Implications of groundwater quality to corrosion problem and urban planning in Mekelle area, Northern Ethiopia

Gebremedhin Berhane*, Tesfahunegn Abera and Solomon Gebreselassie
Department of Earth Science, CNCS, P.O.Box:1202, Mekelle University, Mekelle, Ethiopia
(*gmedhin_berhane@yahoo.com)

ABSTRACT

Surface and groundwater chemistry being an important factor in urban planning and infrastructure development, present paper tries to present the problems of corrosiveness due to groundwater chemistry in Mekelle city. Iron corrosion in distribution systems and engineering structures are common problems in many urban areas. Corrosiveness of groundwater at different localities in Mekelle and its environs has been evaluated on the basis of AAS-UV spectrophotometer-generated hydro-geochemical data. Corrosiveness of water was estimated by using corrosion indices like Larson Index, LI and Aggressive Index, AI and total dissolved solids, total carbonate hardness, chloride and sulphate data were evaluated to estimate aggressiveness of the water samples on iron pipes. Analyses of the results have shown that most of the samples from boreholes and hand dug wells compared to spring samples, are potentially aggressive. The result shows that 66.7% spring, 81.3% shallow hand dug wells and 81% borehole water samples have a Larson index (LI) above 0.5, a threshold of corrosiveness of water. This study highlights the basic characteristics of surface and groundwater chemistry and its potential hazard for corrosion of pipes, and provides a baseline information and awareness to the city planners for urban management.

Keywords: Corrosion, Groundwater, Hydrogeochemistry, Larson Index, Mekelle City.

1. INTRODUCTION

With over one billion people worldwide lacking access to clean water and over 2 million deaths annually attributable to water-borne diseases, there has been massive increased reliance upon groundwater resources in many rapidly developing countries, including those of east, south-east Asia and Africa. More than 50% of the world's population lives in cities and the proportion is rapidly increasing (Afonso et al., 2006). The urban subsurface includes a network of pipes, conduits, metallic rods, reinforced concrete footings and other structures that modify the natural hydraulic conductivity of the geological materials and result in interaction with subsurface water. Being the major structural material used in the construction industry, steel corrosion problem has been attracting much attention only in developed countries (Hong et al., 2012). The problem of corrosion and scaling is quiet significant in developing countries and researches towards understanding and solving the problem are extremely low. Surface water and groundwater system is one of the most important influencing factors in foundation engineering and urban development and is required for design of structures. Hence monitoring and conserving this important resource is essential (Chatterjee et al., 2010). Understanding the hydrogeology of cities is imperative from various perspectives such as; urban planning, water resource utilization and protection, foundation of structures, waste disposal and septic tank site selection etc.In general, the magnitude of damage that could occur on urban structures due to surface and groundwater depends on the amount of water table lowering and its fluctuation and chemical characteristics.

Describing the overall water quality and its impact on water pipes in the Mekelle area is complicated due to the spatial variability of the geology, hydrogeology and wide range of indicators that could be measured. Many organizations and scholars have studied the hydrogeology of Mekelle area (e.g. Abdelwassie Hussien, 2000; Hailmariam Hailu, 2010, Samuel Yehdego, 2003; Teklay Zeray, 2006; WWDSE, 2007). All of these studies focused on groundwater potential assessment, recharge and discharge estimation and few of these dealt with hydrogeochemistry but none on the impact of water quality on water pipes and other engineering structures. So, present paper tries to fill this gap and report the possible impact of water quality on water supply metal pipes.

2. GEOLOGICAL CONTEXT

Regionally, the geology of northern Ethiopia is well documented (e.g. Beyth and Shachnai, 1970; Beyth, 1971; Levitte, 1970; Bossellini et al., 1997; Russo et al., 1996) and locally few studies were conducted (e.g. Worash and Valera, 2001; Gebremedhin Berhane, 2010; Gebremedhin Berhane and Tenalem Ayenew, 2010; Tesfamichael Gebreyohannes, et al., 2010). The geology of northern Ethiopia is generally sub-divided into four major units: Basement complex, Paleozoic-Mesozoic Sedimentary Sequence, Cenozoic Trap volcanics and Sediments of the Ethiopian Rift (Levitte, 1970). The study arealies within the Mesozoic sedimentary sequences of the Mekelle Outlier (Fig. 1) which is a near circular area of about 8000 km^2. According to Danielle (1943) the formation of sedimentary basins and deposition of sediments during Mesozoic in east Africa is supposed to be the result of Mesozoic transgression, which covered east Africa. This transgression is believed to be caused by general subsidence and/or the worldwide rise of the sea level (Bosellini et al., 1997). The history of the sedimentary basin in Mekele Outlier began in either Ordovician or Carboniferous and probably ended in lower Cretaceous before the eruption of the Trap volcanics (Beyth, 1971). Beyth (1971) studied the structure and tectonics of the sedimentary rocks of the Mekele Outlier and the escarpment. He also identified two main fault systems: the WNW running fault belts (Wukro, Mekelle, Chelekot and Felega Mariam) and Rift Valley fault system, which formed the escarpment and the Danakil depression (Fig. 1).

The study area, located at the center of the Mekelle Oultier, is mainly covered by limestone-shale-marl intercalation, dolerite, limestone, minor sandstone and alluvial deposits. Detail geological and structural descriptions of the study area are documented in Gebremedhin Berhane (2010); Gebremedhin Berhane and Tenalem Ayenew (2010) and Gebremedhin Berhane and Kristine Walraevns (2011) (Fig. 2).

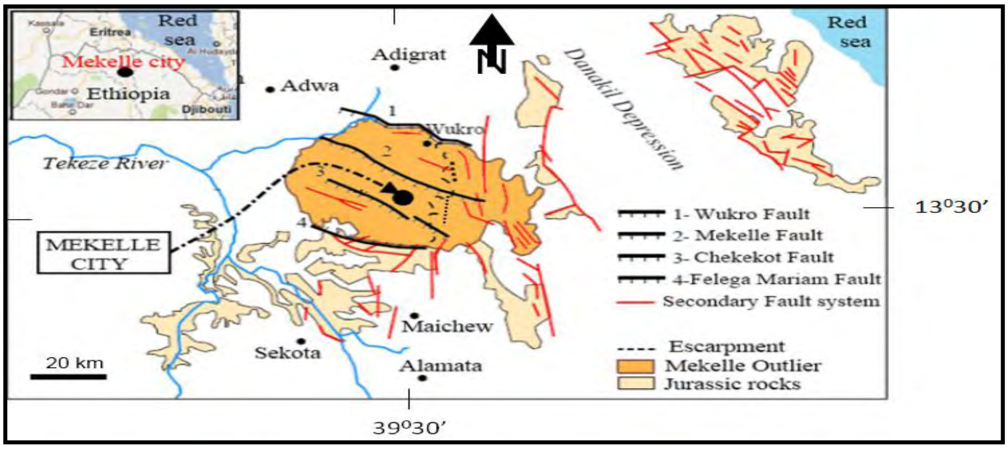

Figure 1. Location of Mekelle City and schematic representation of the outlier and major structures near the city (modified after Bossellini et al., 1997).

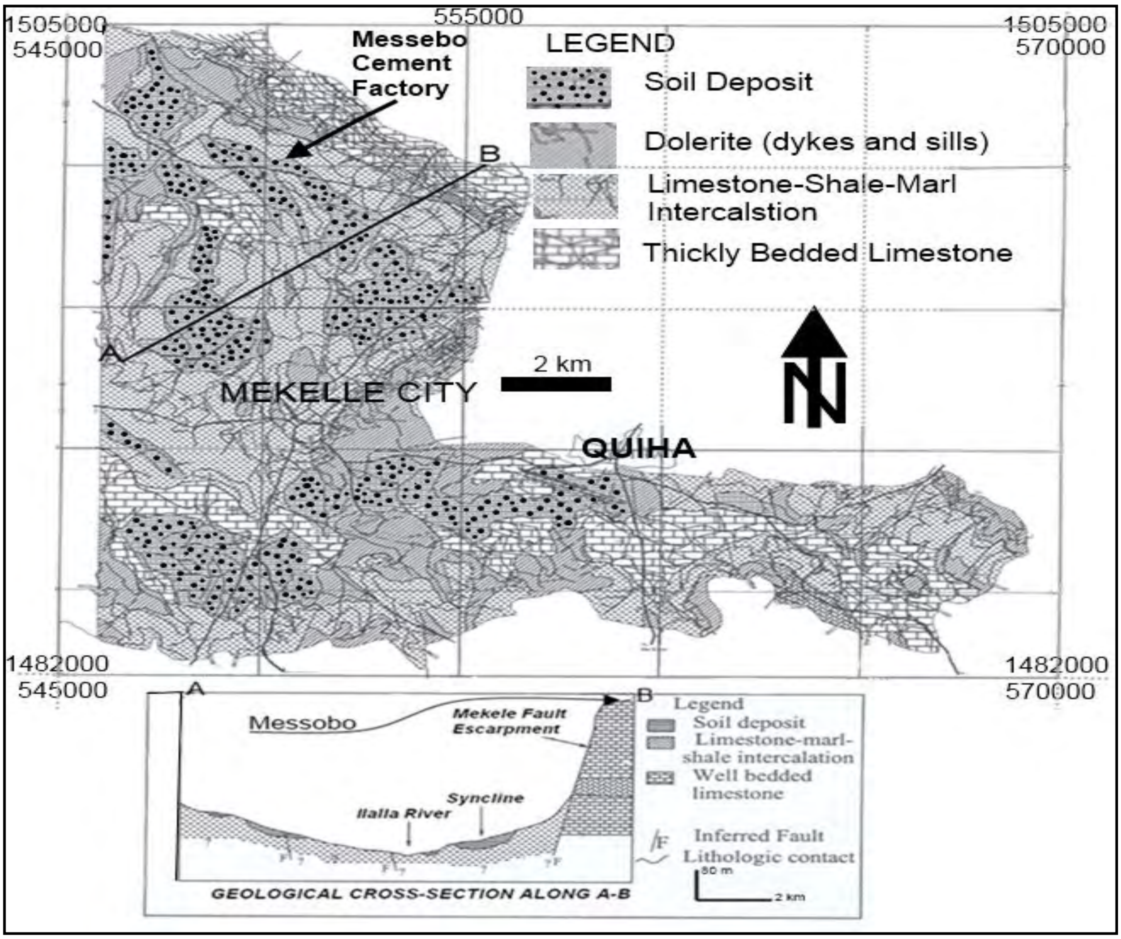

Figure 2. Geological map of Mekelle area and simplified cross-section along line AB. Grids are in UTM zone 37 (in meters East and North)(after Gebremedhin Berhane and Tenalem Ayenew, 2010).

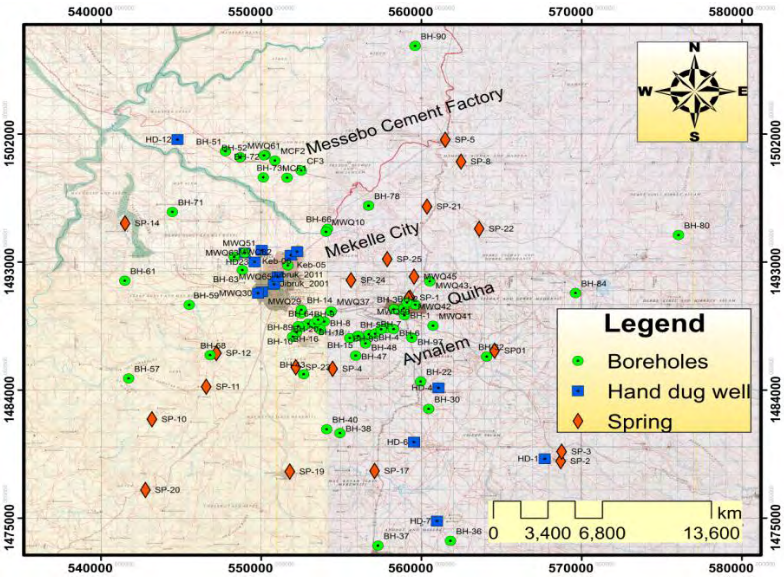

Figure 3. Location of water sample points with a topographic map published in 1997 by Ethiopian Mapping Authority in the background.

3. METHODOLOGY

100 water samples presented in the paper were collected in and around Mekelle City during 2001, 2002, 2007, 2010 and 2012 in different seasons (Fig. 3). Out of 100, 19 samples data (2 from springs and, 8 shallow hand dug wells and 9 from boreholes) represent primary data collected during 2012 by the authors and 81 represent unpublished secondary data (19 springs, 8 shallow hand dug wells and 54 boreholes) from Ethiopian Ministry of Water Resources generated on water samples collected during 2001, 2002, 2007, 2010 and analyzed in the central laboratory of Geological Survey of Ethiopia.

19 samples collected in the present study were collected in properly rinsed plastic 500 ml bottles and kept in refrigerator until delivered to the laboratory for analysis. The parameters like pH, electrical conductivity and temperature were measured in the field itself and the cations and anions were measured in the hydrogeochemical laboratory, Department of Earth Science, Mekelle University using atomic absorption spectrophotometer (VARIAN50B) and UV-spectrophotometer (Lamda EZ201) respectively. For reliability of the results the charge balance was computed and found it to be less than 5% for all data used in this study.Similar analytical technique was employed in the case of secondary data. Samples location (coordinates), geology, all measured parameters and simple statistics like maximum, minimum and average are given in tables 1, 2 & 3.

As the study is mainly focused on effects of water quality on metallic pipes, Larson Index (LI) proposed by Larson (1975) and Aggressive Index (AI) (American Water Works Association, 1977) are used in the present paper to check the corrosiveness of water to metallic pipes and other engineering components. LI is the ratio of the sum of twice the sulphate and chloride contents to the concentration of bicarbonate (Larson 1975; McNeill and Edwards 2001).

$$LI = \frac{2[SO4]+[Cl]}{[HCO3]} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

The Larson Index (LI) is an empirically derived ratio of specific ions which expresses the corrosive nature of a particular water sample with regard to the rate of metal corrosion. Water with LI values more than 0.5 values indicates high corrosive character (Singley et al., 1985). The LI emerged from work with experimental solutions containing bicarbonate, chloride, and sulphate ions (Larson, 1975), and is not designed to be applied to waters with low hardness and small concentrations of dissolved solids (Singley et al., 1985). The LI may be applicable to waters containing dissolved solids ranging from 250 to 1,000 mg/l (the range of dissolved solids in Larson's experimental solutions).The Aggressive Index (AI) essentially is a simplified version of the Langelier Saturation Index (LSI), and is given by the equation:

$$AI = pH + log[AH] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

where, ‘A’ is alkalinity and ‘H’ is calcium hardness (or concentration of calcium expressed as mg/l of equivalent $CaCO_3$) (American Water Works Association, 1977).AI values of 12.0 or greater indicate non-aggressive (non-corrosive) water. Values from 10.0 to 11.9 indicate that the water is moderately aggressive, and for values less than 10.0, the water is considered to be highly aggressive.

4. RESULTS AND DISCUSSION

4.1. Hydrogeological framework

4.1.1. Groundwater dynamics

The study area forms upper part of Atbara–Tekeze River basin. Surface drainage is generally in east to west direction and is controlled by geological structures. During the wet season, runoff from the upland area and hills is channeled by a number of gullies, rills and small streams, which in turn joins the major rivers. Floods generated from nearby cliffs passes through the city posing considerable challenges and threat to people by affecting and eroding footpaths, roads, culverts and houses. Depending on the degree of weathering and discontinuities, groundwater exists in all rock units in the form of a stratified or multi-aquifer system. Previous drilling data (e.g. Gebremedhin Berhane, 2002, WWDSE, 2007) showed that depth to groundwater ranges from 4.35 m to 25.43 m below ground level (b. g. l) in the northern part of the city. Fractured limestone and dolerite aquifers form the main sources of

Table 1. Chemical constituents and other properties of spring water from Mekelle area.

S. No.	**Sample code**	**X**	**Y**	**Z**	**EC µS/cm**	**TDS mg/l**	**TH mg/l**	**pH**	**Ca mg/l**	**Mg mg/l**	**Na mg/l**	**K mg/l**	**HCO3 mg/l**	**Cl mg/l**	**SO4 mg/l**	**NO3 mg/l**	**AI**	**LI**	**Geology**	**source**
1	SP-21	560347	1496897	2340	1165	835	590.1	7.58	218.4	10.71	34	1.2	316.22	35.52	250.6	52.8		1.70	Limestone	1
2	SP-22	563602	1495337	2373	1032	705	567	7.4	193.2	20.4	22	1.2	401.14	20.16	174.07	39.6		0.92	Limestone	1
3	SP-23	552160	1485603	2184	821	528	411.6	7.29	126	23.46	26	0.8	412.85	36.48	59.3	18.48		0.38	dolerite & Lst	1
4	SP-17	557078	1478316	2203	992	676	520.8	7.28	162	24.5	21.5	1.7	333.8	29.9	168.8	28.2		1.10		1
5	SP-20	542769	1476976	2225	579	345	273	7.75	96.6	7.65	23	1.9	301.58	11.52	38.24	12.32		0.29		1
6	SP-1	559289	1490495	2223	863	556	411.6	7.77	151.2	8.2	21	1.1	316.2	21.2	116	38.2		0.80	Lst & dolerite	3
7	SP-2	568690	1479000	2230	1476	990	699.3	7.6	218.4	37.2	60	2.9	357.2	100.4	229.5	98.6		1.57		1
8	SP-3	568746	1479672	2286	1346	936	651	7.77	193.2	40.8	58	2.5	257.7	86.8	316.5	78.3		2.79		2
9	SP-4	554457	1485491	2258	596	352	294	7.46	100.8	10.2	11	2.8	330.9	10.6	15.3	23.7		0.12		2
10	SP-5	561486	1501596	2222	1775	1312	947	7.57	324	26	61	5.8	342.6	66.6	580.2	48		3.58	Lst & Shale	2
11	SP-19	551781	1478274	2015	1672	1308	921.9	7.78	310.8	35.19	38	3.6	178.61	36.48	712.09	4.4		8.18		2
12	SP-24	555605	1491726	2247	575	330	306.6	7.65	105	10.71	13	0.9	354.29	5.76	14.77	9.24		0.10		2
13	SP-25	557864	1493201	2112	668	396	346.5	7.94	110.9	16.83	14.4	0.9	333.79	15.36	46.15	31.68		0.32		1
14	SP-8	562470	1500055	2327	682	464	344.4	7.58	111.8	13.1	17	1.3	260.6	18.3	150	18.9		1.22	Lst	1
15	SP-10	543178	1481950	1846	1632	1220	930.3	7.27	315.9	27	50	2.6	380.9	44.4	559	19.8		3.05	Lst & dolerite	1
16	SP-11	546564	1484237	2183	790	472	367.5	8.13	121.5	12.8	31	0.7	361.1	17.4	44.8	37.8		0.30	Dolerite & lst	1
17	SP-12	547201	1486597	2112	1190	782	600.6	7.61	186.3	28.6	32	0.9	298.6	27.02	290	22.9		2.03	Dolerite & lst	1
18	SP-14	541502	1495725	1960	1007	710	543.9	7.01	186.3	14.8	26	1	363.1	27	168.8	41.4		1.00	Dolerite & lst	1
19	SP01	564560	1486767	2321	683	570	327.8	7.4	105	16	13	1.2	355	14	61	4.7		0.38	dolerite	1
20	MWQ42	559192	1490424	2215	891	635.38	458.33	8.17	150	20	14	2	390.7	27.24	252.2	0.33	1.97	1.36	Lst & dolerite	4
21	MWQ45	559542	1491972	2138	1304	929.89	616.67	8.5	175	43	34	1	475.55	83.11	297.8	0.27	3.62	1.43	Lst	4
	Average				**1035.19**	**716.77**	**530.00**	**7.64**	**174.40**	**21.29**	**29.52**	**1.81**	**339.16**	**35.01**	**216.43**	**29.98**		**1.55**		
	Maximum				**1775**	**1312**	**947**	**8.5**	**324**	**43**	**61**	**5.8**	**475.55**	**100.4**	**712.09**	**98.6**		**8.18**		
	Minimum				**575**	**330**	**273**	**7.01**	**96.6**	**7.65**	**11**	**0.7**	**178.61**	**5.76**	**14.77**	**0.27**		**0.10**		

AI: Aggressive Index; LI: Larson Index; Source: 1) water works design and Enterprise (2007); 2) Hailemariam Hailu (2010); 3) Gebremedhin Berhane (2002); 4) Present work; Lst – Limestone

Table2. Chemical constituents and other properties of water from hand dug well source from Mekelle area

S. No.	**code**	**X**	**Y**	**Z**	**EC µS/cm**	**TDS mg/l**	**TH mg/l**	**pH**	**Ca mg/l**	**Mg mg/l**	**Na mg/l**	**K mg/l**	**HCO3 mg/l**	**Cl mg/l**	**SO4 mg/l**	**NO3 mg/l**	**AI**	**LI**	**Geology**	**source**
1	HD-1	567696	1479172	2320	1199	780	504	7.7	142.8	35.7	72	3.3	456.8	36.6	200.4	6.6		0.96		1
2	HD-4	561072	1484157	2335	722	436	252	7.84	84	10.2	58	4	424.6	15.4	24.3	6.2		0.15	Limestone	1
3	HD-6	559545	1480345	2288	917	596	432.6	7.48	151.2	13.3	46	0.9	377.7	21.2	134.5	17.6		0.77	Lst & dolerite	1
4	HD-7	560974	1474794	2271	1020	660	228.4	7.33	151.2	12.2	58	2.2	412.8	63.7	52.7	42.2		0.41		1
5	HD-12	544780	1501607	1906	885	600	346.5	7.45	126	7.7	37	2.6	415.8	23.2	34.3	52.4		0.22	Lst & shale	1
6	Keb-05	551843	1493480	2023	1036	873	537.6	7.1	166	30	24	1	415	21	178	37.3		0.91	Lst & shale	3
7	Keb-06	552246	1493738	2027	2320	1668	1120.1	7.4	350	60	50	3.1	340	298	230	336.1		2.23	Lst & shale	3
8	Jibruk_2001	550806	1491426	2071	5300	3454	2041	7.4	620	120	260	4.7	412	231	1607	198.5		8.36	Lst & shale	4
9	HD23	549588	1493004	2045	1154	934	584.5	7.5	198	22	22	3.5	350	42	218	78.3		1.37	Lst & shale	3
10	Jubruk_2011	550806	1491426	2071	2700	1961	926.2	8.45	285	52	18	0.5	593.24	196.5	513.7	0.29	12.06	2.06	Lst & shale	4
11	MWQ29	550053	1490912	2075	1117	796.55	837.5	7.9	300	21	24	1	405.47	90.23	392.1	0.21	2.73	2.16	Lst & shale	4
12	MWQ30	459807	1490804	2088	1342	956.99	966.67	7.88	350	22	22	1	502.48	81.66	247.7	0.35	2.89	1.15	Lst & shale	4
13	MWQ51	550035	1493830	2014	1833	13007.13	620.8	8.5	175	44	69	1	449.36	143	487.3	0.35	3.43	2.49	Lst & shale	4
14	MWQ62	549588	1493004	2045	1284	915.64	836.67	8.33	303	19	27	1.3	465.8	61.9	310.8	75.45	11.63	1.47	Lst & shale	4
15	MWQ63	548960	1493639	2032	1413	1009.6	845	8.17	288	30	20	0.67	691.1	25.11	280.5	8.503	11.57	0.85	Lst & shale	4
16	MWQ65	551033	1491964	2060	2390	1704.3	1650	7.15	600	36	107	0.4	657.87	218.5	419.6	124.2		1.61	Lst & shale	4
	Average				**1664.5**	**1897.01**	**795.60**	**7.72**	**268.14**	**33.44**	**57.13**	**1.95**	**460.63**	**98.06**	**333.18**	**61.53**		**1.70**		
	Maximum				**5300**	**13007.13**	**2041**	**8.5**	**620.00**	**120.00**	**260.00**	**4.70**	**691.10**	**298.00**	**1607.00**	**336.10**		**8.36**		
	Minimum				**722**	**436**	**228.4**	**7.1**	**84**	**7.7**	**18**	**0.4**	**340**	**15.4**	**24.3**	**0.21**		**0.15**		

AI: Aggressive Index; LI: Larson Index; Source: 1. water works design and Enterprise (2007); 2. Hailemariam Hailu (2010); 3. Gebremedhin Berhane (2002); 4. Present work, Lst– Limestone

Table 3. Chemical constituents and other properties of water from borehole source from Mekelle area

S. No.	**code**	**X**	**Y**	**Z**	**EC µS/cm**	**TDS mg/l**	**TH mg/l**	**pH**	**Ca mg/l**	**Mg mg/l**	**Na mg/l**	**K mg/l**	**HCO3 mg/l**	**Cl mg/l**	**SO4 mg/l**	**NO3 mg/l**	**AI**	**LI**	**Geology**	**Source**
1	BH-1	558941	1489255	2265	851	600	399	7.35	151.2	5.1	20	1.2	292.8	22.2	102.9	59.4		0.78		1
2	BH-3	558284	1489689	2271	985	708	462	7.48	168	10.2	21.5	1.3	322.1	42.4	97.6	82.1		0.74	Lst & dolerite	1
3	BH-4	557809	1488359	2237	688	447	308.7	7.43	109.2	8.67	18	1.6	319.2	12.5	47.5	23.8		0.34	Marl	2
4	BH-5	556722	1487915	2227	1089	785	514.5	7.52	193.2	7.65	29	1.2	289.9	18.3	250.5	18.9		1.79	Lst & dolerite	1
5	BH-6	558268	1488286	2243	769	528	401	7.64	151.2	5.6	21	1.4	272.3	12.5	150	18		1.15	Lst & dolerite	1
6	BH-7	557115	1487967	2233	785	500	394.8	7.38	142.8	9.2	20	1	351.4	17.4	63.3	24.6		0.41	lst & dolerite	1
7	BH-8	553941	1488821	2214	1034	763	531.3	7.6	176.4	1.9	31	1.4	287.2	20.3	280	17.6		2.02	Lst & dolerite	1
8	BH-9	552945	1488663	2202	1256	960	640.5	7.6	253	12.8	40	3.4	216.7	17.4	474.7	6.16		4.46	Lst & dolerite	1
9	BH-10	552219	1488072	2183	1056	812	541.8	7.53	210.6	9.18	35	3	248.9	22.2	316.5	3.5		2.63	Lst & dolerite	1
10	BH-11	552590	1488475	2194	917	620	459.9	7.42	168	9.7	34	2.8	266.4	17.4	260	3.96		2.02		1
11	BH-12	552313	1488491	2195	1053	796	552.3	7.48	210	6.6	37	3.1	245.9	19.3	324.8	3.1		2.72		1
12	BH-13	552490	1489376	2208	1650	1210	835.8	7.46	319.2	9.2	48	3.4	178.6	18.3	685.7	3.5		7.78	Dolerite & sst	1
13	BH-14	552506	1489646	2209	1900	1404	963.9	7.66	369.6	9.7	56	4.3	155.2	19.3	810	3.1		10.56		1
14	BH-21	559618	1490000	2247	863	534	409.5	7.61	142.6	12.8	20	1.1	319.2	21.2	97.6	29.9		0.68		1
15	BH-22	559953	1484601	2312	1090	698	518.7	7.58	168	23.97	26	2.6	348.4	64.6	113.4	53.2		0.84		1
16	BH-32	564070	1486356	2323	680	434	327.6	7.49	109.2	13.3	17	1.4	342.6	9.7	68.6	11.4		0.43		1
17	BH-30	560456	1482673	2317	631	385	270.9	7.73	84	14.8	34	2	348.4	9.7	44.8	7.48		0.29		1
18	BH-36	561812	1473402	2284	1405	970	615.3	7.34	226.8	11.7	78	2.4	395.3	67.6	329.6	16.7		1.84		1
19	BH-38	554920	1480973	2249	1292	840	621.6	7.48	226.8	13.1	18.5	3.1	368.9	34.7	258.5	65.6		1.50		1
20	BH-37	557291	1473063	2324	883	534	375.9	7.48	134.4	9.7	21	2.4	468.5	29.4	30	18		0.19		1
21	BH-43	552650	1485112	2205	1090	710	470.4	7.46	159.6	17.3	42	2.7	322.1	81.1	70	75.2		0.69		1
22	BH-40	554088	1481242	2255	820	516	363.3	7.6	134	6.6	11	2.2	380.6	21.2	31.6	58.9		0.22		1
23	BH-98	557115	1487960	2232	965	760	455.7	7.76	168	8.67	37	3.2	152.26	12.48	369.23	4.4		4.93	Dolerite& Lst	1
24	BH-16	553706	1488251	2210	830	586	430.5	7.89	151.5	12.75	20	1.6	266.45	13.44	174.07	15.84		1.36	Lst & dolerite	1
25	BH-89	551965	1487745	2172	1734	1523	959.7	7.3	319.2	39.27	60	2.5	14.64	56.64	896.7	4.4		126.37	Lst & dolerite	1

Table 3. Continued

S. No.	code	X	Y	Z	EC µS/cm	TDS mg/l	TH mg/l	pH	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	HCO3 mg/l	Cl mg/l	SO4 mg/l	NO3 mg/l	AI	LI	Gelogy	Source
26	BH-90	559605	1508191	2119	1730	1302	810.6	7.27	235.2	54.06	80	4.2	406.99	149.76	279.56	79.64		1.74		1
27	BH-91	564983	1513674	2040	1175	865	562.8	7.45	193.2	19.38	47	2.3	351.36	48.96	329.67	5.28		2.02		1
28	BH-72	550247	1500526	1980	1438	1015	840	7.4	260.4	45.9	29	2.3	409.92	34.6	448.35	31.24		2.27	Lst & gyp	3
29	BH-66	554141	1495331	2016	2540	2068	1486.8	7.31	502.2	44.9	81	2.2	278.2	73.3	1100	3.5		8.17	Lst & marl	1
30	BH-67	551668	1492754	2068	2680	2136	1520.4	7.35	518.4	42.8	93	9	295.8	121.6	1051	11.9		7.52		1
31	BH-69	548981	1493639	2049	1374	1044	777	7.38	243	35.7	33	1.9	366	32.8	395.6	34.3		2.25		1
32	BH-70	548313	1493357	2058	1435	1136	850.5	7.24	307.8	12.8	30	2.1	395.3	22.2	448.4	37.4		2.32	Lst	1
33	BH-71	544459	1496518	1995	2600	2150	1743	7.38	631.8	25.5	36	3	210.8	12.55	1347	2.46		12.84		1
34	BH-94	553320	1488680	2203	863	596	430.5	7.62	145.8	12.8	32	2.4	184.4	15.4	253	14.5		2.83	Lst & dolerite	1
35	BH-64	553347	1488703	2202	687	456	325.5	7.66	105	12.8	28	1.7	181.6	14.5	168.8	3.96		1.94	Lst & dolerite	1
36	BH-2	558901	1489740	2256	752	510	369.6	7.5	134	8.16	20	1.2	307.4	19.3	73.8	32.1		0.54		1
37	BH-47	555901	1486423	2252	900	540	411.6	7.31	151.2	8.16	15.5	1	348.4	36.7	52.7	86.2		0.41		1
38	BH-48	556519	1487277	2249	649	400	336	7.43	117	10.2	17	1	351.4	11.6	36.9	24.2		0.24		1
39	BH-51	547768	1500782	1946	1132	790	497.7	7.23	184.8	8.7	46	2.1	348.4	48.3	197.8	47.5		1.27	Lst and gyp	1
40	BH-52	548688	1500360	1956	1713	1149	793.8	7.3	285.6	19.4	47	1.7	313.3	127.4	205.7	272.8		1.72	Lst and gyp	1
41	BH-78	556707	1496957	2081	2520	2195	1491	7.64	504	56.1	49	4	304.5	23.04	1265.9	4.4		8.39	Lst	1
42	BH-84	569617	1490817	2434	627	373	315	7.77	105	12.75	20	0.6	319.2	10.56	36.92	37.84		0.26		1
43	BH-20	553549	1488948	2208	844	540	430.5	7.84	151.2	12.75	28	2.8	297.22	17.28	205.71	10.56		1.44	Lst & dolerite	1
44	BH-18	555526	1487648	2221	1890	1522	1113	7.57	428.4	10.2	55	3.7	202.03	15.36	892	3.52		8.91	Lst & dolerite	1
45	BH-73	550130	1498943	1960	1896	1432	900.9	7.82	302.4	35.19	111	2.3	263.52	101.76	738.46	14.96		5.99	Lst	1
46	BH-80	576048	1494893	2480	2350	1884	1404.9	7.55	478.8	50.49	55	4.4	342.58	30.72	1186.81	3.96		7.02		2
47	BH-97	559405	1487676	2262	823	612	363.3	7.69	134.4	6.63	26	2.1	202.03	22.1	187.25	33.88		1.96	Lst	1
48	BH-15	556050	1487809	2211	542	350	210	7.56	53.8	18.36	24	2	49.78	17.28	153	4.84		6.49	Lst & dolerite	1

Table 3. Continued

S. No.	code	X	Y	Z	EC µS/cm	TDS mg/l	TH mg/l	pH	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	HCO3 mg/l	Cl mg/l	SO4 mg/l	NO3 mg/l	AI	LI	Geology	Source
49	BH-57	541722	1484813	1850	1783	1384	1087.8	7.3	348.3	44.9	41	2.8	389.4	36.6	638	4.4		3.37		2
50	BH-58	546813	1486455	2106	1183	757	535.5	7.5	178.2	17.8	26	2.7	351.4	56.9	116	69.5		0.82		2
51	BH-59	545504	1489984	2131	672	426	344.4	7.39	121.5	7.14	6.6	0.4	336.7	6.76	11.6	56.3		0.09		2
52	BH-61	541483	1491682	2231	800	480	420	7.36	113.4	30.6	26	0.4	474.3	15.4	10.5	25.1		0.08		2
53	BH-63	548820	1492435	2070	1243	924	669.9	7.51	243	9.7	27	1.6	310.4	39.6	395.6	48.8		2.68		1
54	BH-95	557487	1488269	2248	705	448	361.2	7.36	121.5	11.2	17	1.4	322.1	15.4	39.6	29		0.29		1
55	MCF1	551617	1498923	1984	1774	1376	283.5	6.91	315.84	44.88	62	4.6	345.9	38.11	652.4	18.3		3.88	Lst & marl	2
56	MCF2	550855	1500131	1977	1751	1296	317.1	7.01	222.6	50.49	152	3.9	386.9	74.16	562.3	3.18		3.10	Lst and gyp	2
57	MWQ10	554049	1495122	2005	2290	1633.0	1058.3	7.88	350	44	62	2	320.86	55.21	674.6	0.29	10.4	4.38	Lst & marl	4
58	MWQ37	554369	1489536	2219	841	599.73	400	8.2	130	18	15	2	330.25	11.17	279	0.29	2.85	1.72	Lst	4
59	MWQ43	560528	1491641	2161	947	675.32	516.66	8.31	170	22	14	3	460.28	11.06	401.1	0.31	3.25	1.77	Lst	4
60	MWQ50	559092	1490160	2218	1099	783.71	400	7.94	125	21	16	2	344.69	52.45	321.6	0.29	2.63	2.02	Lst & dolerite	4
61	MWQ41	560730	1488518	2284	762	543.39	532.5	8.07	178	21	11	2	403.94	14.61	274	0.29	2.89	1.39	Lst & marl	4
62	MWQ61	550174	1500497	1981	1174	837.2	656.67	8.22	201	37	16	1.7	588	25.11	182.7	29.63		0.66	Lst & marl	4
63	CF3	552500	1499429	2022	1937	1382	409.5	6.95	188.16	69.36	202	7.7	499.6	77.25	532.6	22.44		2.29	Lst & marl	2
	Average				**1245.03**	**908.47**	**615.91**	**7.53**	**219.47**	**20.67**	**39.54**	**2.45**	**313.79**	**35.21**	**357.04**	**27.58**		**4.66**		
	Maximum				**2680**	**2195**	**1743**	**8.31**	**631.8**	**69.36**	**202**	**9**	**588**	**149.76**	**1347**	**272.8**		**126.37**		
	Minimum				**542**	**350**	**210**	**6.91**	**53.8**	**1.9**	**6.6**	**0.4**	**14.64**	**6.76**	**10.5**	**0.29**		**0.08**		

AI: Aggressive Index; LI: Larson Index; Source: 1. water works design and Enterprise (2007), 2. Hailemariam Hailu (2010), 3. Gebremedhin Berhane (2002), 4. Present work; Lst–Limestone; gyp– gypsum; sst– sandstone drinking water supply for Mekelle City and its environs. Mekelle city is a good example for cities in the developing countries which rely on groundwater for their water supply. In general, the aquifers in Quiha and Aynalem area are dominantly related to fractured dolerite with minor limestone and at places fractured sandstone (e.g. BH-4 to BH-110, BH-89, BH-98), while the aquifer in the Mekelle city and Messebo area are dominantly found to be fractured limestone and marl/shale intercalated with gypsum layers (e.g. BH-52, BH-66, BH-70, BH-72, BH-73, BH-78, MCF-1, MCF-2, CF-3).

Recent groundwater level measurements along the Illala River in five boreholes show variation in depth from 2 m to 6.3 m b. g. l. In the case of shallow hand dug wells, the depth is about 0.3m b. g. l. during rainy season in many parts of the city. An inventory of 70 boreholes and hand-dug wells within the city and its environs resulted in an average water level of 18 m b. g. l with a range of 0 to 70 m b. g. l. Fall and rise of groundwater, particularly the rising water levels affect the structural properties of soils and can reduce bearing capacity, cause swelling, and create hydrostatic uplift pressures (Brassington, 1990).

Groundwater level fluctuation is increasing from 3m in 2002 (Gebremedhin Berhane, 2002) up to 5m in 2012 (present study) indicating influence of expanding city on groundwater level fluctuation. It is expected to increase further in future if present trend continues, due to excessive abstraction and other anthropogenic impacts. Thus causing subsidence of structures and drying up of grazing and wet lands.

4.1.2. Physical and chemical characteristics

4.1.2.1. pH, Total dissolved solids, Electrical conductivity and Total hardness

In water samples pH varies from 6.9 to 8.6 with mean value of 7.6 and temperature from 25.6°to 18.7°C with a mean value is about 22.4°C.Electrical conductivity (EC) varies from 542 to 5300 μS/cm with a mean value of 1289.7μS/cm andTotal dissolved solids (TDS) from 330–1,312 mg/l for spring, 436–13007.13 mg/l for hand dug wells and 350–2195 mg/l for boreholes (Figs. 4&5; Tables 1-3). The relationship of conductivity versus total dissolved solids (Fig. 4a) resulted in to the equation: TDS = 0.8089EC – 117.59 with coefficient of correlation r = 0.9892. Most of the TDS values (Fig. 5) for the study area are beyond the permissible limits for corrosion (27 samples) and other domestic purposes (WHO, 2008). Higher TDS shows longer residence times and increased water–rock interaction. TDS content is usually the main factor, which limits or determines the use of groundwater for any purpose and controls corrosion (Mahadevaswamy et al., 2011).Except in spring water, which represent rainwater composition, TDSin most of the hand dug wells and boreholes is high due to high solubility of carbonate minerals in the Mesozoic carbonate rocks which is dominant in and around Mekelle City and its environs. Anthropogenic activities could be another reason for high TDS in the case of hand dug wells. The electrical conductivity (salinity) of the groundwater in Mekelle area is mainly associated to the intercalation of gypsum layers in the shale and limestone, which dissolves to increase the sulphate value in groundwater. It is shown in Fig.5b where electrical conductivity shows high coefficient of correlation (0.8) with sulphate ($EC=1.845SO_4+692.39$).

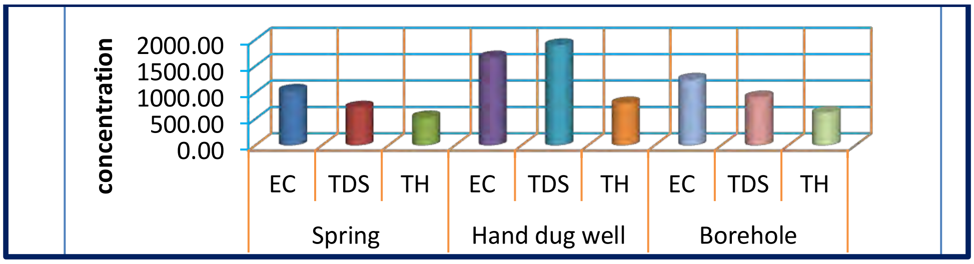

Figure 4. Average values of physico-chemical properties of spring, hand dug well and borehole water samples from Mekelle area. TH: total hardness; all concentrations are in mg/l, except EC (µS/cm).

Calcium and magnesium, along with sulfates, chlorides, and bicarbonates, account for water hardness. The total hardness (TH) as $CaCO_3$ – ranges from 273 to 947 mg/l for spring, 228.4–2041 mg/l hand dug wells and 210–1743 mg/l boreholes. The data indicate that only two samples from springs, two samples from hand dug wells and three samples from boreholes (only 5%) have TH values below 300 mg/l, which is the portable limit (WHO, 2008). The remaining samples exceed the limit, which accounts for the encrustation on water-supply distribution systems. Water with TH greater than 80 mg/l cannot be used for domestic purposes, because it coagulates soap lather.

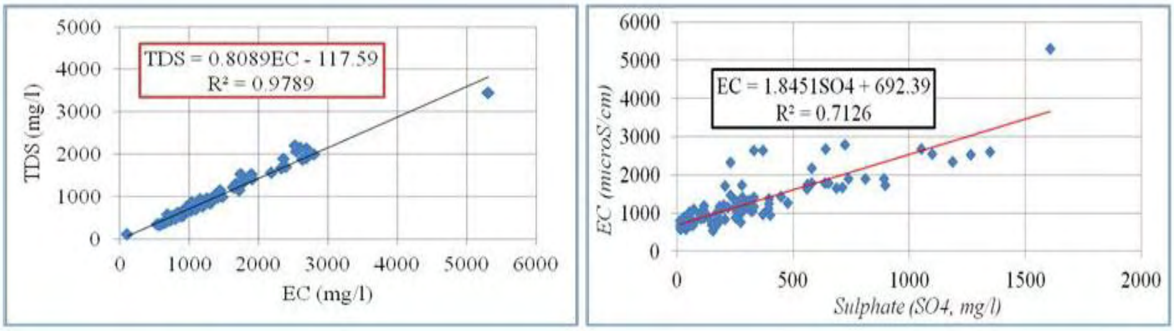

Figure 5.a. Relationship of total dissolved solids (TDS) and electrical conductivity (EC) and b. electrical conductivity (EC) and sulphate concentration (SO_4) of water samples from Mekelle City and its environs (100 samples).

4.1.2.2. Major Cation Chemistry

The relation between anions and cations (r=0.95) and the average ionic distribution of major cations and anions are shown in Fig. 6a& b. Among cations, Ca^{2+} is the most dominant ranging from 96.6–324 mg/l for spring water, 84–268.14 mg/l for shallow hand dug well and 53.8–631.8 mg/l for borehole water followed by Na^+, Mg^{2+} and K^+. Na^+ is next to calcium, varies 11–61 mg/l for spring, 18–260 mg/l hand dug wells and 6.6–202 mg/l for boreholes. High concentrations of Ca^{2+} and Na^+ in the groundwater are attributed to presence of calcite and gypsum in the rocks, mobile nature and cation exchange among minerals. Na^+causes corrosion of metals and at high concentrations reduce the clay rich soil permeability and affects the soil structure (Seneviratne, 2007), but it is highly soluble and do not cause scaling.

4.1.2.3. Major anion chemistry

Bicarbonate is the dominant anion in shallow hand dug wells (340–691 mg/l) and springs (178.6–475.55 mg/l) followed by SO_4^-, Cl^- and NO_3^-. Samples from boreholes show SO_4^- (10.5–1347 mg/l) as dominant anion followed by HCO_3^-, Cl^- and NO_3^- (Fig. 6b).The main source of bicarbonate seems to be calcite and gypsum present in limestone and marl. In shallow hand dug wells CO_2facilitates dissolution and solubility of calcite in comparison to springs and deep boreholes. Sulphate values range from 14.77 to 712; and 24.3 to 1607 mg/l for springs and shallow hand dug wells respectively. Higher values for sulphate are observed mainly in Messebo area and Mekelle city and gypsum beds which are reported in many boreholes logs (Samuel Yihdego, 2003; Hailmariam Hailu, 2010; WWSDE, 2007) form the main source. Pyrite present in shale, also contributes but very limited. Sulfate concentrations more than 250 mg/l are objectionable for many domestic purposes (WHO, 2008).

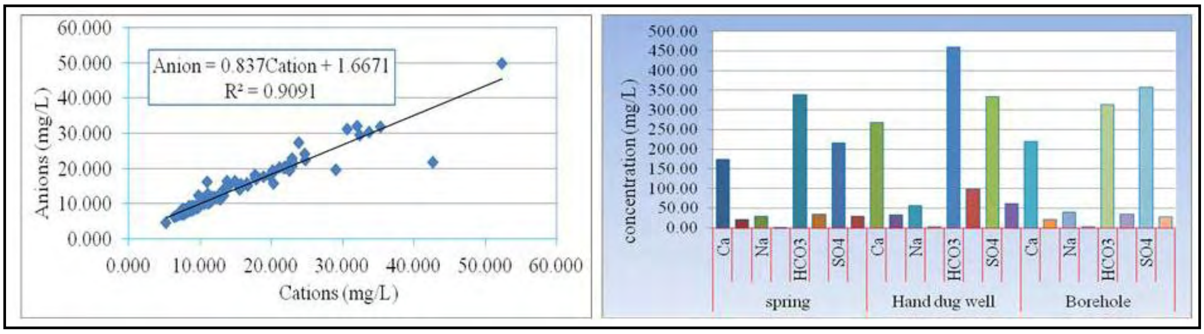

Figure 6.a) Relation between concentration of anions and concentration of cations and b) Average ionic concentrations in water samples from springs, hand dug wells and boreholes (100 samples).

Chloride values range from 5.76 to 100.4 mg/l for springs, 15.4 to 298 mg/l for hand dug wells and 6.76 to 149.76 mg/l for boreholes. The high lateral variability in chloride concentration in the area indicates some local recharge or infiltration of surface water to shallow unconfined aquifer or shallow hand dug wells. Source for chloride in groundwater could be attributed to natural processes and anthropogenic activities. Higher values for chloride in shallow hand dug wells could be attributed to human and animal activities or contamination of surface and subsurface water and saline residues in soils. Chloride ions accelerate corrosion of stainless steel even at values as low as 50 mg/L (Seneviratne, 2007).

Nitrate is seldom contributed by decaying organic matter, sewage wastes, and fertilizers (Subrahmanyam and Yadaiah, 2001). Nitrate values range from 0.27 to 98.6; 0.21 to 336.1 and 0.29 to 272.8 mg/l for springs, hand dug wells and boreholes respectively. Higher values for nitrate in many shallow hand dug wells and few springs and borehole water samples is due to contamination directly from surface run-off and sewage.

4.2. Effect of groundwater chemistry on pipes, foundations and distribution system

Many studies suggest that urban and suburban development is closely associated with groundwater quality (Shanahan, 2009; Shanahan and Jacob, 2007). Chemical composition of groundwater is a measure of its suitability for domestic consumption; industrial purposes, and is considered as one of the important parameters in the selection of type of pipes that are used for water supply(lifting, transportation and distribution). Groundwater data in and around Mekelle (Tables 1–3)not only show lateral variability but also show higher values for SO_4, TDS, Ca and HCO_3 which are mainly attributed to geology and to a limited extent to anthropogenic processes. In one of the studies, Mebrahtu and Zerabruk (2011) reported 1000mg/l mean value for TDS by for Mekelle City.

Generally, TDS above 1000 mg/l indicates its ability to conduct electric current, which is enough to cause serious electrolytic corrosion (USACE, 1994). As per the data about 27% samples were found to be above the minimum limit (Fig. 7). Thus suggests potential problem of corrosion for metal pipes in water supply systems and other engineering structures buried in the ground or in contact with water. Samples from limestone aquifer (e.g. Messebo area and Mekelle city) are found to be high in TDS compared to Quiha and Aynalem area. Total carbonate hardness in excess of 300 mg/l is considered as an indicator of incrusting water. About 92% of the samples interestingly show >300mg/l total hardness (Fig.8).

Water can cause corrosion involving many metals. Its deposition results in the development of scale depending on pH and alkalinity, hardness of water above 200 mg/l $CaCO_3$, temperature (WHO, 2008). All samples from city show hardness above this threshold. Alkalinity, pH, chloride, calcium and sulphate are primary water quality parameters that facilitate iron corrosion (Tang et al., 2006, WHO, 2008). Corrosion may uniformly attack a metal surface (uniform corrosion) or it may be focused at specific sites (Sarin et al., 2001). The concentration of these major cations and anions were found to be high (Tables, 1-3). The corrosiveness of water can be estimated by the calculation of one or more corrosion indices.

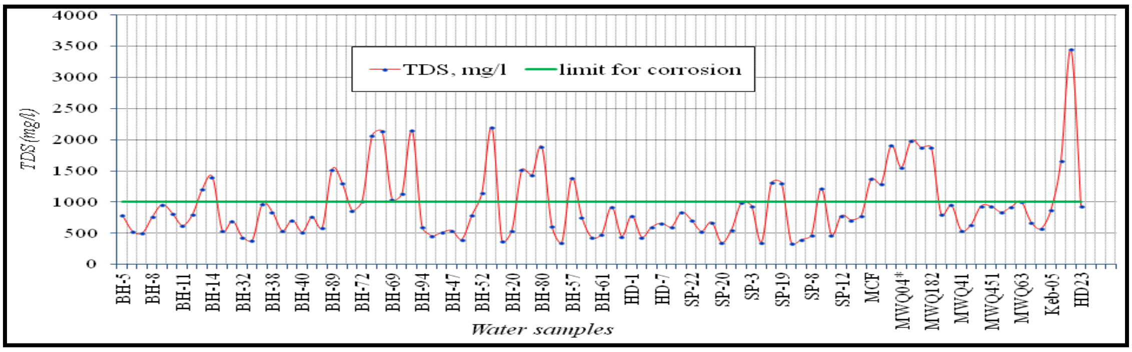

Figure 7. Variation of TDS in the water samples from Mekelle City.

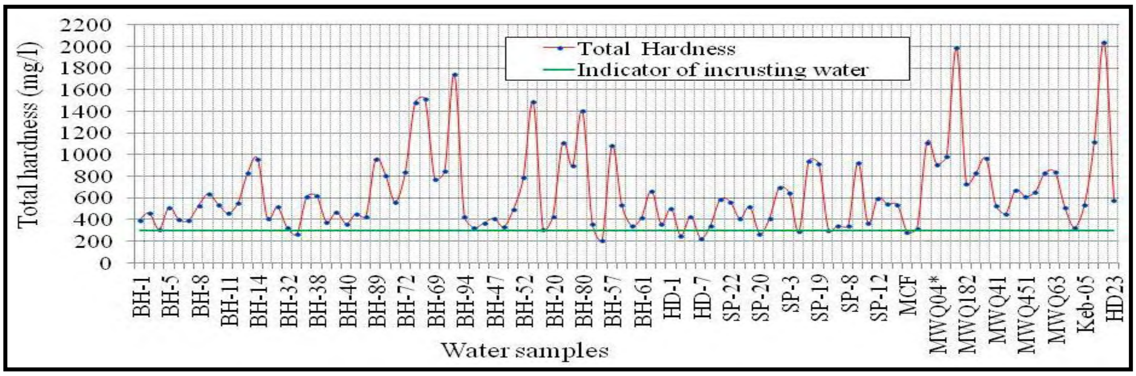

Figure 8.Variation of total hardness in the water samples from Mekelle City and its environs.

As a general insight for corrosion, the Larson Index was calculated, based on measures of chloride and sulphate concentrations. Higher concentrations of sulphate and chloride, and lower concentration of bicarbonate in soil and/or water suggest potentially corrosive environment. The result shows that 66.7%, 81.3% and 81% of spring, shallow hand dug well and borehole water samples have a Larson index (LI) above 0.5, which is considered as a threshold of corrosiveness of water to iron and related pipes and foundation materials. Higher LI value was obtained mainly from Mekelle city and Messebo area where the dominant aquifer is limestone and shale intercalation. The result is found to be in agreement with field observations where many water distribution pipes and iron used in reinforcement concretes were damaged by corrosion and rusting (Fig. 9). Hence, close follow up and monitoring of 'pH', and adjusting to the range of 6.8–7.3 (WHO, 2008), is important before entering the water into the distribution system, depending on the pipe type and in selecting foundation materials for other engineering structures.

Aggressive Index (AI) indicates the degree of saturation with respect to calcium carbonate. Very few water samples show moderately aggressive to non-corrosive (18.18%), but most of the results (81.82%) show highly aggressive water. Similarly, more aggressive water is from

Mekelle city and Messebo area and other locality were the dominant aquifer is dominantly limestone.

Higher concentration of chloride and sulphate also increases the rate of corrosion. The presence of chloride and sulphate in water promotes corrosion and pitting of iron and copper (Seneviratne, 2007). Because both ions form strong acids, they tend to increase the acidity of water. In addition to this they may increase corrosion rates by increasing the conductivity of the water. Sulphate may inhibit the formation of protective films by ion-pairing with calcium and magnesium (Schock and Neff, 1982). Figure 10 presents variation of concentration of Ca^+, Cl^- and Sulphate of the water samples. In general, the methods used in this research have shown that the groundwater in Mekelle City is potentially aggressive or corrosive to metallic materials (pipes, iron used foundations, etc.) and has the tendency to affect behaviour of geologic materials used as foundations and as construction materials.

Figure 9.Selected indications of metallic pipe corrosion and scale from Mekelle City and Messebo Cement Factory water distribution systems: a) gate valve out of use, b) tread of pipe damaged, c) gate valve start to scale and rusting and d) metallic material, pipe, almost changed into soil due to corrosion.

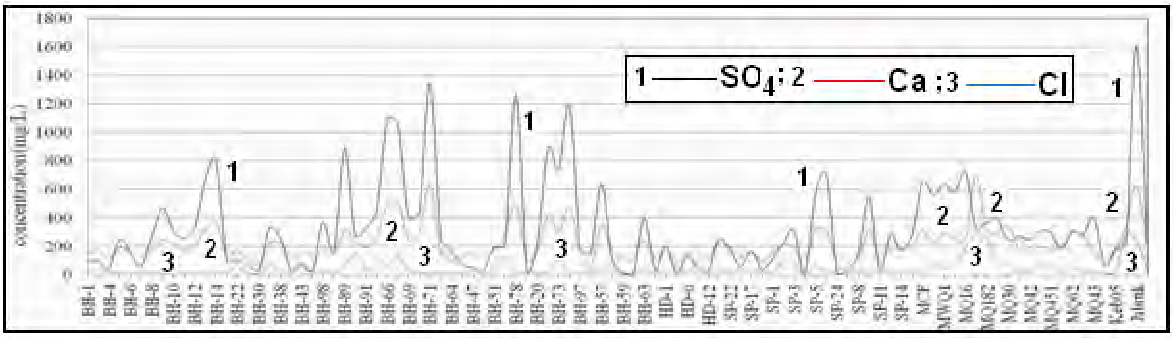

Figure 10.Variation of calcium, chloride and sulphate in the water samples, Mekelle.

At places, the problem being high, the City water and sewerage authority and others are forced to replace the existing metal pipes with polyvinyl chloride (PVC) as they are chemical resistant and affordable (Fig. 11). This situation demands an alternative solution. Possible solution to the problem in view of geology may include: a. understanding of the aquifer system and water quality before drilling the production wells for various uses; b. make efforts to locate water wells on fractured dolerite and sandstone than limestone and marl/shale; c. utilizing surface water using different storage technologies (e.g. dam & reservoir construction) and d. blending or mixing of different water sources to achieve suitable quality.

Figure11.a) Metallic pipes being replaced by PVC after leakage and clogging problems, b) corrosion problem on metallic pipe joints.

5. CONCLUSION AND RECOMMENDATIONS

Water from shallow hand dug wells and boreholes not springs, shows high content of TDS and unsuitable water quality and its implications to corrosion and related problems.

The Larsen Index (LI)is found to be above 0.5 for 84% of the water samples, an indication for corrosive character of water and Aggressive Index (AI) is found below 10 for 82 % of water samples, similarly an indication for corrosive character. Hence, both indices show similar result and in close agreement with field observations.

The hydrogeological conditions and chemical composition of groundwater are important constraints and limiting factors in the future developments, type of materials used in water distribution systems and quality of constructions in the City. Unless such information is valued and updated during planning, design and construction, the damages and concerns presented in this paper are only warnings to other costly hazards. The paper highlights the importance of adequate groundwater studies in terms of dynamics and composition, for integration into design and city planning. As a summary, the following geo-hydrological issues in Mekelle City are important to planners and decision makers:

- Shallow groundwater systems susceptible to pollution and with high TDS and TH, which may interfere with construction activities and completed engineering structures.
- Potentially aggressive groundwater to pipes and other metallic materials used in water distribution systems and engineering structures.

Detailed and integrated study on corrosion, possible chemical reactions and impact of groundwater and soil/rock chemistry on engineering structures (e.g. concrete footings) is recommended. Corrosion issue though tolerated at present, can become serious with time, becomes expensive to reverse unless proper timely action is taken.

6. ACKNOWLEDGEMENT

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