of sodium, making wastewaters becoming less in hardness (Townsend and Whittemore, 2005), and this is contrary to what is known about non-contaminated groundwater quality in the study area, which contains sodium bicarbonate ($NaHCO_3$).

For characterizing wastewaters entering the WWTP and those which are discharged from the plant, wastewater sample analyses were also plotted on the same Piper Diagram discussed above, and were found that the samples were nearly plotting in the same zone, indicating that the treated wastewaters are not much different from the treated ones. This indicates that the treated wastewater is not much different in chemical composition from that entering the plant. Such finding is mainly due to several reasons, among which is that the WWTP is not conducting full treatment for the wastewaters and limited work on pre-treatment is done, neglecting most often chemical treatment work. Furthermore, during the peak hours of city wastewater flow, or during heavy rainstorm runoff flows, large portions of the sewage and runoffs are diverted directly into surface channels without treatment, mainly due the lack of capacity of the plant to absorb or process such load. Moreover, at other times, the presence of undesirable substances, such as, dyes and used oils, affect the activity of bacteria that work on dismantling the complex organic material, turning it into the most basic materials that can be separated easily. Other reasons are thought to be related to the designing efficiency of the station, not taking into account water scarcity in Yemen. Findings of the current study are in agreement or in line with those reported earlier, more than two decades ago, by Al-Eryani (1991), (Al-Hamdi (1994), and those published later by Foppen (2002), and those produced by Alsubai and Al-Mikhlafi (2008) and Al-Aswadi (2010).

Table 2: Concentration of chemical components (mg/l) in groundwater samples of the study area.

Sample No.	EC	TDS	Tot Alk	Tot H	K	Na	Mg	Ca	NO3	HCO3	SO4	CL
1	552	359	100.8	88	1.93	92	15	22.44	19.4	122.976	55	39
2	590	384	97.6	44	1.64	82	20	12.82	26	119.072	34	43
3	1271	826	137.6	116	2.31	127	41	17.63	29	167.872	295	88
4	978	636	196.8	244	4.15	135	21.33	62.52	24	240.096	77	107
5	593	385	150.4	308	4.70	69.6	28.13	76.95	27	183.488	43	120
6	595	387	209.6	224	4.15	65	19	74.23	22	255.712	40	30
7	1082	703	196.8	244	4.15	135	27	62.52	3.6	240.096	234	43
8	1930	1255	150	700	5.22	104.4	58.17	184.37	93.76	183	185	403.8
9	1970	1281	380	820	43.3	120	26	272.54	5.2	463.6	176	355
10	1044	679	324	540	17.5	93	39	140	14	395	257	56
11	1072	679	12	392	7.90	82.6	41	115	17	14.64	284	70
Standard (WHO)	450-1000	650	-	-	12	200	30	75	45	-	200	200

	pH	EC	TDS	T. Alk.	T.H.	K^+	Na^+	Mg^{2+}	Ca^{2+}	NO_3^-	HCO_3^-	SO_4^{--}	Cl^-
pH	1	-.252	-.252	.328	-.474	.014	.246	-.449	-.417	-.613(*)	.328	-.405	-.463
EC		1	1.000(**)	.648(**)	.809(**)	.603(*)	.564(*)	.826(**)	.717(**)	.711(**)	.648(**)	.847(**)	.817(**)
TDS			1	.648(**)	.809(**)	.603(*)	.564(*)	.826(**)	.717(**)	.711(**)	.648(**)	.847(**)	.817(**)
T.Alk.				1	.302	.690(**)	.708(**)	.366	.208	.251	1.000(**)	.397	.230
T.H.					1	.222	.025	.945(**)	.959(**)	.824(**)	.302	.767(**)	.959(**)
K^+						1	.553(*)	.367	.103	.238	.690(**)	.411	.235
Na^+							1	.136	-.087	.149	.708(**)	.483	.056
Mg^{2+}								1	.826(**)	.788(**)	.366	.812(**)	.883(**)
Ca^{2+}									1	.786(**)	.208	.657(**)	.954(**)
NO_3^-										1	.251	.797(**)	.779(**)
HCO_3^-											1	.397	.230
SO_4^{--}												1	.757(**)
Cl^-													1

(*) = Correlation is significant at the 0.05 level (2-tailed).
(**) = Correlation is significant at the 0.01 level (2-tailed)
Negative sign indicates low correlation

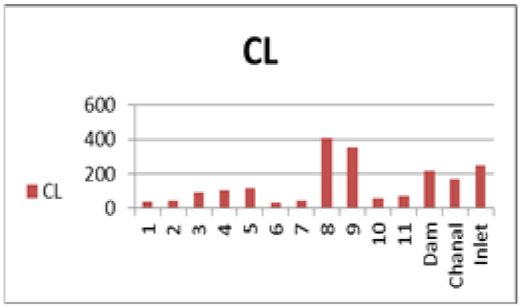

Figure 4: Increase in concentration of chlorine in wells near WWTP inlet, contaminated channel and dam.

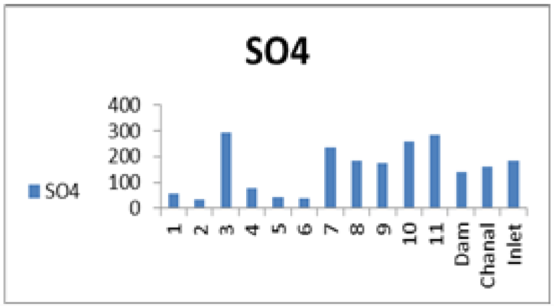

Figure 5: Increase in concentration of sulfate in wells nearby pollution source, dam and channel.

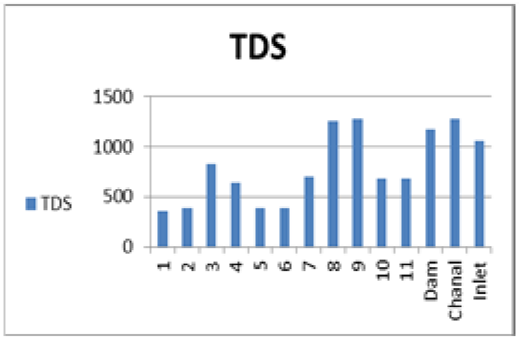

Figure 6: Increase in total dissolved solids in wells nearby pollution source, dam and channel.

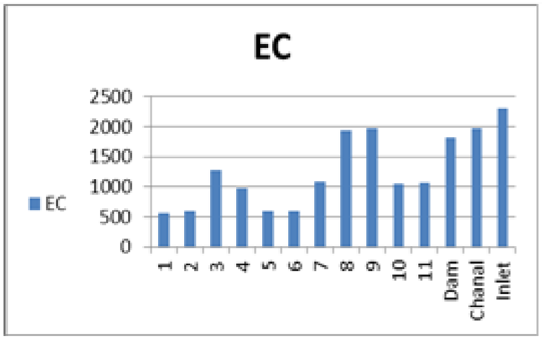

Figure 7: Increase in electrical conductivity in wells nearby pollution source, dam and channel.

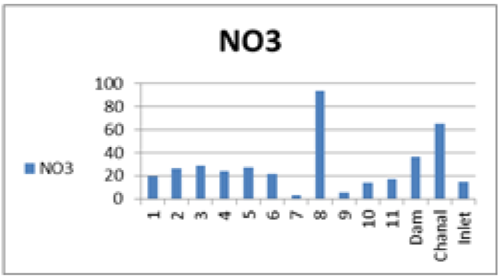

Figure 8: Increase in concentration of nitrates in wells nearby pollution source, dam and channel.

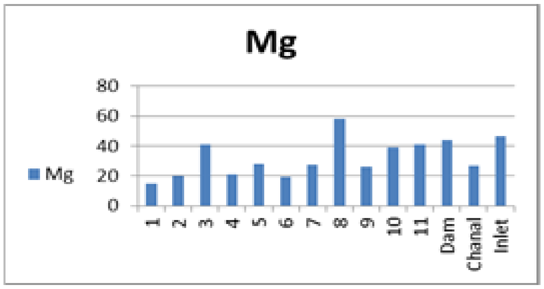

Figure 9: Increase in Magnesium concentration in wells nearby pollution source, dam and channel.

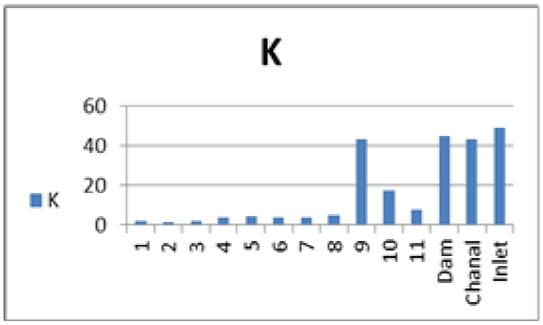

Figure 10: The concentration of sodium in wells nearby pollution source, dam and channel.

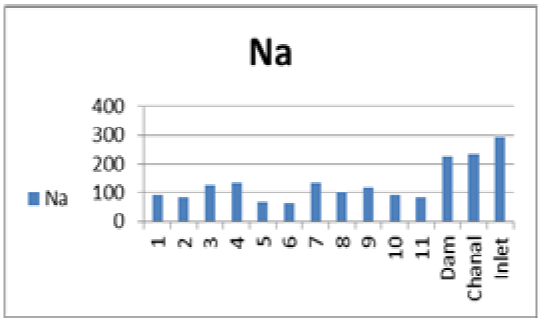

Figure 11: increase in concentration of Potassium in wells nearby pollution source, dam and channel.

Plate 1: Increase in concentration of elements (in mg/l) in wells nearby pollution source, effluent channel and contaminated dam.

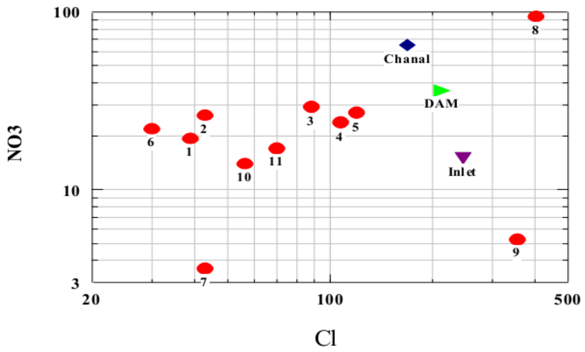

Figure 12: Increase of nitrate (NO_3) with increase in concentration of chlorine (Cl).

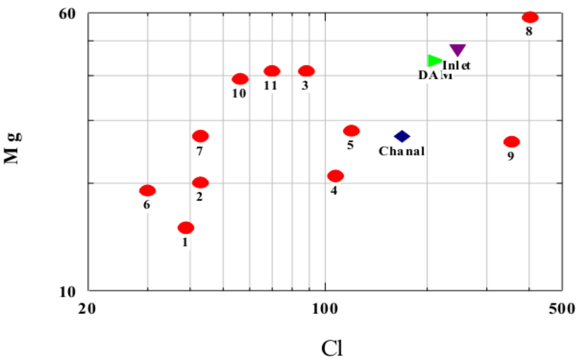

Figure 13: Increase of Magnesium (Mg) with increase in concentration of chlorine (Cl).

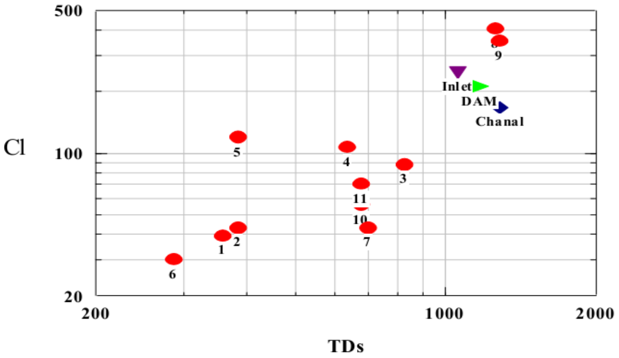

Figure 14: Increase of total dissolved solids (TDS) with increase in concentration of chlorine (Cl).

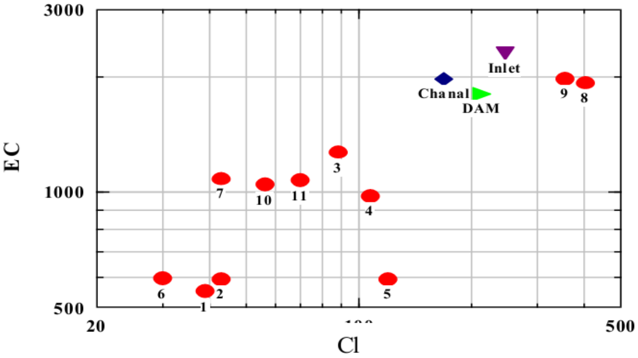

Figure 15: Increase of electrical conductivity (EC) with increase of chlorine (Cl).

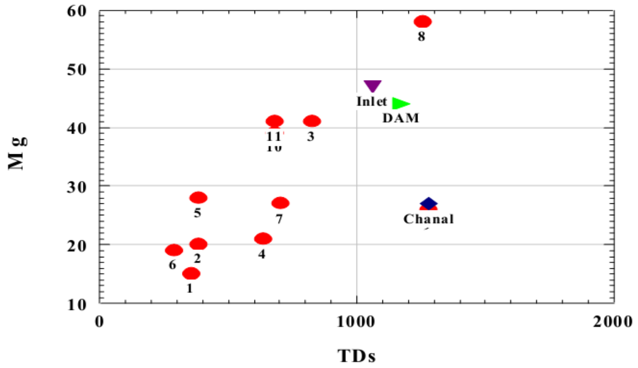

Figure 16: Increase of Magnesium (Mg) with increase of total dissolved solids (TDS)

Plate 2: Correlation of increase in concentrations (mg/l) of NO_3 with Cl, Mg with Cl, EC with Cl, Cl with TDS and Mg with TDS.

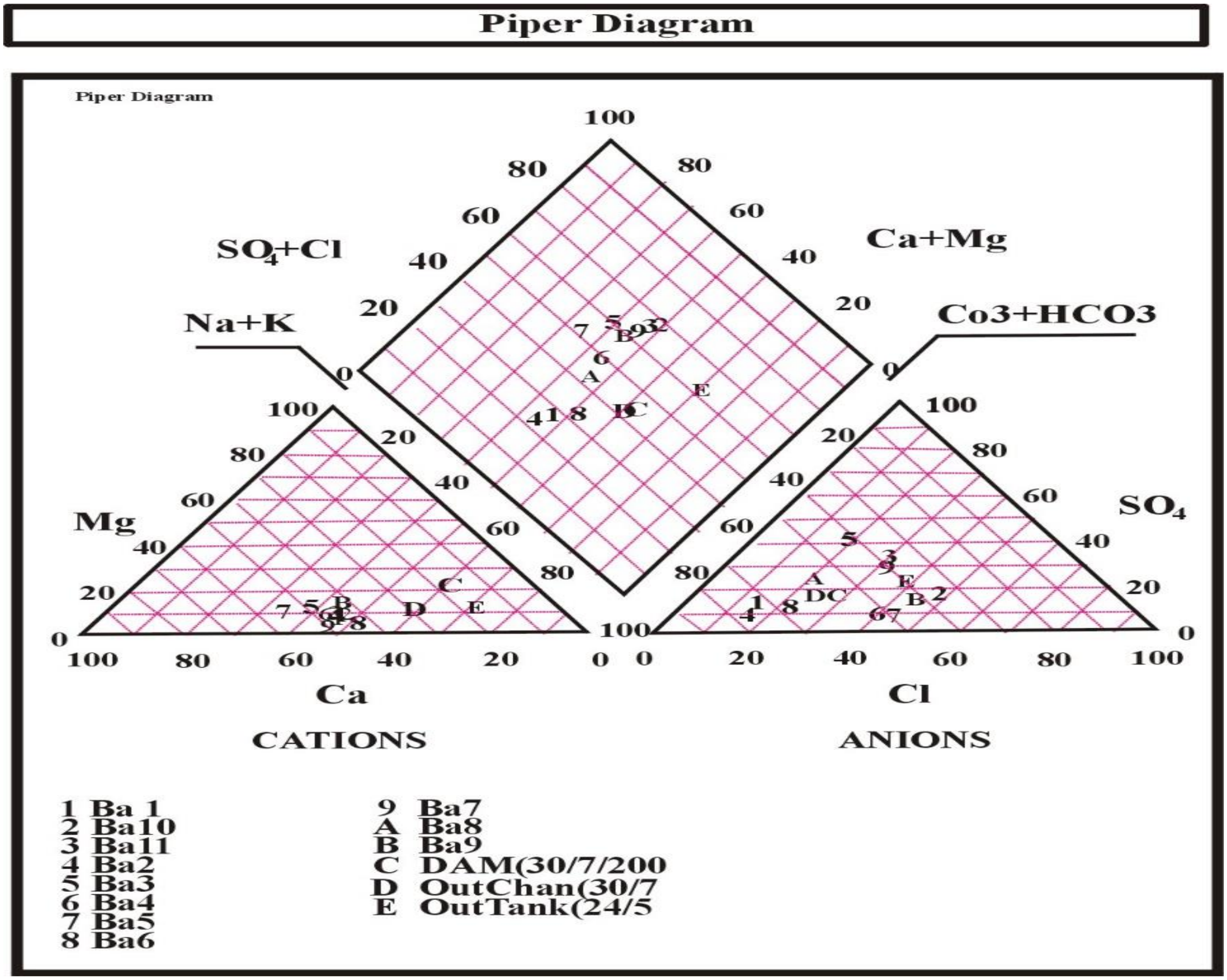

Figure 17: Piper Diagram used for characterizing the groundwater quality and wastewater of the study area (Piper, 1944).

7. Conclusions

The following is concluded from the current study:

1. Wells near treatment plant are chemically polluted with nitrate and ammonia beyond the WHO permissible limits.
2. Wells near polluted dams have waters that are highly contaminated with Fecal Coliform (FC).
3. Some wells have waters that contain high Total Coliform (TC) and Fecal Coliform (FC) bacteria counts, beyond the permissible WHO limits.
4. Few wells have waters that are not showing any contamination.
5. Wastewater samples of the effluent channels that are extending for nearly 10 km downstream from the WWTP, and wastewater samples collected from the two dams (dams initially constructed for groundwater recharge) are chemically and biologically contaminated.
6. Pollution monitoring wells in the study area and nearby areas are urgently needed.

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