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Ministry of Water and Environment
Sana’a Basin Water Management Project
Project Coordination Unit

HYDRO GEO CHEMISTRY
OF
SANA’A BASIN

Sana’a Basin Water Management Project
Sana'a, Republic of Yemen

Final Report
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الدرويش لخدمات المياه والبيئة
Al DERWISH Water & Environmental Consulting Services

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Annexes of chemical analysis results, calculation, modelling output etc.

1. INTRODUCTION

1.1 BACKGROUND

This section describes preparatory arrangements, sampling, laboratory analysis, results, discussion and interpretation of groundwater chemistry and pollution in Sana’a Basin, as part of the Sana’a Basin Water Management Project. The project area covered by the hydrochemistry and pollution study is the entire basin 3200 Km^2.

The quality of groundwater in Sana’a Basin depends upon several factors such as lithology and chemical composition of the aquifer material, climatic conditions prevailing during formation, and the quantity of water available in the aquifer and rate of circulation. The complex depositional, solution and decomposition processes result in different hydrogeochemical conditions in groundwater. This study was based on analysis undertaken by SBWMP team and interpretation undertaken in close participation of Head of the Project and NWRA Sana’a Branch staff.

1.1.1 AIM AND OBJECTIVES

The aim of the assignment is to assess hydrogeochemical condition of the Sana’a Basin based on output of recent sampling program undertaken by NWRA Sana’a Branch’s staff. The proposed work include: data evaluation, interpretation and writing report. The purpose of the present hydrochemistry study is to update and obtain information about the hydrogeochemical properties of the main water bearing strata, and to identify and characterize groundwater pollution. More specifically, it aims to provide data on spatial variations in groundwater chemistry and differences in hydrochemistry of the groundwater in different aquifers within the Sana’a basin.

1.1.2 OVERVIEW

Detailed information on climate, lithology, runoff, human activities within the study area are described in detail within other components of SBWMP studies. Here only a brief geological and geographical context is provided in Section 1.2 and 1.3.

Numerous groundwater analysis programs have been undertaken in Sana’a Basin in several previous studies. Main studies with considerable amount of chemical analysis results are:

- Russian Study 1986
- Alderwish PhD. Study 1996
- Hydrosult study 2007

Other data gathered from NWSA Sana'a Branch covering the well fields are of insufficient quality to be used for understanding chemistry, origin and flow paths of groundwater in the Basin.

Appraisal of the available data as well as some general statements drawn from previous hydrochemical studies are provided in Section 1.3. Detailed and accurate analysis is possible only if a suitable number of appropriately distributed samples are collected and analysed, the samples are hydrochemically representative of the aquifer conditions, and the degree of external factors causing variation is minimised. Before commencing the field and laboratory works, selection of appropriate sampling sites and preparation/establishment of quality assurance procedures (ISO 2000) for sample laboratory analyses should be undertaken. These are described in chapter 2, together with sample collection procedures and sample analysis results.

The distribution of major ions in groundwater in the study area reflects the major ion chemistry of the precipitation and runoff waters recharging the aquifer, and the lithology of each of the units that the water flows through. Presentation of the spatial distribution of chemistry is presented in chapter 3 for specific aquifers. Groundwater is described on the basis of both chemical composition and chemical change, and the hydrochemical variation in the Sana'a Basin groundwater system is also described. Also in Section 3 hydrochemical cross sections are used to show vertical and lateral variation within the aquifer system. The chemical characteristics of the groundwater in the investigated area with respect to water use is described in Section 4. The effects of human activities on groundwater is found to be more pronounced in the shallow aquifers, as expected, and is discussed in Section 5, which also discusses groundwater vulnerability in the project area. Finally, the main conclusions drawn from the study are provided in Section 6.

1.2. CATCHMENT CHARACTERISTICS CONTEXT

The topography of the Sana'a basin was greatly influenced by its geological evolution, involving tectonic processes and volcanic activity. In the north, where the Amran Group outcrops, the area is represented by a high plateau with a general gentle dip (1-3^{o}) northwards. At the boundaries of the basin, elevated plateaus and mesas alternate with wadis cutting through them. These wadis in most cases run along the tectonically weakened zones and often have a canyon-shape (50-100 m width), and rarely are of trough shape 'U-shape' (200-300 m wide). Secondary valleys are mainly V-shaped, frequently with "hanging mouths" which testify to the area's higher rate of uplift, as compared with the rate of erosion of the hard carbonate rocks by water courses. Most of the area is mountainous desert topography. The watersheds between the valleys look like mountain plateaus, dissected by the valleys of higher order wadis.

Where the Cretaceous Sandstone outcrops, the topography becomes more pronounced as the sandstone is less resistant to weathering and erosion than the limestone. Wadis here are characterized by a U-shape up to several hundred metres wide, and only acquire a V-like shape in their upstream reaches. The mountain summits are often shaped like ridges, but closer to the watersheds, they are shaped like plateaus with absolute heights from 2300 to 2817 m.a.s.l. The mountain slopes formed by sandstone and shales of Mesozoic age, vary in steepness from 15o-30o, but toward the foot of the mountain become flatter by several grades. The varying amplitudes of lifting of individual tectonic blocks, as well as the uneven distribution of the volcanic cones over the area, are responsible for the step-like arrangement of the old surface of weathering. The wadi valleys developed over the volcanics are canyon- or V-shaped in their upstream reaches, but in their middle and lower parts, the valleys reveal a U-shape or flattened profiles. Their bottom width varies from tens to several hundred metres. The main primary wadis embrace a dense network of secondary wadis. The gradient of the wadis becomes gradually flatter toward the downstream direction. The Quaternary basalt forms a smooth topography of gently sloping surfaces, with numerous volcanic cones. The elevation of these cones is usually about 250-300 m above the plain.

The drainage system of the Sana'a basin forms the upper part of the catchment of Wadi AlKharid, a sub-catchment of the Wadi Al-Jawf. The hierarchy of Sana'a basin, based on valley shape and runoff, has been divided into two main types of catchments. The primary wadis have well developed valleys, with a trough-shaped configuration in the middle and lower reaches and discharge their flow into the central plain (Sana'a plain). These include 22 wadis and they are shown in Figure (2.1).

In the western and southern parts of the basin the people have terraced the hillslopes in an effort to capture the rainfall and runoff. This has led to a decrease in the intensity of the floods. Nevertheless, these wadis are very important because they concentrate the rainfall in certain zones, i.e over wadi bottoms which tend to be runoff absorbing areas, where infiltration predominates. The direct runoff produced in the Sana'a basin was reported by Mosgiprovodkhoz (1986) in probability of occurrence. However, Nash (1991) reported 29 MCM/year (9 mm/yr) (i.e 2.7% of the precipitation) as an average estimate for direct runoff based on Mosgiprovodkhoz reports. The figure estimated in 1995 was 20 MCM/year at the outlet of the Sana'a basin Alderwish (1995). A recent estimate by TSHWC, (1992) of the annual average runoff produced over part of the Basin (1925 km2) was 44 MCM/yr (10% of average annual precipitation). The present study estimates an annual average of runoff from upland areas of 74 MCM (8.3% of average annual precipitation).

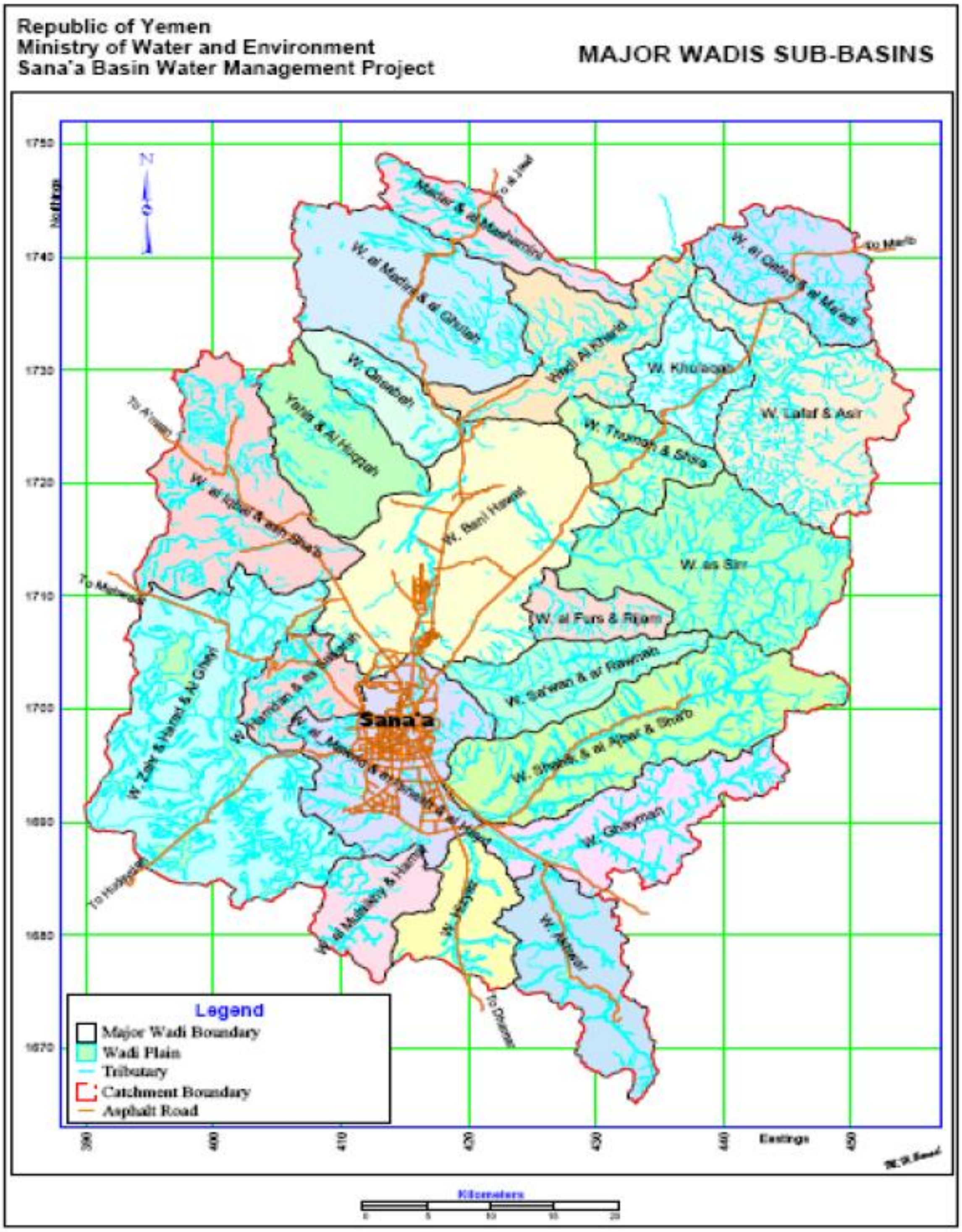


Figure (2.1) the divided 22 sub-basins of the entire Sana'a Basin (Mos. 1986)

1.3. GEOLOGICAL AND HYDROLOGICAL CONTEXT

Figure (1) shows the main litho-hydro-stratigraphic units outcrops in the basin. Abrief description for each unit is given below;

Amran Group, (Middle to Late Jurassic) it covers 370 km^2 of the basin. It conformably overlies the Kohlan formation and is characterized by rapid lateral variation in facies; nevertheless, the calcareous nature is still the main characteristic feature of the Group. Wadi Al-ahjur formation is equivalent to the Unnamed formation referred to by all the hydrogeological investigators after Italoconuslt (1973). It is generally marked by angular unconformity with the overlying quartzitic sandstone of Tawilah formation. However, in very few places, the sequence of Wadi Al-Ahjur formation is found to grade upward into the quartzitic sandy conglomerate beds of the Tawilah sandstone without interruption, this is probably due to partial subsidence of the basin in such places before the deposition of the Tawilah, a matter which prevented the erosion and deposition of the calcareous basal conglomerates. The Amran group is being disrupted by many block faulting and many of these faults are filled with igneous intrusion as well as the fissures and the stratigraphic planes. The Amran Group as reported by Howard Humphreys,(1983) has a maximum thickness of 700-900 m.

The Amran Group is generally a poor aquifer with significant permeability along fractured zones only. It shows a wide range of transmissivity, from 10 m2/d to 104 m2/d. Results of permeability tests in the of AlKharid dam shows very low intergranular permeability of about .3 m/day. The factured permeability is common in beds with fine-grained dense limestone and varies between 5 m/d to 22 m/day. Thus the formation is practically impermeable except along fault zones. Reported specific yield varies between .001 and $2*10^{-4}$.
The depth to water table is over 100 -130 m in the plateau area in the north west of the outcrop. In the north east along valleys leading to wadi AlKarid, the depth to water is less than 35 m and groundwater is extracted mainly by dug wells.

Tawilah Formation, crops out to the north-west and north east of Sana'a city, over an area of about 180 km^2. It is represented by proper continental cross beddded and graded stratified sandstone, with conglomeratic and argillaceous interbeds that rest (partially unconformably on the marly-sandy mudstone sequence (Wadi AlAhjur formation). The contact of the Tawilah sandstone with the overlying Medjzir formation is generally marked by conformity. The Tawilah sandstone is partially eroded from the areas where the overlying Medj-zir was not deposited. In these cases its upper part is generally immediately below the Tertiary volcanic or Quaternary volcanic. Italoconsult examined this formation in the outcrop in Sana'a basin plus nearby well ST-4, to find the thickness reaches 350-400 m. Medjzir formation, (Palaeocene) overlies the Tawilah, and it can be recognized easily from the underlying Tawilah Sandstone in that it is a slightly fossiliferous, finer grained, very hard, massive, compact ferruginous sandstone, with a high proportion of siltstone, clays and decomposed argillites. Its top is usually eroded or immediately underlying Tertiary or Quaternary volcanics. The presence of the decomposed volcanic tuff and "soapy clay beds" reflect the first sign of volcanic activity.

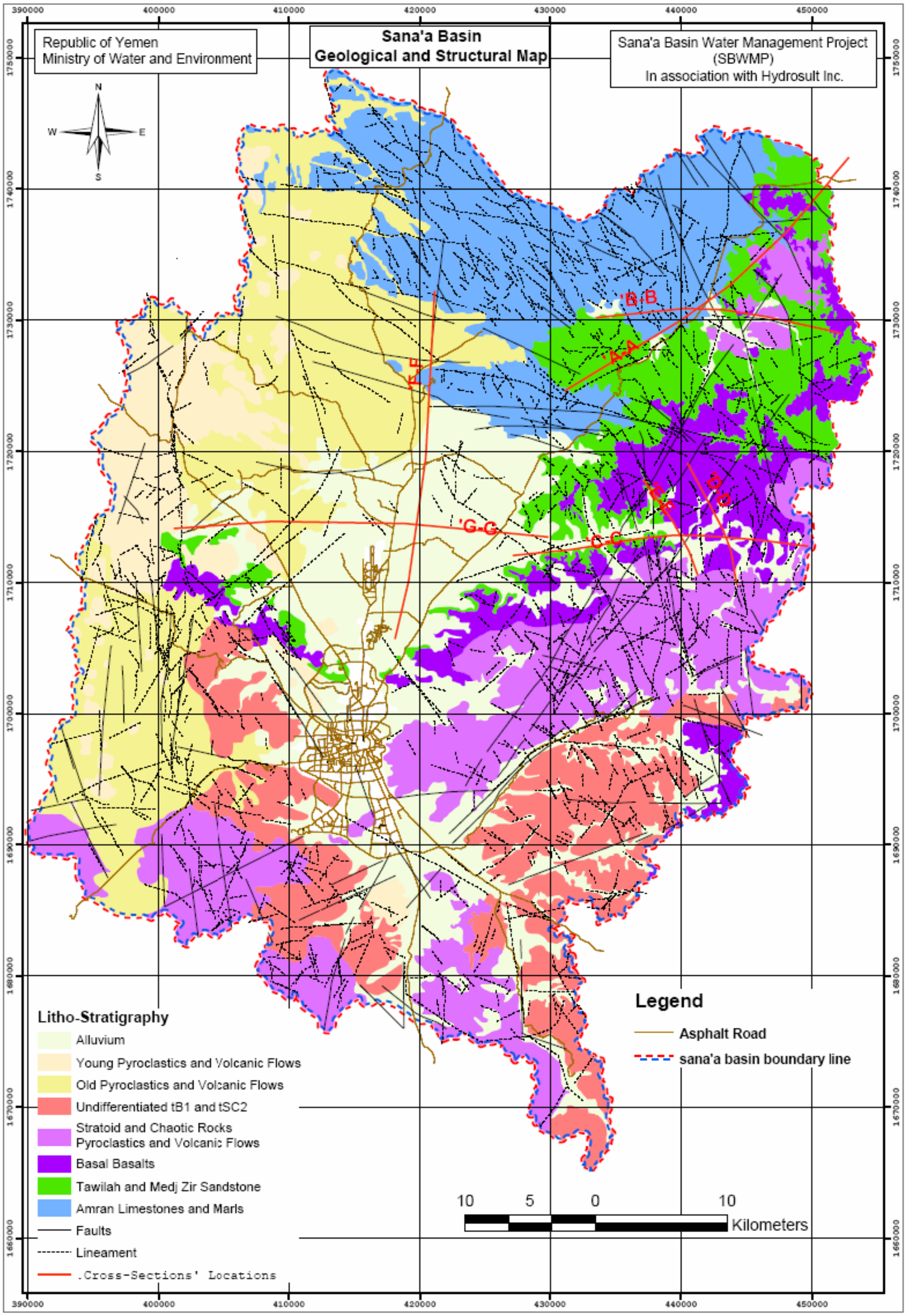


Figure (2.2) Map showing the major features of the Sana'a basin indicating Sana'a city location inside the basin.

The permeability of the Cretaceous Sandstone is characterized by both primary (intergranular) and secondary (fractures) permeability. The secondary permeability is due to fractures of variable density depending upon whether they result from dislocation alone (fault) or with volcanic intrusions (e.g. dykes). Although geophysical logging indicated fracturing throughout the sequence, calculated transmissivity values from pumping do not increase with increased penetration of aquifer (Howard Humphreys, 1983) as became apparent when some shallow existing well were deepened in 1988. This implies the fractures are tighter at depth (Nash, 1992). the highest transimissivity values ranges are 400-2000 m2/d Mos.(1986) and the lowest is 10 m2/d which is related to an unfractured location (Howard Humphreys, 1983). Where the aquifer outcrops or occurs beneath up to 50 m of unconsolidated cover, the aquifer is mainly under unconfined condition and has specific yield range of 1% to 2% (22%). The aquifer becomes semi-confined or confined when it is covered by other formations, particularly the Tertiary volcanics with storage coefficient ranging from $5x10^{-3}$ to $5x10^{-4}$.
Depth to water level in this aquifer depends upon the topography and the rate of abstraction. In areas of low abstraction, it varies from 25 to 30 m in the lower lying areas, to more than 150-280 m on the highland of the plateaux surrounding the Sana'a plain. In areas of high abstraction, as a result of development of cone of depression, the water levels exist at depth of more than 130 m.

Tertiary Volcanic, Covers 1280 km^2 and can be subdivided into three units; *basal basalt*, which consists of the first basalt lavas which covered the Paleocene sediments. It is very homogeneous, bulk greenish-black dense basalt, with columnar jointing. Small, scattered lenses of trachytic-rhyolitic material can also be found. This unit is intensively fractured and mineralogically composed of Sodic alkaline feldspar, monoclinic pyroxene and quartz. It is exposed in the periphery of the Sana'a basin, on the slopes of the deeply-cut wadis, and has been encountered by some boreholes in the Sana'a plain at depths of 150 to 190 m. Their thickness increases from 150-200 in north to more than 300m in the south. *Stratoid rocks*, covered the basal basalt and are essentially pyroclastic, mainly of a rhyolitic nature. They occur as well-bedded tuffs and ignimbrites, green, red and pink in color, with gravelly sands and gravels of a fluvio-lacustrine type sometimes interbedded. The formation is of about 100-200 m thick. It crops out in lower part of the mountain slopes, where it has thickness of 100 m. In the south of Sana'a plain, it occurs at depth of 190 m from earth's surface and has similar thickness (120-200m). *Chaotic and stratoid rocks*, consist of flows of basalt and rhyolite lavas chaotically intermingled, the former predominating. Above this horizon, bedded pyroclastic rocks resembling the first stratoid rocks are again to be found. This formation has a thickness of several hundred meters, (maximum of 500 m) with the top usually eroded. It is more widespread in the southern part of the basin, occurring only on the highest peaks in the more northerly parts. They include rhyolite, trachyte, andesite, basalt and ankramite besides a large variety of tuffs. Apart from the extensive formation of Tertiary volcanic, basic intrusive rocks are also present, and represented by necks, dykes, and often intrusions of larger dimensions. Dykes are frequent, especially near the neck, these almost vertical intrusions trending NNW-SSE and NNE-SSW occur in tectonic fractures. They are composed mainly of basalt, but rocks of a decomposed tuff type are also found.

The largest intrusion of granite occurs in Wadi Hada upstream and covers about 8 km^2 (Mos, 1986).

Low permeability of 0.5 m/d reported by Italoconsult. The contact between the basal basalt and Cretaceous Sandstone aquifer was examined by Italoconsult (1973). They concluded that there is no real boundary between these units and hydraulic interconnection was evident at Shamlan area (15 km NW of Sana'a city). More recently it was shown by Alderwish, (1992) from hydrochemical evident, the interconnection between the two aquifers occurs through zones of high vertical transimissivity. Transmissivity varies between 1 and 200 m^2/d. Measured specific yields were varies between 0.001 and 0.005.
Occurrence of groundwater table in the unit does not depend much on the elevation of the ground surface but rather to the complicated structure of this multi-layered aquifer and hence is more related to the variation of permeability. Although the static water level in the Tertiary volcanic show great variability, the general trend of the groundwater is from the mountains towards the axial plane of the wadi and then down stream toward Sana'a plain, where it moves northward towards wadi Al Kharid. In the fault zones, the groundwater flow direction depends upon the orientation of the fault.

Quaternary Basalt, Widely occurs in the west and north western part of the Sana'a basin and covers an area of 600 km^2. It is made up of basalt, augite basalt, nepheline basalt, scoriaceous and vesicular basalt and basalt tuffs. The latter found near eruption cones. No erosion at all can be recognized on some flows and cones, particularly in Arhab Mountains, and the inner most parts of the Sana'a basin. The thickness of Quaternary Basalt varies between 100 and 500 m. Generally there is no cover at all and the surface is rough and broken. In Arhab plateau, where this unit outcrops, its thickness decreases from 200 m in the south eastern part to 50 m in the eastern part. In this part the unit consists mainly of fractured basalt, tuff, pyroclastic interbedded with sand, and sandy silt. In contrast to the north western part of the outcrops where most of the unit represented by dense, hard, basalt with a thickness of up to 300 m .

The hydraulic characteristics of the Quaternary basalt depend on both fracturing and the presence of clastic deposits between flows (i.e two type; intergranular and fracture permeability). Based on the hydrodynamic map and the report by Mos., (1986), an average transmissivity for the eastern and south-east part is 51 m^2/d and storage coefficient of $3X10^{-3}$, whereas in north western part of the outcrops, the values are 1 m^2/d and .001, respectively.
Where the Quaternary basalt is saturated, it provides water-table conditions. The static water levels are deep, ranging from 61 to 138 m, depending on the elevation of the ground surface (i.e. run parallel to the topography). The groundwater flows to the east and north east toward Wadi Al Kharid (Mos. 1986). Italoconsult (1973) considered the unit of importance to the recharge of the underlying formations, but Charalambous (1983) considered they were too thick to allow significant vertical infiltration. The former is more likely, as the basalt are highly permeable since there are no perched springs or other evidence of perched water tables which would be expected if the basalt prevented the vertical flow of water. The high permeability was observed in an excavation during field work of Alderwis 1995.

Quaternary Deposits, unconsolidated deposits, are widespread and covers about 779 km^2 of the Sana'a basin. They are confined to wadi beds and low elevations forming the Sana'a plain. Their deposition has been controlled by the presence of block-faulted depressions and appears to have been of fluvio-lacustrine in nature which leads to the accumulation of silts and clays in basins. Coarse grained colluvium and alluvium mainly occur in wadi beds and at the foot of hills. The coarse detrital material have been derived from the nearby bed rock. According to isopach map of this aquifer (Mos, 1986), it shows existing of a number of small basins in the Sana’a plain.

The hydraulic parameters of the Quaternary deposits aquifer vary considerably depending on their fine-grained particle content. The reported permeability is 0.9 m/day ($1*10^{-3}$cm/s), which is indicative according to Freeze and Cherry,(1979) of silty sand, moderate permeability aquifer material. Other values of permeability for clean coarse-grained (gravelly) horizons within the aquifer, it varies between 10 to 35 m/d; for "dirty" coarse-grained horizons that are filled with silt and clay, it is 1.1 m/d, and that for the sandy loam horizons, the value is 0.7 m/d Mos. 1986. The porosity varies depending upon the material within the horizon. The specific yield was determined as 2% Mos. (1986). The static water level in this aquifer occurs at a depth of 5 to about 50 m within primary wadis, the shallower at the upstream direction. In Sana'a plain, however, it varies and it is believed that the groundwater flow is generally northward along the major axis of Sana'a plain and down stream direction in wadis.

1.4 AVAILABLE DATA AND INFORMATION

Literature review for the water quality studies within the entire Sana'a basin was performed. The extensive water quality data of previous studies were found to be study that was performed in 1983/84 by the Russian (Mos.1986), and in 1994 by Alderwish (Alderwish, 1995) and in 2006 by Hydrosult (Hydrosult, 2007).

Alderwish in 1992 and part of hydrosult study in 2007 were based on the intensive study that was performed for Sana’a basin in 1983 by the Russian (250 samples). Hydrosult in 2007 developed hydro-chemical maps for the different water quality parameters for the data of 1986 and used them as base map to assess temporal variation on water quality. The maps were developed for total dissolved solids; pH, Calcium, Magnesium, Sodium, Sulfate, Chloride, Bicarbonates and Carbonates. In 2007, Hydrosult conducted study by collecting 150water quality samples. These samples were analyzed and hydro-chemical maps for Sana’a basin were developed for year 2007. Accordingly, very simple comparison between the water quality status in 1986 and 2007 were conducted. The comparison showed that there are significant changes between the hydro-chemical maps of 1986 and 2007 in some locations. However, during 1986 the limestone aquifer was not developed as its during 2007, thus very few samples were collected from this aquifer. On the contrary, several water quality samples were collected from the alluvial aquifer. The alluvial aquifer by 2007 has been depleted in many regions, thus during the 2007 study only few samples were collected from this aquifer. Hence in general, only two aquifers have been compared between 1986 and 2007 that are the volcanic aquifer and the sandstone aquifer.

Results and conclusions from previous studies will be drawn upon while discussing the present situation and conditions. However, several general groundwater quality trends and interpretations were noted during the major previous studies (Mos. 1986, Alderwish, 1995; Hydrosult 2007). A part of Alderwish, (1992) and (1996),

- All previous study missing the relation between the chemistry and the geology. This necessitate groundwater/geology should always be involved in interpretation of groundwater chemistry.
- All previous pollution studies shows deficiency for the typical background of groundwater quality from the aquifers investigated elsewhere than at the areas of the pollution sources, to enable determination ambient mean quality and variability in terms of major constituents.
- All previous studies did not dealt with the origin and evolution of groundwater in the basin chemically. Hydrosult did not describe water types in the Sana'a basin. The main objective was to obtain field data on the chemical and bacteriological quality of groundwater in the basin in general, and at potential site source of groundwater pollution due to sewage treatment plant, north of Sana'a plain.
- Russian study only stated the chemical analysis results of water quality without reporting their distribution over the Sana'a basin. However, they reported the water type per each aquifer. Hydrosult (2007) mainly done hydrochemical mapping of major constituent of water quality (not chemistry).

2. SAMPLING, ANALYSES AND DATA PROCESSING

The chemistry survey team for this project was based in Sana'a. The chemistry team was formed from NWRA Sana'a branch staff, with responsibility for collecting groundwater samples and supervising laboratory analysis.

2.1. SAMPLING METHOD

2.1.1. SITE SELECTION

Hydrosult, in 2007 contracted to conduct a continues and regular monitoring for water quality within the basin boundary. The basis for site selection, however, was not mentioned but in general, there are three different types of monitoring stations that can be listed as follow:

1. First Priority Monitoring Stations: These locations for each aquifer are obligated;
2. Enhancement Priorities Monitoring Stations: These locations are assigned for enhancing the hydro-chemical maps developed on 2007 for the basin, the locations can be changed based on scientific reasons so that better enhancement can be performed. In addition, it is recommended that these stations can be moved to another locations where there are essential scientific needs to perform better enhancement for the spatial distribution maps. The modified locations should be discussed with the client prior to start measurement.

3- Vulnerability Monitoring Stations: These locations indicate location of highly sensitive locations for ground water pollution.

As has been noticed for these wells there are no sufficient information regarding borehole construction, casing and screen depths.

During the survey of 2009 by NWRA Sana'a Branch staff, they noticed the following:

- One well penetrate Sandstone was reported as limestone by Hydrosult.
- Some of the monitoring wells found dry and/or not operational. So these wells have been changed to adjacent ones.
- Additional borehole locations were selected as important points and should be included in the monitoring program.

In the details the following reported by the field team (Sultan, 2009), regarding monitoring network proposed by Hydrosult (2008):

HSA100 dry, HSA102 out of work, HSA83 dry, HS119 dry, HS106 dry, HS107 dry, HSA96 abandoned, HS82 dry
HSS44 dry and instead NWRA3 selected
HS57 dry and instead NWRA1 selected
HSS11 out of work and instead NWRA7 selected
HS139 dry and instead NWRA5 selected

The following wells could not be reach due to security reason (disputes between tribes):
HS27 432478 1724413 sandstone
HS28 430758 1724836 sandstone
HS25 432883 1724121 sandstone
HS24 433352 1724317 limestone
HS123 440981 1725057 sandstone
HS95 444245 1742667 limestone
New selected boreholes as NWRA believe they are important.
HS26 430466 1697999 volcanic
NWRA 8 417896 1691471 volcanic
NWRA 4 430387 1675973 volcanic
NWRA 2 401968 1698153 volcanic
Problems occurred during 2009 field survey:

1. wells are located in inaccessible areas without roads for cars, with very rigid and tough topography.
2. tribes problems between themselves hender arrive to some wells
3. several wells are either dry, or out of works
4. the field team has confronted by troubles (bad words, throw stones etc.) by some well owners

2.1.2. SAMPLE COLLECTION

In total, 103 samples were collected from wells. No duplicates samples were collected. Samples covered the alluvial aquifer (10 samples), Volcanic aquifer (35 samples), sandstone aquifer (25 samples), and Limestone aquifer (33 samples). Sample locations are shown separately for each aquifer. .

During sampling, the well owner was asked for any further information about the well, Field parameters measured at the well site were include PH, EC and Temperature. Only wells in current use were sampled, and only after the water standing in the well had been pumped out for a minimum of 10 minutes, in order to get a representative groundwater sample.

Samples were taken in a clean, new polythene 250-500 ml containers. At the site, the containers were rinsed using the water being collected. Then the containers were filled with water so that there was no air left in the containers. In the case of a closed irrigation well connected with a pipeline system, the outlet was chosen as close to the well as possible to decrease the influence of warming by the sun.

Labels were written on thick card with indelible pen, recording the time, date, sample location, sample number and analysis type, and attached securely to the sealed containers. The groundwater samples were stored in cool boxes while being transported to the lab, where they were analysed shortly after arrival.

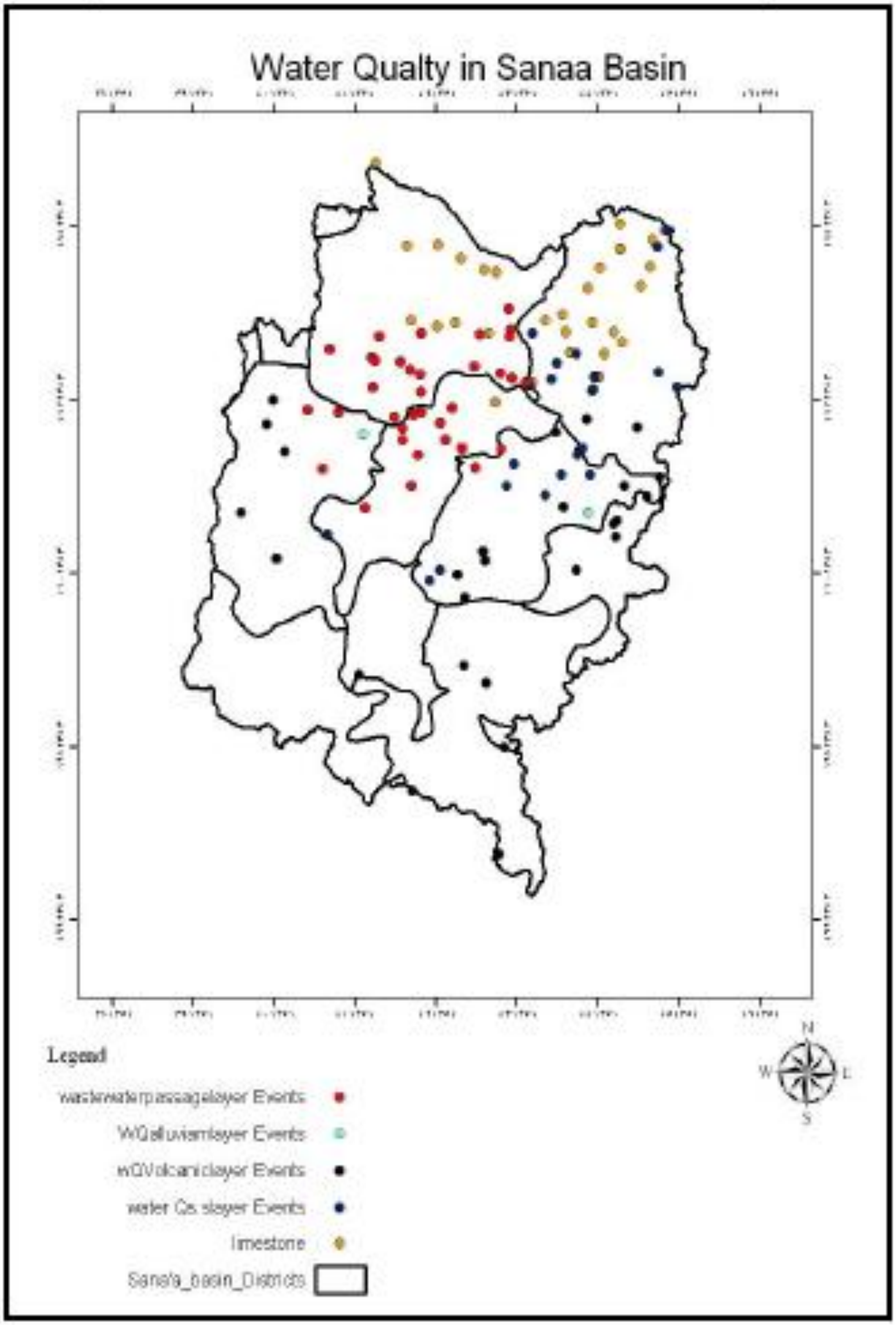


Figure (2.3) Samples locations in the Sana'a Basin

2.1.3. MEASUREMENT OF FIELD PARAMETERS

The purpose of making measurements at the wellhead is for convenient rapid assessment and to provide control for laboratory measurements. The latter is important as the physical conditions of a sample may change between the time of sampling and the laboratory measurements. The field parameters measured in the field were, pH, electrical conductivity, and temperature using a multi-function Eijlklimeter.

The simplicity of measurement of electrical conductivity (EC) makes it a practical standard, giving an indication of the total dissolved solids of the water sample.

The measured pH is an important parameter in geochemical equilibrium and speciation calculations. The degree of precision of pH measurements, however, requires attention to electrode maintenance, buffer solutions, and temperature corrections. Measurement of temperature is required for control of other measurements, as all other parameters are sensitive to temperature. Also it may be used to differentiate between recharge and discharge areas and may refer to depth of water origin. For all water samples, temperature varied between 18.2^{o} C and 37^{o}C.

2.2. LABORATORY ANALYSIS

2.2.1. SAMPLE ANALYSIS

During the present study, the following chemical parameters in groundwater were determined at NWRA's chemical laboratory in Sana'a. The methods used are shown below. These methods are described by APHA (Standard Methods of water and waste Analysis 17th edition, 1989), and were agreed and verified before start of laboratory analysis.

1. Carbonate volumetric method
2. Bicarbonate volumetric method
3. Chloride volumetric method
4. Sulphate turbidity method (colorimetric)
5. Nitrate reduction (HACH) method
6. Nitrite colorimetric – sulf & NED
7. Calcium titration by EDTA
8. Magnesium titration by EDTA
9. Sodium flame photometer
10. Potassium flame photometer
11. Fluoride SPADNS
12. Phosphate colorimetric – Ascorbic acid
13. Iron colorimetric – 1,10 phenanthrolein
14. Ammonium Distillation method by Nesslar

2.2.2. QUALITY ASSURANCE (QA)

Analysis of samples for main ions was conducted in the NWRA Sana"a Branch laboratory in Sana'a. The laboratory was selected for the staff to be trained and gain experience of similar analysis. A chief chemist from NWSA was involved to develop suitable protocol and methodologies for sample analysis for the NWRA branch. In addition, SBWMP directly provided the laboratory with complete sets of fresh chemicals to be used for analyzing samples.

While these efforts produced a substantial improvement in lab performance compared to before the project start, the laboratory is nonetheless not capable of working to international accredited standards. N such accredited lab currently exists in Yemen, and this must be seen as a future development priority for Yemen in the water resources sector.

Quick assessment of the laboratory performance, there is no clear procedure to follow the sample through the entire laboratory process from log-in at the laboratory through to sample reporting. A better procedure should be put in place which may include:

- Decision on methods for all proposed analytes, should be as listed below;
- Development of a scheme for training the staff;
- Demonstrating competence of staff with the proposed methods, and validation of the methods;
- In conjunction with the above, recording and retaining records of training and method validation;
- Development of recording and tracking sheets for the laboratory; and
- Development and documentation of a QA/QC system for the laboratory.
- Training of one NWRA staff to ensure they understood the sampling methods and operation of the field analytical equipment.
- Submission of triplicate and duplicate samples to ensure laboratory consistency;

2.3. DATA PREPARATION

Sampling results have allowed development of a general description of the hydrochemistry of the Sana'a Basin. The hydrochemical results support the overall hydrogeological interpretation developed for the Basin. The hydrochemistry of each of the main aquifer units is discussed below, focusing on the main parameters of interest, and the overall hydrochemical speciation, and its relationship to overall observed groundwater flow patterns and use.

The chemical analyses results of 103 samples undertaken by SBWMP (2009), were processed using the quaChem version 4.0 for water quality data analysis, plotting and modeling Lukas Calmbach and Waterloo hydrogeologic Inc. (2003). The program can calculate the following:

1. ion balance error
2. molar concentrations of each ions
3. total dissolved solid
4. electrical conductivity
5. activity of each ions
6. ionic strength
7. saturation indices
8. ion ratios

A typical program out put is given in the appendix II. Description of this program found in the User's manual. A copy of the program has been installed in NWRA'a Sana'a Branch counterpart staff and he has been trained on using it.

While the hydrochemistry interpretation included the following:

- Reliability check report for laboratory data;
- Hydro -chemical characteristics for water at different aquifers;
- Groundwater classification;
- Statistical analysis;
- Distribution of major ions;
- Descriptive statistical analysis;
- Rock source deduction;
- Spatial distribution maps for the different measured parameters
- Water quality index maps to present suitability of water quality for different intended uses;
- Hydro-chemical relation between different aquifers;
- Hydro-geological connections between different aquifers

2.3.1. RELIABILITY CHECK

Before using the chemical data, the quality of the analyses was checked. The Reliability Check report allows you to confirm the validity of the measured sample data. There are a number of tests provided in AquaChem which can provide insight into the reliability of your analysis. The reliability check report provides a number of checks which can provide insight on the reliability of the water sample analysis. If the analysis value passes the test, then a pass will be displayed in the Result column; if not, then a fail will be displayed. Each analysis is explained in the Table below:

Table (2.1) Available Tests in the reliability check report

Check number	Test	Attention Value	Comments	Test used in present study
1	Balance (C-A)/(C+A)*100	<5%	The solution must be electrically neutral or within: sum of cations = sum of anions.	Used
2	TDS: [(Entered-calculated)/Entered]*100	<5%	Calculated TDS = sum ions (mg/L) + SiO2 must be similar to measured dry residue.	Not used as SiO2 not used
3	TDS: [(Entered - TDS180o calculated)/Entered]*100	<5%	Calculated TDS = sum ions (mg/L) + SiO2 - 0.5082 * bicarbonate. Must be similar to measured dry residue at 180°.	Not used as SiO2 not used
4	TDS Entered/Conductivity	0.55 < x < 0.75	There is a linear relation between TDS and conductivity within a range of 0.55 to 0.75.	TDS measured from EC or vice versa
5	Conductivity/Sum MEQ Cations	90 < x < 110	There is a linear relation between Conductivity and Sum of Cations within a range of 90 - 110.	Not used
6	K+/[Na++ K+] meq/l	<20%	Na >>K	Used
7	Mg++/[Ca++ + Mg++] meq/l	<40%	Ca > Mg, unless provided by the dissolution of dolomite.	Used if explained
8	Ca++/[Ca+++SO4--)	<50%	Most SO4 concentration can be attributed to the dissolution of gypsum. Therefore the Ca/SO4 ratio must be 1:1 or lower, if some Ca is also provided by the dissolution of carbonate.	Used if explained
9	Na+/(Na+ +Cl-)	>50%	Chloride is mainly provided by the dissolution of Halite (NaCl). Therefore the ratio Na/Cl is 1 or higher, if some Sodium is added to the solution by the solution of silicates or by ion exchange.	Used if explained

NOTE: Some attention values are displayed as "acceptable ranges". This means that the Analysis value must be within this range. The analysis (calculated) values can be positive or negative. If the analysis values are outside this range (either positively or negatively) then the value will not "pass" this check, and the report will display a "fail", indicating that the sample did not pass this analysis check.

If the calculated values are not within the attention values (i.e. the Result is fail), then this does not necessarily signify an error; it does mean however that there should be an explanation for the value. This is true for the last four parameters as other explanation could be provided example of model out put is given in Table (2.2) For example, if Na/Cl<1 then the explanation could be that some Na has been removed from the solution by Na > Ca exchange: this should be confirmed by a suitable aquifer geology (exchange friendly minerals such as Ca-rich clay). Ca/SO4 < 1 can be explained by the dissolution of ferrous minerals such as pyrite. This effect is often observed in mine tailings. However, normal groundwater samples should fulfill all the criteria mentioned above.
For more details please see the reference below:
Hounslow, A.W. 1995. Water Quality Data – Analysis and Interpretation. CRC Press LLC. p.75.

Table (2.2) Output sample of reliability check by Aquachem

Sample Designation: HS100, 09/08/2009			
Check	Attention Value	Analysis Value	Result
Balance (C-A)/(C+A)*100	<5%	-3.09	Pass
TDS: (Entered - calculated)/Entered*100	<5%	24.39	Fail
TDS: (Entered - TDS180 calculated)/Entered*100)	<5%	-1.53	Pass
TDS Entered/Conductivity	55< ## <75%	65	Pass
Conductivity/sum MEQ Cations	90< ## <110%	4312	Fail
K+/(Na+ + K+)	<20%	2	Pass
Mg++/(Ca++ + Mg++)	<40%	65	Fail
Ca++/(Ca++ + SO4--)	>50%	50	Pass
Na+/(Na+ + Cl-)	>50%	60	Pass

Errors in Analysis:
Checking the ion balance is good practice to eliminate gross errors mainly arise as a result of:

- failure to measure rapidly changing parameters in the field (pH, alkalinity, etc)
- poor or no filtration (removal of suspended solids)
- improper sample storage (pressure, temperature, buffering, sealing)

Additionally, the check of correctness of analyses is carried out through the following parameters

(1) Ionic balance
The possible reasons where there is an electrical imbalance include:

1. The design of the sampling program neglected a major dissolved species - An important anion or cation was not included in the analysis. Sometimes this can point out

the presence of a high concentration of an unusual anion or cation. Standard Solution: Ca^{+2}, Mg^{+2}, K^{+}, Na^{+}, HCO_3, CO_3, Cl-, NO_3 , SO_4
2. Laboratory error - A serious, systematic error has occurred in the analysis.
3. Using unfiltered water samples that contain particulate matter that dissolves in the sample when acid is added for preservation purposes.
4. The precipitation of a mineral in the sample container that removes the constituents of the mineral from the water.
5. In certain cases the dissolved species of the element of compound may not correspond to the typical species used in making the ion balance calculation.

Results of calculation of ionic balance of the 103 samples is shown in Table (2.3)

Table(2.3) Summary of Ionic balance findings

Aquifer	Total samples Analyzed	Samples with micro-biological analysis	Samples with chemistry analysis	Number Of samples with Ionic balance error >5%	Remaining Valid samples for interpretation
Amran	32	12	20	4	28
Sandstone	27	2	25	1	26
Volcanic	34	8	26	5	29
Alluvial	10	8	2	0	10
Total	103	30	73	10	93

Details of samples removed from further analysis due to their large ionic imbalance are shown below:

Table (2.4) Details of samples shows ionic balance >5%.

Well ID	E	N	well type	Aquifer	Sum Cations	Sum Anions	Ion Balance %
HSA72	421515	1730889	Bore	limestone	13.8	10.4	13.9
HSA91	429370	1725365	Bore	limestone	31.1	27.4	6.5
HSA110	418279	1712455	Bore	limestone	7.1	6.2	6.8
HSA67	427306	1737420	Bore	limestone	11.0	9.6	7.1
HS146	434905	1711413	Bore	Sandstone	7.0	6.3	5.6
NWRA 4	430387	1675973	Bore	Volcanic	5.2	4.5	7.9
HSS10	424849	1691790	Bore	Volcanic	4.6	4.0	6.8
HS134	449088	1713454	Dug	Volcanic	12.5	10.8	7.4
HSS19	438762	1702751	Bore	Volcanic	4.1	3.6	5.9
HS129	436267	1718700	Dug	Volcanic	5.6	4.8	8.2

(2) TDS Check

Three measured TDS are provided by Aquachem.

Calculated TDS = sum ions (mg/L) + SiO2 must be similar to measured dry residue.
Calculated TDS = sum ions (mg/L) + SiO2 - 0.5082 * bicarbonate. Must be similar to measured dry residue at 180°.
There is a linear relation between TDS and conductivity within a range of 0.55 to 0.75.

As no measurement for SiO2, TDS check involve SiO_2 has not been used. i.e. TDS1 and TDS2 while the third test by Aquachem not applied because EC or TDS was calculated from the other parameter. As TDS was not measured as a solid residue at lab no checks through TDS were undertaken for any sample.

(3) Concentration value of CO_3 when PH is less than 9,

When PH is about 9 the CO_3 is only 4% and HCO_3 is 96%. HCO_3 is commonly the most abundant species of inorganic carbonate. According to bjerrum plot 15 samples with PH of less than 8 show high value of CO_3. For examples, one sample (HSA92) with PH of 6.55 has CO_3 of 34.6 mg/l. The error here is apparently related to the late measurements of the PH and Alkalinity in the lab. This

(4) Electrical conductivity

The analyses of groundwater samples collected from Sana'a Basin were then double checked by comparing total cations and anions with the electrical conductivity. The EC is related to the ions which are present in solution. An EC of 100 mS/cm is equivalent to a concentration of about 1 meq/l of dissolved ions (Appelo and Postma, 1993).

The percentage deviation of the calculated EC from the field measured EC was calculated, and the deviation found to range from 2 to 49%. While One sample with deviation of 94% has been excluded form any further analysis (NWRA5). In fact only 2 samples shows deviation of less than 10%. Therefore, EC parameters was not used in any further analysis. Also comparing measured EC at lab with calculated EC, 43 samples (50%), have deviation of more than 10%. Consequently, as measured TDS was based on the measured EC in the lab have not been used. Instead Calculated TDS (sum of all ions) have been used to describe the total dissolve solids. The results of the chemical analyses are given in Annex.

3. GROUNDWATER CHEMISTRY OF SANA’A BASIN

The distribution of major ions in groundwater in the study area is the result of the initial major ion chemistry of the precipitation, runoff, and the lithology of each of the unit that the water flows through. Some ions have also been affected by man, however this is found more pronounced in the shallow aquifers. Hydrogeological conditions also have their affect for example for a given rock type, areas of low permeability usually have higher ion concentration due to the longer residence time in comparison to the more permeable one.

Hydrochemical classification, Spatial and temporal variability in water properties has been used to gain more understanding of the aquifer characteristics, origin of groundwater, delineation of recharge zone, and aquifers interaction within the system and to assess groundwater vulnerability. These have been achieved through parameters distribution over all aquifers system within the entire basin and not through considering parameters distribution separately for each aquifer alone.

3.1. HYDROCHEMICAL CLASSIFICATION

The classification of water chemistry is intended to describe the hydrochemical variations in the Sana'a basin system. The basis of the classification used in this study includes both chemical composition and chemical change, together with elements of geological and geographical control. The latter elements are found essential to provide meaningful interpretation.

The Sana'a basin received most of its natural recharge from infiltration along wadis from atmospheric rainfall and runoff water. Generally this water is expected to be saturated with respect to atmospheric CO_2 (partial pressure $<10^{-3.5}$,atm) and oxygen. As infiltrated water passes through the soil zone, it accumulates additional CO_2. The dissolved gases increase the capacity of the groundwater (H_2O) to dissolve minerals. Goldich (1938) studied the weathering of igneous and metamorphic rocks and proposed a silicate mineral-stability series associated with rock weathering. He attributed the differences in mineral stability to the changing equilibrium conditions during formation of the minerals (such as changing temperature and pressure in a magma), which have been described by Bowen (1922). He suggests that equilibrium conditions at the time of silicate-mineral formation are significantly different from surface conditions and that this is the reason for mineral weathering and the variability in rates of mineral weathering. For example, plagioclase is less stable under surface conditions than potassium feldspar, which in turn is less stable than crystalline quartz.

Garrel (1976) on the basis of normative mineral calculations, inferred a 'rank list' of minerals and their relative rates of reaction. This list is in general agreement with Goldich's stability series. Conversely, other minerals such as calcite and pyrite, that are formed at or near the Earth's surface, do not undergo large changes in temperature and pressure. The stability of these minerals is influenced more by changes in pH and concentrations of dissolved gases, such as carbon dioxide (CO_2) and oxygen. In general however, calcite is more prone to weathering than are feldspar minerals (Stumm and Morgan, 1981).

The relative abundance of minerals in an aquifer also has an effect on water chemistry. For example, Garrels (1976) concluded that the rate of alteration of hornblende in a rhyolite is greater than that of plagioclase feldspar (on the basis of normative mineral calculations), even though the calculations indicate that plagioclase makes a larger contribution of ions to the reconstructed water chemistry. These observations and the fact that the predominant mineral in the rhyolite is plagioclase indicate that dissolution of minerals that constitute a large percentage of the parent material (but are less reactive) can contribute to water chemistry. Therefore, in this report it is assumed that the groundwater in Sana'a basin aquifer water chemistry is dominated by the faster reacting and more abundant minerals and that the effects of slow-reacting minerals are negligible.

The hydrochemical variation for each unit is described, together with the comparison and interrelation between the aquifers in Sana'a Basin hydrogeological systems.

3.1.2. AMRAN GROUP

29 samples analyses results were used to evaluate water classification in the limestone aquifer. The correlation matrix of these samples is shown below:

Correlation coefficient	pH	Na	Mg	Ca	Cl	K	SO4	HCO3
pH	1	-0.32	-0.296	-0.468	-0.214	-0.384	-0.45	-0.37
Na		1	0.2	0.174	0.412	0.553	0.419	0.349
Mg			1	0.784	0.522	0.453	0.713	0.584
Ca				1	0.269	0.655	0.907	0.601
Cl					1	0.187	0.165	0.207
K						1	0.714	0.611
SO4							1	0.478
HCO3								1

Highest correlation coefficient noticed between Ca and SO_4 with 0.907 which indicate gypsum solution. Other elements show lesser correlation coefficient. Summary of statistics of limestone samples is given in Table (3.1).

Table (3.1) Summary of 29 samples statistics representing Limestone aquifer

Parameter	Unit	Min	Max	Average	St. Dev.	Dev. Coef	Q25	Q50	Q75
Ca	mg/l	6.4	579.4	133.4	126.9	95.1	62.0	85.5	144.5
Mg	mg/l	4.5	154.1	49.0	35.2	72.0	23.7	37.6	68.0
Na	mg/l	20.0	423.0	128.8	94.5	73.4	64.0	94.5	179.0
Cl	mg/l	8.8	314.6	87.4	89.6	102.5	29.9	60.6	76.1
HCO3	mg/l	112.3	905.1	359.7	178.1	49.5	244.4	311.1	376.6
SO4	mg/l	23.0	1700.0	362.5	413.4	114.0	65.6	162.5	509.4
TEMP	°C	21.5	33.0	25.4	2.6	10.4	23.0	25.0	27.0
pH		6.9	8.5	7.4	7.4	100.0	0.0	0.0	0.0

calc TDS	ug/l	330.3	3421.3	1149.3	742.3	64.6	585.7	802.9	1482.5

The Amran Group is characterized by rapid lateral variation in facies, and the outcrop of this unit falls in the area of the least rainfall. The groundwater from this aquifer is classified into, Figure (3.1):

I *calcium bicarbonate water*, is not so common in the water samples (4 samples), in spite of the dominance of carbonate material. Presence of gypsum and evaporites appear to control the groundwater chemistry of this aquifer due to they are more soluble than carbonate materials. The TDS of the three samples are more than 500 mg/l which indicate carbonate weathering and only (HS104) with TDS <500. The Cl/sum ions <0.8 confirms rock weathering and the water had not passed through evaporites layers. The four samples are saturated/oversaturated with respect to Calcite. For the sample (HAS77) the ratio of Ca/Ca+SO4 is more than 0.5 indicates that the calcium source other than gypsum - carbonate or silicates. This sample is collected from Dugwell in Bani Al Harith with groundwater table of 8 mbgs. Similarly sample HS104 with shallow groundwater table in Wadi Al Maadi.

II *calcium sulphate water,* presents in wadi A'sir (HSA120 and HAS 122 samples) and Al Maadi (HS96). Gypsum dissolution result in water has value of Ca/(Ca+SO4) equal 0.5. IOt has been found this value for sample HS120 is 0.45 which indicate water originating from gypsum dissolution. While for sample HSA122 is 0.38 and for sample is 0.407 indicating additional processes of calcium removal - ion exchange or calcite precipitation.

III S*odium sulphate water type,* mainly present at wadi Qasabah. Three possible processes combined together probably are resulted in this water type. The first one is the dissolution and precipitation of gypsum\ anhydrite. The annual potential evaporation in Sana'a basin exceeds annual precipitation by a considerable amount. Thus, water that infiltrates in normal precipitation years evaporates and deposits small quantity of gypsum. Repeated rain events results in accumulation of grypsum in the upper part of the soil horizon. The rate of accumulation process would increase significantly in the case of irrigated land, which is appear to be more likely, as indicated from the density of shallow dug wells in this area. Exceptional recharge can dissolve some of this soluble material and move it down and into the groundwater system. This process is accompanied by cation exchange reaction with Ca and Mg in the water exchange with sorbed Na as groundwater move down into the aquifer. This process requires a large reservoir of exchangeable sodium. Availability of clay minerals deposited in a marine environment in the Amran Group has been evident Alderwish (1992). Presence of shale within the geological section of Amran Group may be considered as another source for sodium (Hem, 1985). However, the samples have large value of Na/Cl (4.6 -4.9), which may support ion exchange process. The third process is the oxidation of pyrite.

IV *Sodium Bicarbonate water type;* 2 samples at wadi Al Kharid (HSA109) and wadi Al Mashami (HSA68). The ratio of (Na/(Na+Cl) for these samples are > 0.5 indicating Sodium source other than halite – albite. The responsible process is probably the cation exchange reaction with Ca and Mg in the water exchange with sorbed Na as groundwater move down into the aquifer. This process requires a large reservoir of exchangeable sodium. Availability of clay minerals deposited in a marine environment in the Amran Group is discussed by Alderwish (1992). Presence of shale within the geological section of Amran Group may be considered as another source for sodium (Hem, 1985). However, the samples have larger value of Na/Cl (5.5 -8.6) seems to support ion exchange process.

Mixed water type with some samples dominated with a cation or an anion represent transient water, between the main water types. 8 samples of these water have TDS >1000 mg/l. Dominated HCO_3 water type is commonly has TDS of less than 500 mg/l and represent recharge fresh water, Alderwish (2010).

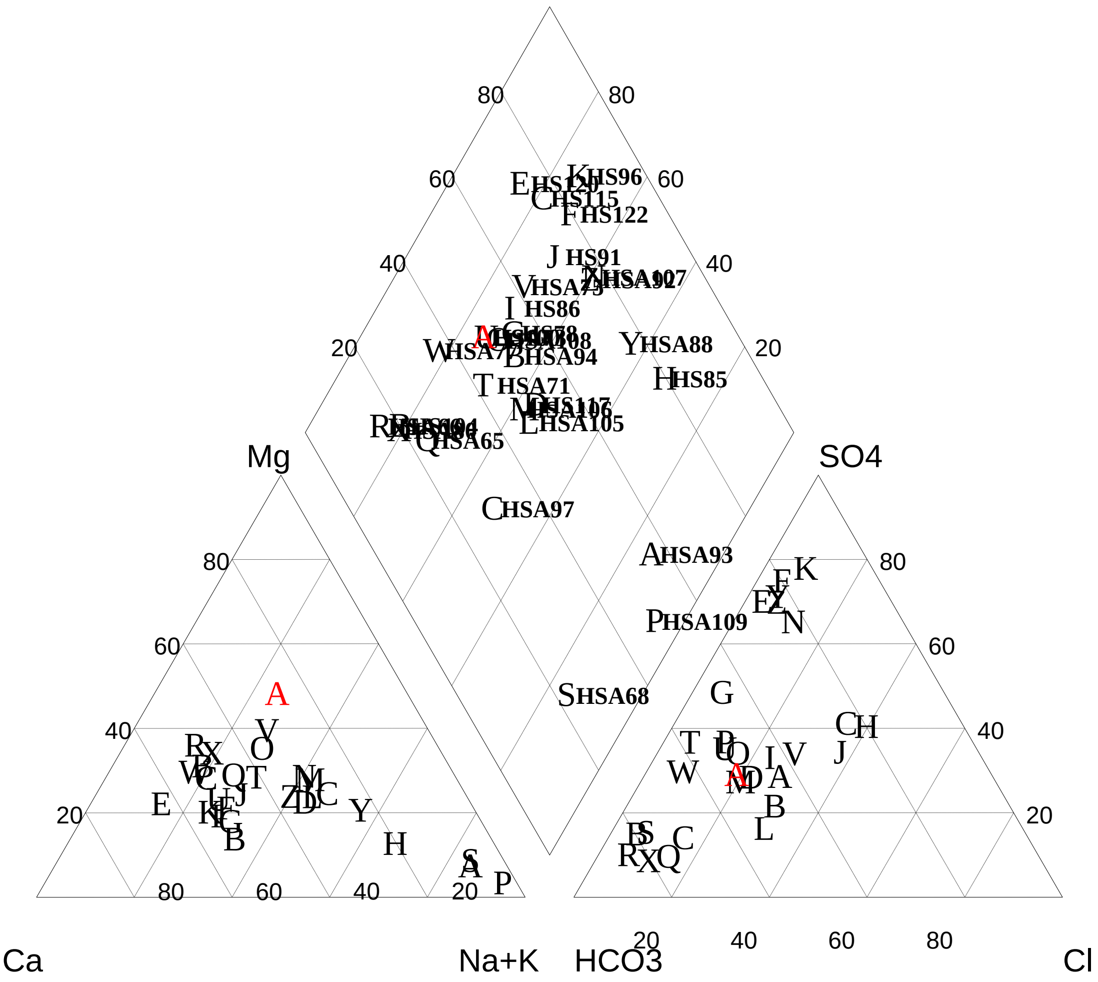


Figure (3.1) Piper Diagram for limestone aquifer

3.1.3. CRETACEOUS SANDSTONE

24 samples analyses results were used to evaluate water classification in the Sandstone aquifer. The correlation matrix of these samples is shown below:

Correlation coefficient

	pH	Na	Mg	Ca	Cl	K	SO4
pH	1	0.145	-0.132	0.136	-0.321	0.232	0.186
Na		1	0.499	0.795	0.322	0.887	0.854
Mg			1	0.724	0.504	0.609	0.68
Ca				1	0.231	0.902	0.972
Cl					1	0.133	0.13
K						1	0.936
SO4							1

Highest correlation coefficient noticed between: SO_4 and Ca 0.972, SO_4 and Na 0.854, SO_4 and K 0.936, K and Na 0.887, and K and Ca 0.902. Summary of statistics of Sandstone samples is given in Table (3.2).

Table (3.2) Summary of 24 samples statistics representing Sandstone aquifer

Parameter	Unit	Min	Max	Average	St. Dev.	Dev. Coef	Q25	Q50	Q75
Ca	mg/l	48.9	414.1	124.4	84.9	68.3	65.3	88.0	154.0
Mg	mg/l	13.4	88.5	34.5	20.2	58.5	20.2	25.5	43.4
Na	mg/l	18.0	355.0	74.1	71.2	96.1	32.0	48.8	88.0
Cl	mg/l	12.8	238.1	69.9	57.4	82.1	28.8	54.3	88.6
HCO3	mg/l	205.0	598.8	298.0	104.8	35.2	216.0	250.6	353.9
SO4	mg/l	25.0	1325.0	249.0	295.5	118.7	75.0	137.5	262.5
TEMP	°C	20.2	37.0	29.5	4.1	13.8	27.5	29.0	32.3
pH		6.3	7.9	7.1	6.9	97.6	0.0	0.0	0.0
Calc TDS	ug/l	360.3	2849.9	863.9	570.3	66.0	526.7	593.7	909.7

This aquifer received three type of recharge. Direct from precipitation, where it crops out, wadi flow and through drainage of the overlying formations. Four water types can be identified within the aquifer:

I. ***Calcium-Bicarbonate water,*** four samples presents in Wadis Assir, Sawan and Khulaqa. All samples shows TDS of less than 500mg/l which indicate fresh recharged water along wadi bottom from generated runoff that drains secondary wadis and flow into the main channel. The low TDS, despite the shallow groundwater table observed for wells HS110 and

HS31 indicate clearly that upper reaches Wadi Assir (tributaries) has not been contaminated from man surface activities.

II. ***Calcium sulphate water***, presents in six samples withdrawn from Wadi lasaf (3 samples), Bani Huwat, khulaqa and Thoma. The four samples from Wadi lafaf and Bani huwat are of the shallow aquifer. The most important source for sulphate is gypsum. However, the high concentration of SO4 at these shallow, unconfined aquifers could be from receiving large inputs of sulphate from atmospheric deposition, fertilizer use and land application of animal wastes. The outcrop of the aquifer at this part falls in the least rainfall area. However, presence of iron in all sample but (HS127) deep borehole at Thoma (which probably of limestone Group), may suggest different process responsible from $Ca\text{-}SO_4$ water in these wells. In Sana'a basin wadis are developed in fault zones, which commonly accompanied with volcanic intrusion which usually lead to dense fracturing of the adjacent area. Presence of fault has been established, however its hydrogeological significant was not identified yet. In recharge areas, fault zone may act as a conduit, through which groundwater leaks downward into the underlying formation. In discharge areas a reverse of the flow is to be observed and water flow from underlying unit into the overlying units. The presence of iron suggests mixing of water along these fault zones and hence oxidation of pyrite according to:

$$FeS_2 + H_2O + 3.5\,O_2 = Fe^{2+} + 2H^{+} + 2SO^{-2}{}_4$$

and dilution of Cl, (Low Cl concentration observed in all samples but HS127). It is well known that iron minerals are common in the Cretaceous Sandstone. Iron oxides, are present as a cementing material (iron stone). Presence of secondary iron cementation pattern are common at or near the contact of coarse and fine-grained sediments interfaces, Mos., (1986) which in agree with the above equation. As water from reducing environment mixes with water from oxidizing environment, the dissolved Fe^{2+} (ferrus ion) become unstable and is oxidized to produce solid ferric hydroxide.

$$2\,Fe^{2+} + 5H_2O + 0.5\,O_2 \text{ ----- } 2\,Fe(OH)3 + 4H^{+}$$

Moreover the hydrogen ion released by oxidation reaction increase the aggressiveness of the water to attack and dissolve aquifer material.

III ***Sodium Bicarbonate Water,*** is present at Wadi Sawan where the aquifer overlain by a volcanic rocks. More than one process appears to affect the chemistry of the groundwater in that area. Chapelle and Knobel (1985) suggest that concentration of sodium plotted as a function of bicarbonate should fall on a straight line having a slope of two, if dissolution of carbonate material and ion exchange occur in an environment that is closed with respect to CO_2 , the following reaction can take place

$(Ca_{1-X}\ Mg_X)CO_3 + H_2O + Na_2.Ex$ --- $2Na + HCO_3 + OH + Ca_{1-X}\ Mg_X).Ex.$

Conversely, if the system is open with respect to carbon dioxide, the same chemical processes would generate sodium and bicarbonate concentration that would plot on a straight line having a slope of one.

$(Ca_{1-x}\ Mg_x)CO_3 + H_2O + CO_2 + Na_2.Ex$ --- $2Na + 2HCO_3 + (Ca_{1-x}\ Mg_x).Ex$

The concentration of Na and HCO_3 from groundwater obtained from this area are plotted in figure where the Na and HCO_3 are plot as straight lines. The plot of data from the groundwater of wadi Alser shown close to that predicted by second equation. This implies that the processes of ion exchange coupled with carbonate dissolution in an open system with respect to CO_2, can explain the presence of sodium bicarbonate water in this area. The presence of calcareous material as a cement is common in the upper part of Cretaceous Sandstone (Medj-zir formation). Other process that may explain the presence of equal Na and HCO_3 is ion exchange coupled with incongruent dissolution of silicate minerals (feldspars).

IV Indiscriminate ions water type. 13 samples representing this water type. 8 samples show no domination of certain ions. However, in general samples with high concentration of Ca and HCO_3 show lower TDS values. Sharing of other ions SO4 and Cl commonly show higher TDS. It can be concluded that, water with lower TDS representing initial stage of water evolution. For example, domination of HCO_3 presents in Hamdan HSH15, Assir (HS147), and Sawan (HS158), all with TDS of less than 500 mg/l and indicate fresh recharged water. Their location at upper reaches of wadis (recharge area) confirm their initiation of water evolution. Similarly in wadi Khulqa, Ca is dominant ions (HS113) with high concentration of HCO_3 and TDS <500 mg/l. This trend changes, however, for sample (HS112) of wadi Khalaqa with SO_4 domination and high TDS value (>1500mg/l) indicating later water evolution stage.

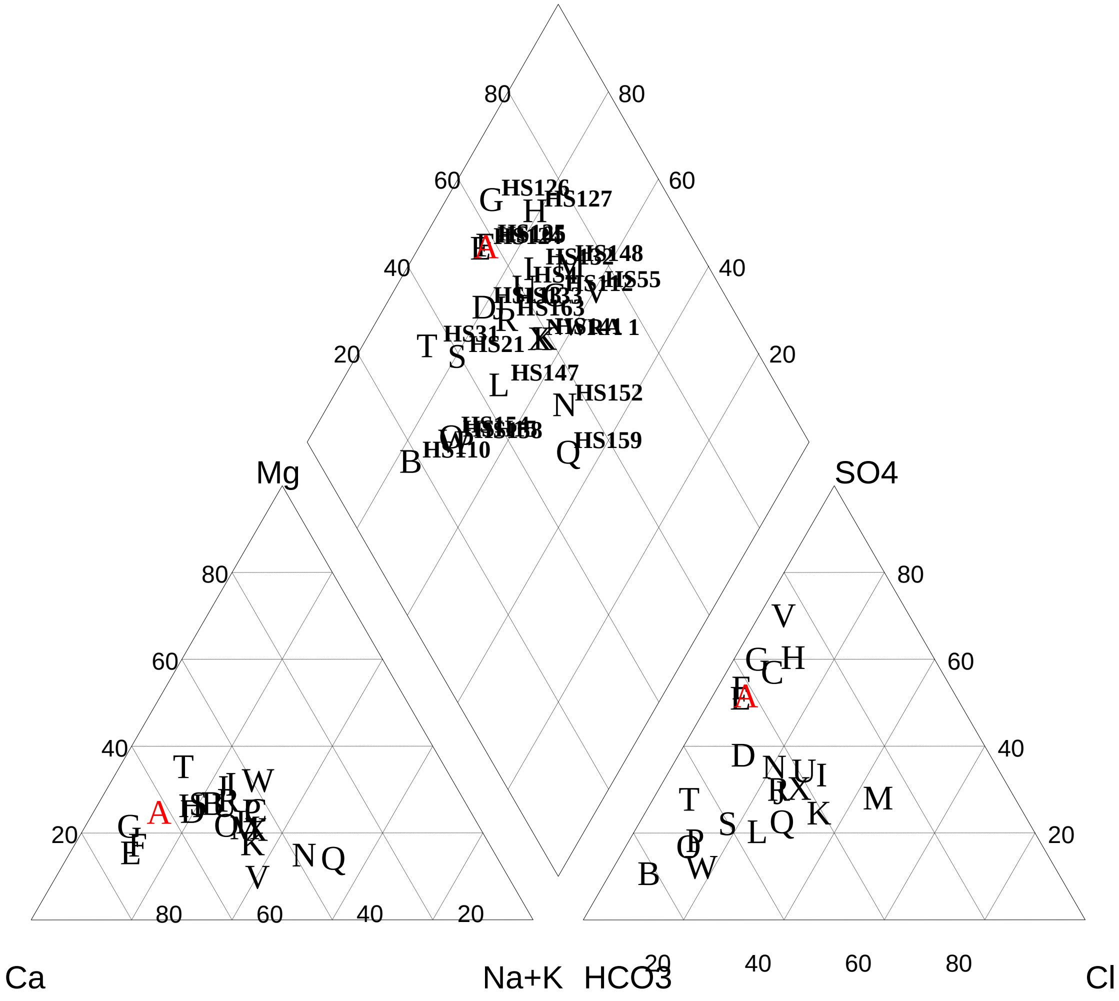


Figure (3.2): Piper Diagram for Sandstone Aquifer

3.1.4. VOLCANIC AQUIFER

30 samples analyses results were used to evaluate water classification in the Volcanic aquifer. The correlation matrix of these samples is shown below:

Correlation coefficient

	pH	Na	Mg	Ca	Cl	K	SO4
pH	1	-0.312	-0.736	-0.63	-0.335	-0.594	-0.466
Na		1	0.79	0.656	0.366	0.888	0.762
Mg			1	0.899	0.552	0.926	0.808
Ca				1	0.802	0.777	0.878
Cl					1	0.339	0.819
K						1	0.689
SO4							1

High correlation coefficient noticed for the following: Ca and Mg 0.899, K and Mg 0.926. Summary of statistics of Volanic samples are given in Table (3.3)

Table (3.3) Summary of 29 samples statistics representing Volcanic aquifer

Parameter	Unit	Min	Max	Average	St. Dev.	Dev. Coef	Q25	Q50	Q75
Ca	mg/l	1.8	136.8	43.4	36.1	83.2	18.5	29.6	51.8
Mg	mg/l	2.9	45.7	13.8	9.2	66.8	7.4	11.5	16.9
Na	mg/l	17.0	176.0	64.4	34.7	54.0	37.4	57.5	76.3
Cl	mg/l	7.5	138.1	42.9	38.6	90.2	17.3	28.9	42.0
HCO3	mg/l	109.4	319.7	196.9	54.6	27.7	149.5	185.1	227.3
SO4	mg/l	8.0	250.0	60.8	61.5	101.2	25.3	33.0	71.2
TEMP	°C	18.2	34.8	27.1	3.6	13.2	24.8	27.0	29.2
pH		6.7	9.2	7.6	7.4	96.8	0.0	0.0	0.0
calc TDS	ug/l	236.1	976.5	437.8	187.5	42.8	310.7	380.1	469.3

The recharge water infiltrate from the surface is expected generally to be saturated with respect to CO_2 and to react with H_2O and the silicate mineral to produce dissolved ions and a residual solid phase, either kaolinite or illite. To test which is the stable weathering product of the aluminosilicate minerals in the system, this is done through plotting the data on the stability diagram (Freeze and Cherry 1979). Unfortunately, silica concentrations had not been determined in all analysis carried by all teams worked in the Basin. This is actually limit quantification of the expected reactions that may have taken place. Instead ionic ratio is used to clarify some of the processes that acting in the groundwater chemistry.

However, this have been carried with great care because even the ionic ratio could be disturbed as result of the solid products of the incongruent dissolution, that form on the mineral surfaces, in some cases, amorphous substances require long time for conversion to crystalline forms, so these amorphous and clay minerals commonly have appreciable cation exchange capacity and therefore have the capability of altering the cation ratio in groundwater (Freeze and Cherry,1979). These carbonate free rocks are dominated by silicates, predominantly feldspars, pyroxene, amphiboles, and quartz. Usually the mineral chemistry of these rocks is greatly complicated by atomic substitution within the minerals. The minerals often dissolve incongruently in several stages. The dissolved ions which are produced by silicate weathering depend on the original chemical composition of the minerals. The definite chemical composition of these rock is unknown, however, in order to proceed, composition have been extracted from the literature of similar rocks.

In this aquifer, four main water types can be identified and these are:

I. ***Calcium Bicarbonate water,*** this water presents Wadi Hamdan, Al Muarid and Akhwar. This water type believes to result from the incongruent dissolution of plagioclase and pyroxene (mafic minerals) which is dominated the aquifer material. The reaction that might have taken place (Alderwish, 1996); is

$$\underset{\text{Anorthite}}{CaAl_2SiO_8} + 2H_2CO_3 + H_2O = \underset{\text{Kaolinite}}{Al_2Si_2O_5(OH)_4} + Ca^{+2} + 2HCO_3$$

$$\underset{\text{Pyroxene}}{(CaMg_{.7}Al_{.3})(Al_{.3}Si_{1.7})O_6} + 3.4H^+ = 0.3\ Al_2Si_2O_5(OH)_4 + Ca^{+2} + 0.7Mg^{+2} + 1.1H_2O + 1.1\ SiO_2$$

Pyroxene is altered faster than plagioclase; hence it gives first nearly equal amount of both Mg and Ca ions to the water. Ca and HCO_3 ions are dominant in the fresher recharge water, and Na concentration increases with the residence time. This conclusion is drawn from the stability series of the feldspar minerals, in which the plagioclase is less stable under surface conditions than potassium feldspar. Even within the plagioclase series the calcic plagioclase is less stable than the sodic-plagioclase. All these water samples have TDS <500mg/l. Alderwish (1992) shows that water sample from spring Nimran (south-west) is dominated by Ca and HCO_3 ions and has low dissolved solids concentration of 213 mg/l. Hygrograph of discharge shows a rapid response to the precipitation, and isotopes analysis from well in this area (Nimran) shows high tritium content of 31.0 ± 1.6 TU, which indicates recent fresh water. Similarly water sample from Hada spring has tritium content of 1.1 ± 0.26 and C-14 measurements of 85.8 ± 0.54 . The chemical analysis of its water shows Ca and HCO_3 are dominant ions but also the Na concentration is significant (HCO_3= 73.4% Ca =56% Na=33%) and total dissolved solids concentration is 383 mg/l which is support what is mentioned above.

II. Sodium Bicarbonate water, present in ten samples all over the volcanic aquifer. Samples with lower TDS <500 probably are originated from rock material that dominated by Na-feldspar. However, samples with TDS> 500mg/l indicate water gained more Na due to increases in the residence time. The sample (HS142) of Wadi Assir, shows Na dominant water and indiscriminate anion with TDS of <500mg/l.

In general, evaporation effect from rainfall, irrigated water is evident in several water samples. In arid areas salts can dissolve in water right at the surface when rain falls. The salts precipitate again when the rain evaporates. With more intense showers, the salt may be flushed deeper down to the groundwater. Because of the short residence time of water before infiltration, alkali salt (NaCl, Na-carbonate) dissolve more rapidly than earth alkaline salts, (Ca, Mg-salts such as calcite). This led to water become more alkaline, as soon as the CO_3 concentrations are high, Ca concentration remains low, since saturation with calcite is rapidly reached. The short residence time may be supported by presence of these wells in permeable fault zone, and their high yields. Dissolution of feldspathoid sodalite Na_8 $(Cl_2(AlSiO_4))$ may accounts of this water type, (Hem, 1985). However, the presence of this mineral in Sana'a basin has not been reported so far.

III. ***Indiscriminate ions water type,*** present in Wadi Assir with TDS value close to 1000 mg/l. In general samples with high concentration level of sodium or magnesium in addition to the calcium probably indicate older water which is being subjected to more dissolution process.(i.e. evolutes from Ca-HCO3 water).
Eleven samples are characterized by **domination of the HCO^{3-} anion**, which is characteristic of recharge areas, especially when associated with crystalline rocks and having low TDS concentration <500 mg/l. The HCO_3 content in groundwater is normally derived from soil zone CO_2, Freeze and Cherry, (1979). It may released due to dissolution of silicate minerals except quartz, consumes hydrogen ion during the incongruent dissolution and results in arise pH alkalinity, (8 samples have PH >7.5). HCO^{3-} is almost invariably the dominant anion in recharge areas in Yemen (Alderwish, 1996, Alderwish, 2008). This is further manifested by abundance of this water type mainly in the tributaries of main wadis in the basin, which represents recharge zone. As the silicate weathering were the probable source of sodium, the water samples have HCO_3 as the most abundant anion than sodium, and it is well supported by high values of HCO_3 than Na^+.

Two samples dominant with Ca with significant chloride and sulphate concentrations found at two shallow dug wells in Assir and Sawan. Irrigation and domestic return are the processes responsible of the chemistry of these water samples, with TDS> 700 mg/l. The well in Sawan shows high concentration of NO_3 (24mg/l).

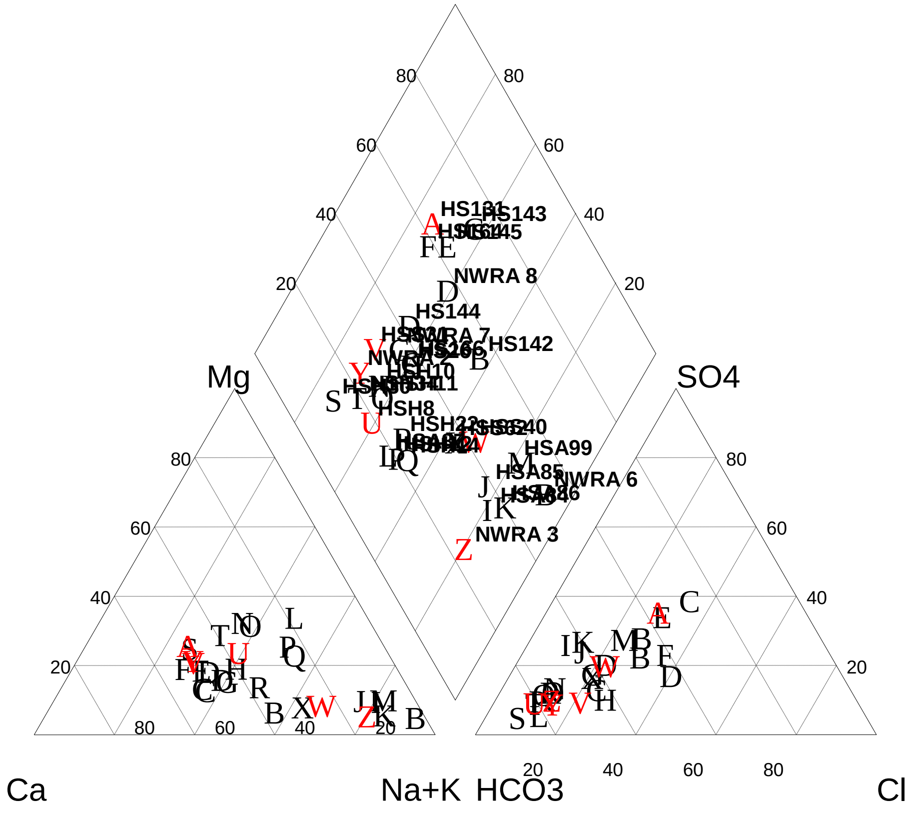


Figure (3.3) Piper for volcanic aquifer

3.1.5. ALLUVIAL AQUIFER

10 samples analyses results were used to evaluate water classification in the Alluvial aquifer. The correlation matrix of these samples is shown below:

Correlation coefficient

	pH	Na	Mg	Ca	Cl	K	SO4
pH	1	0.546	-0.345	-0.347	-0.119	0.217	-7.90E-02
Na		1	0.133	-0.312	0.325	-0.199	0.543
Mg			1	0.72	0.922	0.399	0.723
Ca				1	0.669	0.656	0.368
Cl					1	0.451	0.832
K						1	2.50E-02
SO4							1

High correlation coefficient noticed only between Mg and Cl 0.922. Summary of the statistics of alluvial samples is shown in Table (3.4)

Table (3.4) Summary of 10 samples statistics representing Alluvial aquifer

Parameter	Unit	Min	Max	Average	St. Dev.	Dev. Coef	Q25	Q50	Q75
Ca	mg/l	16.3	140.6	64.2	43.3	67.5	19.3	49.6	87.0
Mg	mg/l	8.5	132.6	29.9	36.6	122.6	12.5	18.5	24.3
Na	mg/l	41.0	250.0	123.9	67.5	54.5	61.0	86.0	167.0
Cl	mg/l	27.7	282.9	99.8	71.8	71.9	57.5	79.8	98.7
HCO3	mg/l	161.6	536.9	283.9	123.0	43.3	189.4	238.8	292.8
SO4	mg/l	25.0	350.0	127.6	105.1	82.4	48.5	66.0	156.3
TEMP	°C	20.0	29.0	24.6	3.0	12.3	21.7	24.0	26.7
pH		6.7	8.2	7.3	7.2	99.0	0.0	0.0	0.0
calc TDS	ug/l	479.9	1612.3	764.1	340.0	44.5	508.8	678.4	864.2

Three water types have been identified in this aquifer, and they are:

I. ***Calcium Bicarbonate water,*** presents in two samples with TDS <1000mg/l in wadi Maadi and Assir and probably indicate recharge water.

II. Sodium Bicarbonate water present in samples (HSA7 and HSA95), with TDS <1000mg/l in Wadi Bani Huwat. This water probably originates from alluvial deposits of volcanic origin. However, HSA7 sample shows 0.32 mg/l phosphate. Both samples show low concentration of NO_3. These samples are collected within the waste water passage. No bacteriological contamination was detected.

III. ***Indiscriminate ions water type,*** founded in six samples. Two samples Na dominant water (HSA101) and (HSA103) and present in wadi Bani Huwat. (Na/(Na+Cl) is greater than 0.5 which indicate Sodium source other than halite - albite, ion exchange. However as TDS is greater than 500mg/l that indicates carbonate weathering. Apparently these samples reflect the material which made up the alluvial.

Two samples are HCO_3 dominant water. Interestingly, although these samples with TDS around 500-550 mg/l, sample (HSA90) shows bacteriological contamination. i.e. sample with least TDS shows bacteriological contamination.

Two samples (HSA74) and (HSA16) with indiscriminate ions. (HSA74) has high TDS of 1611 and PO_4 concentration of 0.4 mg/l. The other sample has TDS of 880 mg/l but with high concentration of NO_3 of 32.12 mg/l.

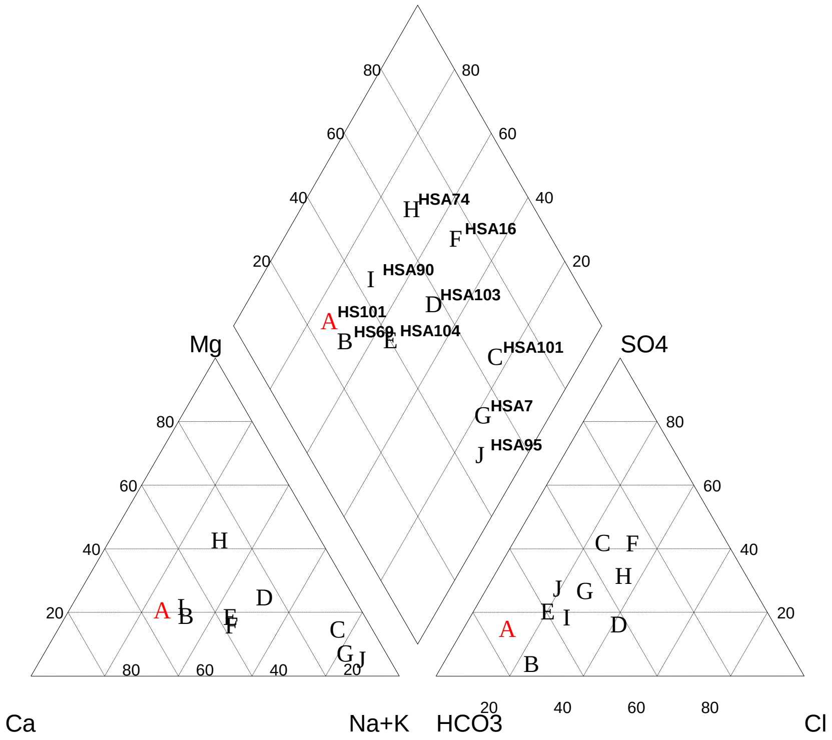


Figure (3.4) Piper Plot for Alluvial Aquifer

3.2. HYDROCHEMICAL SPATIAL DISTRIBUTION

Using a map to show the variation can help not only to observe a systematic areal distribution of water quality, but also allow correlations with other characteristics of the groundwater system (i.e define the hydrogeological conditions). It is a common practice to map the chemical variations first before classification of water type. However, it was found more useful here to distinguish water types using Piper diagram, before and in conjunction with preparation for distribution maps.

In 1992, Alderwish uses Mos. 1986 analysis results to draw first attempt to map variation in the Sana’a Basin. However, it might have not been ideal for the Sana'a basin, but it allows interpretation of areal variation of the water chemistry in the region. Hydrosult, 2007 draw major ions distribution map for each aquifer. That was not very useful as they missed important conclusion that might be drawn from these distribution which is aquifers interaction and groundwater flow etc.

Rainwater composition is determined by the source of the water vapour and by ions which are taken up (or lost) during transport through the atmosphere. The composition of rain in the Sana'a basin is not available. However chemical analyses for samples collected from rain gauges were carried out by Mos., (1986). No rain water have analyzed by other consultants. The sampled analyzed are dominated by magnesium and bicarbonate ions, with TDS relatively high for rainwater (70-120 mg/l) and the pH is always neutral. The composition apparently results from the dust over the city and adjacent areas due to presence of six quarries. This dust either goes into the atmosphere or is deposited on the rain gauge between the periods of rain.

3.2.1. Total Dissolved Solids

Total Dissolved Solids (TDS) is summation of carbonates, bicarbonates, chlorides, sulfates, phosphates, nitrates, calcium, magnesium, sodium, potassium and iron. They do not include gases, colloids, or sediment. The TDS can be estimated from measuring the specific conductance of the water. Since TDS is the sum of all materials dissolved in the water, it has many different mineral sources. The desirable level of Total Dissolved solids in Yemen is 650 mg/l while the maximum permissible value is 1500 mg/l.

Distribution map depicting TDS of water samples from the Sana’a Basin is shown in Figure (3.5)

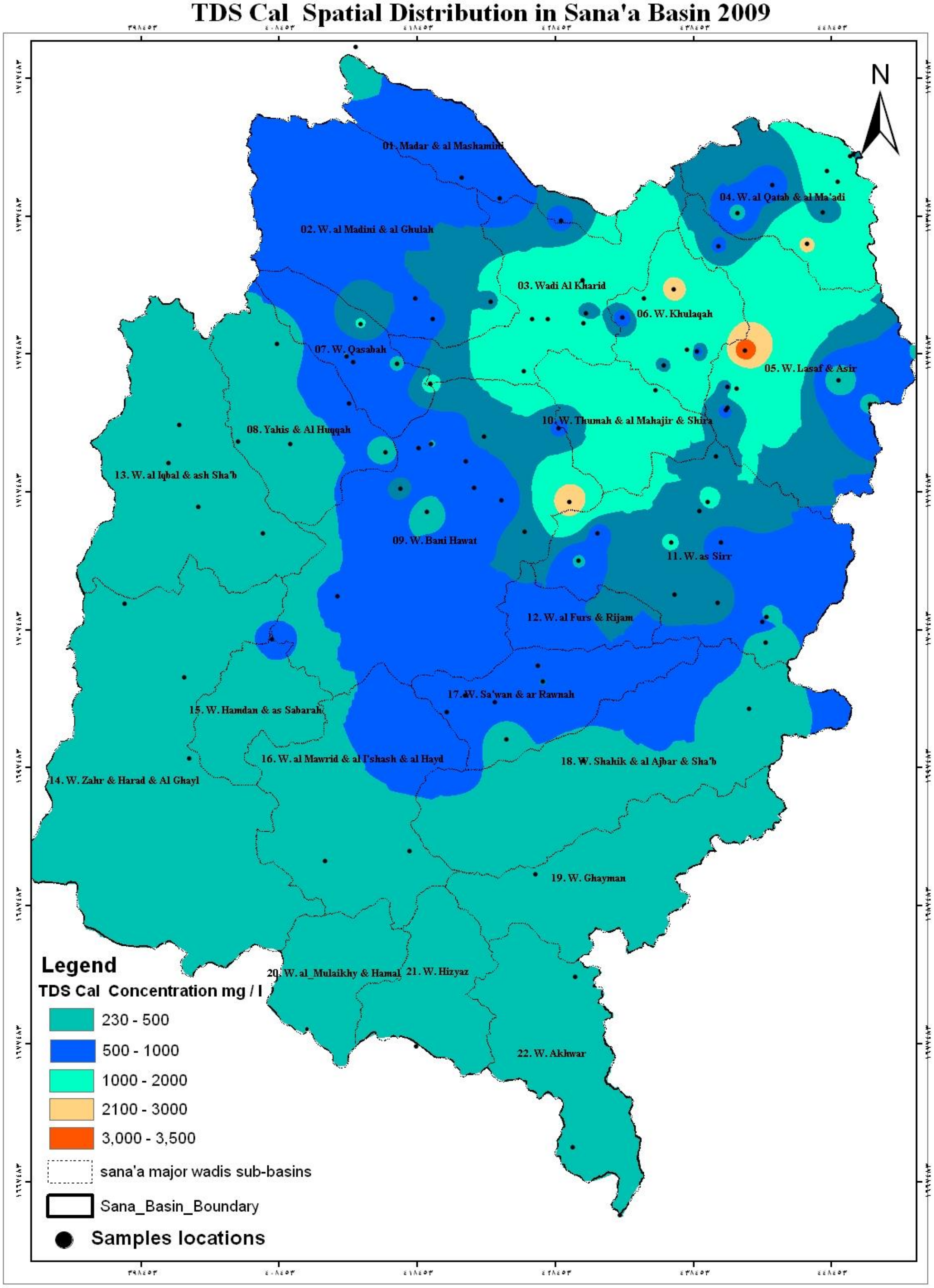


Figure (3.5) Distribution of TDS concentration over Sana’a Basin

The TDS values within **limestone aquifer** have wide range between 330 and 3421 mg/l. The highest value present in dug well sample in Wadi lasaf & Asir (HS120) while the lowest found in Bani Hwuat borehole (HSA93). Thirteen samples have brackish water (TDS>1000mg/l). The considerably high TDS values in these samples is primarily due to the presence of soluble materials in this aquifer, which is major factor controls the natural value of the total dissolved solids plus the agricultural practices in the area. Of the thirteen samples eight drawn from the shallow aquifer. This means, relate salinity to solubility of aquifer material alone is oversimplification of the process and evaporation (irrigation return) is contributing factor to salinity of this water which present in: Wadis Khalaqa, Maadi, lasaf &Asir, and Kharid. It should be noted that out of the sixteen samples with fresh water (TDS<1000), samples from shallow aquifer in wadi Maadi (HS104) and lasaf &Asir (HS117) have fresh water. These wells are located in least developed areas of upstream reaches where fresh indirect recharge from runoff is occurring. Shallow water of Bani Hwuat (HSA77) is fresh with TDS of 708 mg/l. Only Wadi Khalaqa shows high salinity along the whole vertical section of the aquifer. Other sub-basins, deep borehole commonly show fresher water. This means, the location of the water point regardless its depth is the factor for salinity. Fresh water samples are commonly of HCO_3 dominant water type while brackish water are of SO_4 dominant water type. Comparing these values with those of 1986, highest TDS values in Amran group is located in Thoma-khalaqa area.

A wide range of values between 360 and 2849mg/l have been noticed for samples representing **Sandstone aquifer**. Six samples show brackish water (TDS>1000 mg/l). The highest TDS values in the Cretaceous Sandstone observed in Wadi Khulaqa, Thoma, Bani Huwat dominant with SO_4 ions may be related to presence of more highly mineralized old water from the underlying Amran Group through an expected fault at depth. These samples are differ from other SO_4 dominant water type with fresh water (TDS<1000mg/l) which probably related to oxidation of pyrite. Brackish samples from Assir and Maadi show indiscriminate ion water type and quite less TDS values. Eighteen samples from the Sandstone show fresh water (TDS<1000mg/l). Only three samples shows TDS less than 500 mg/l present in Wadi lasaf & Asir and Wadi Assir. Fresh water samples are commonly dominant by HCO_3 and indiscriminate ions. SO_4 originate from oxidation of pyrite. All shallow wells present in Wadi lasaf &Asir are of fresh water and representing fresh recharge water. Only one shallow sample from Bani Huwat has TDS 2841mg/l. This shallow well located at the mouth of Wadi Assir at Sana'a Plain. A fault structure which traverse wadi Assir (along the extension of Wadi Bahman), shows higher TDS value than samples taken from its both side (upstream and downstream side) with TDS of 1110, 904 and 1034 mg/l. with indiscriminate water type with high concentration of Cl and SO_4 beside HCO_3. The four samples of Wadi Khalaqa, two samples with lowest TDS are located along wadi channel. Away from the channel higher TDS values observed. The four samples of Wadi Sawan, lower TDS observed upstream in tributaries this increase toward downstream direction. The TDS distribution map does not reflect the piezometric map of the area. This partially represents a limit of the TDS distribution map to be related to the groundwater flow as it expresses bulk of parameters rather than one.

All samples (29) from **Volcanic aquifer** show fresh water with TDS values range between 236 and 975mg/l. This reflects the control of the lithology as volcanic compose the least soluble material. Only 6 samples show TDS >500mg/l; three in Wadi Assir, and the rest in Sawan, Huqqah and Qasabah. The lowest TDS values (<300mg/l) in the volcanic found in Wadi Zahr Ghyal and Iqbal, followed by Wadi Akhwar then Hizyz. All these zones represent active fresh recharge areas. A part of sample from Thoma, the other four samples from shallow aquifer (in Sawan and Assir) show TDS more than 500 mg/l.
Local trends within this broad trends appear to be controlled by the fault system in the area, which is almost coincides with the topography. This means wadi is commonly developed along weak fractured zone. Example of this situation can be seen through the TDS distribution in the southwestern part of the volcanic aquifer which is variable and appears to have been disturbed by the faulting pattern in that area.

TDS values over **Alluvial aquifer** varies between 479 (HS103) at Bani Huwat and 1612 mg/l (HSA74) at Al Kharid. All other samples fall between 500-920 mg/l. Very few samples make it difficult to establish any trend.

The TDS distribution in general appears to be controlled by the topography which is almost a result of tectonic structures. All secondary and primary wadis in Sana'a basin irrespective of the type of the bedrock show lower TDS value upstream and increases in the downstream direction. Another trends found across (transverse its axial plane) the wadi, shows the lowest TDS found at the foot hill and sometimes additionally along the wadi channel especially in the upstream region. These two areas (wadi channel and foothills) are usually covered by coarse sediments and rock fragments and probably represent recharge areas. The increase of the TDS within the wadi bottom is mainly concentrated at the flood plains which consist of fine-grained sediments. Moreover these areas are generally more populated.

3.2.2. Calcium

The spatial distribution of calcium concentrations is shown in Figure (3.6).

The calcium concentrations in **Limestone aquifer** vary between 6.4 and 579.4 mg/l. The highest value in Sample HS120 in Wadi Lafaf &Alsir while the lowest in sample HSA93 in Wadi Bani Huwat. This low concentration of Ca in a carbonate rock is related to ion exchange process which replace the calcium by sodium in the groundwater. The highest average calcium concentration observed over Wad Lasaf & Alsir and Khulaqa with concentration of 315.5 and 308 mg/l, respectively. The lowest average concentration of Calcium estimated for Wadi Al Mashami.

The calcium value in the **Sandstone aquifer** ranges between 48 mg/l to 414 mg/l. The highest value is found in sample (HS55) with high TDS 2841.4 mg/l and $CaSO4$ water type. This water may be related to presence of old deep water from the underlying Amran Group as a result of reversal of groundwater flow. The lowest value of calcium concentration read in sample (HS110) in Wadi Assir with low TDS value 358.6 mg/l. The highest average Ca in this aquifer seen in Hamadan (60mg/l) and Sawan (68mg/l). While the highest average concentration are for Thoma (299mg/l) and Bani Huwat (250mg/l).

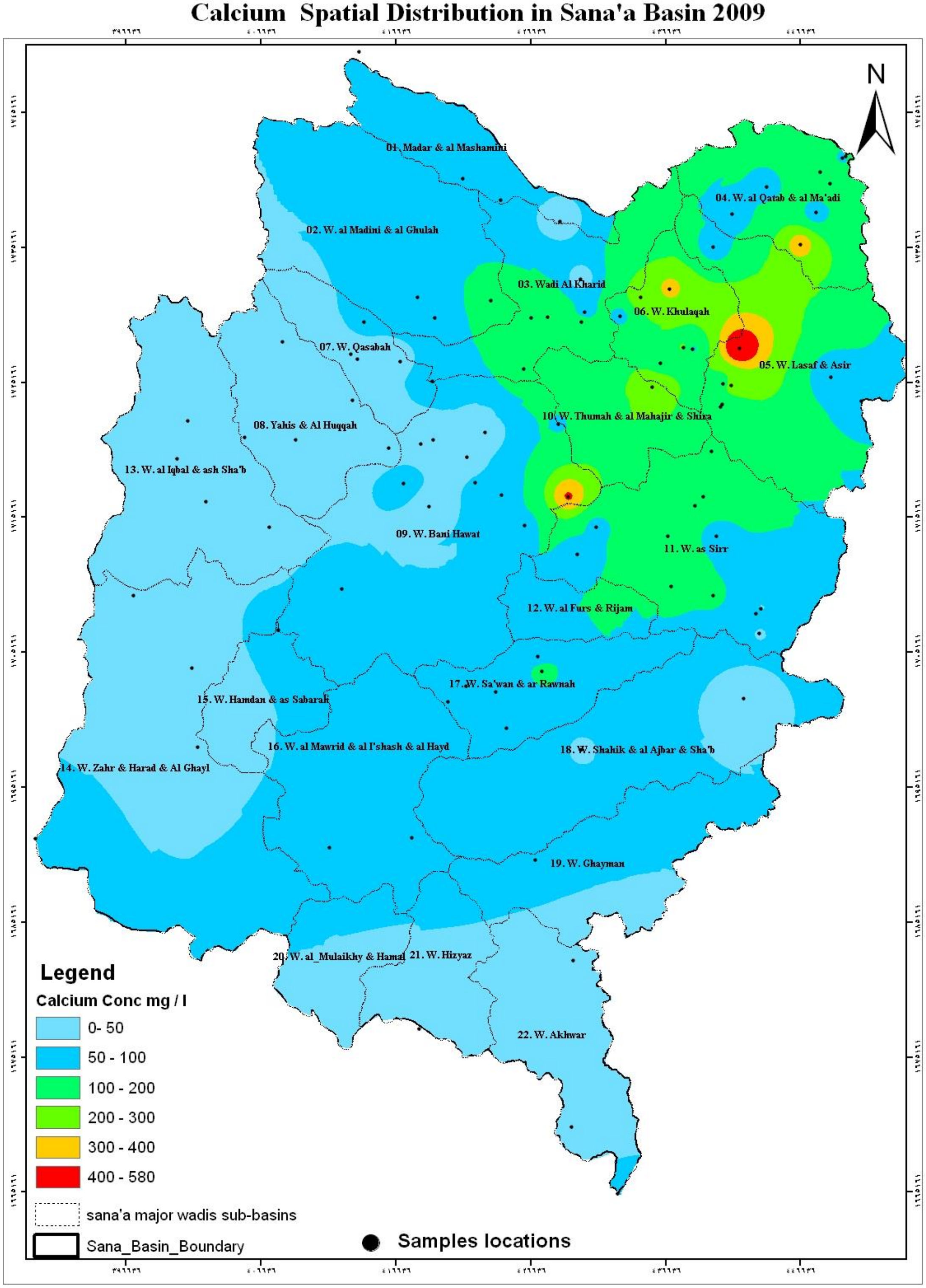


Figure (3.6) Distribution of Calcium concentration (mg/l) over Sana'a Basin

The dominant species of the calcium is the Ca^{+2} (free ions), however other some samples have more than 10 % of their calcium occurring as ion pair mainly $CaSO_4^o$. Except for sample with high TDS value in excess of 1000mg/l (20% of its calcium concentration occur in form of $CaSO^o{}_4$), the complexation and ion pair are insignificant.

In the **Volcanic aquifer** although the concentration of calcium generally varies between 1.8 (NWRA6) and 137mg/l (HS131), only four samples have Ca concentration that exceed 100 mg/l. These samples show higher TDS values (>500 mg/l), and the sample (HS164) of Sawan has nitrate concentration of 24mg/l. As Ca is most abundant of the alkaline-earth metals, derived from nearly all rocks (sedimentary, igneous, metamorphic), the very low concentration value is an ion exchange process. The highest average Ca concentration in this aquifer present in Assir (90mg/l), and Sawan (89mgl), while the lowest present in Shahik (1.8mg/l) and Qasabah (14.7mg/l). In general the distribution of calcium concentrations in the volcanic aquifer show to be combatable to the TDS values distribution. Exception of local anomalies also has been observed in some wells.

In the **Alluvial aquifer**, calcium concentration varies from 16.3 mg/l (HAS95) to 114 mg/l (HS69) at Assir. The only reported brackish water (TDS=1611 mg/l) from this aquifer (HSA74) has Ca concentration of 141 mg/l that present in Wadi Al Kharid. The lowest average concentration of Ca in this aquifer of (44 mg/l) occurs in Wadi bani Huwat.

In general the distribution of Ca is a subdued replica of the TDS distribution.

3.2.3. Magnesium

Magnesium level distribution in the Sana'a basin aquifer system is given in Figure (3.7)

Magnesium concentrations in the **Limestone Aquifer** range between 4.5 mg/l (HSA93) at Bani Huwat and 154 mg/l (HSA75) at Al Kharid. The water table at HSA75 is only 4 meter below ground surface with TDS value of 2089 mg/l. The Mg/Ca ratio in all the samples is less than unity. Except in Al Maadi (HS100) with value higher than unity and is related to evaporites. Concentration of NO_3 at this sample is 54 mg/l. The least average concentration of Magnesium is (18 mg/l) present in Wadi Bani Huwat, while the highest present in wadi Khulaqa (86mg/l).

In **Sandstone aquifer** the Magnesium varies between 13.4 mg/l (HS159) of Sawan, and 88.5 mg/l (HS127) of Thoma. The least average concentration estimated at Sawan and Lafaf &Alsir of 21 mg/l while the highest 88.5 mg/l at Thoma. The origin of Mg in Thoma area seems to be related to dissolution of dolomite. As no dolomite in the Sandstone aquifer, it is either the well error classified to Sandstone, it is penetrating two aquifers, and/or there is groundwater up-flow from the limestone to the Sandstone in this area.
The speciation of the magnesium within this aquifer appears insignificant except for two samples that have more than 20% of their concentration occurring as $MgSO^o{}_4$. These noticed in samples having high concentration of sulphate and TDS values.

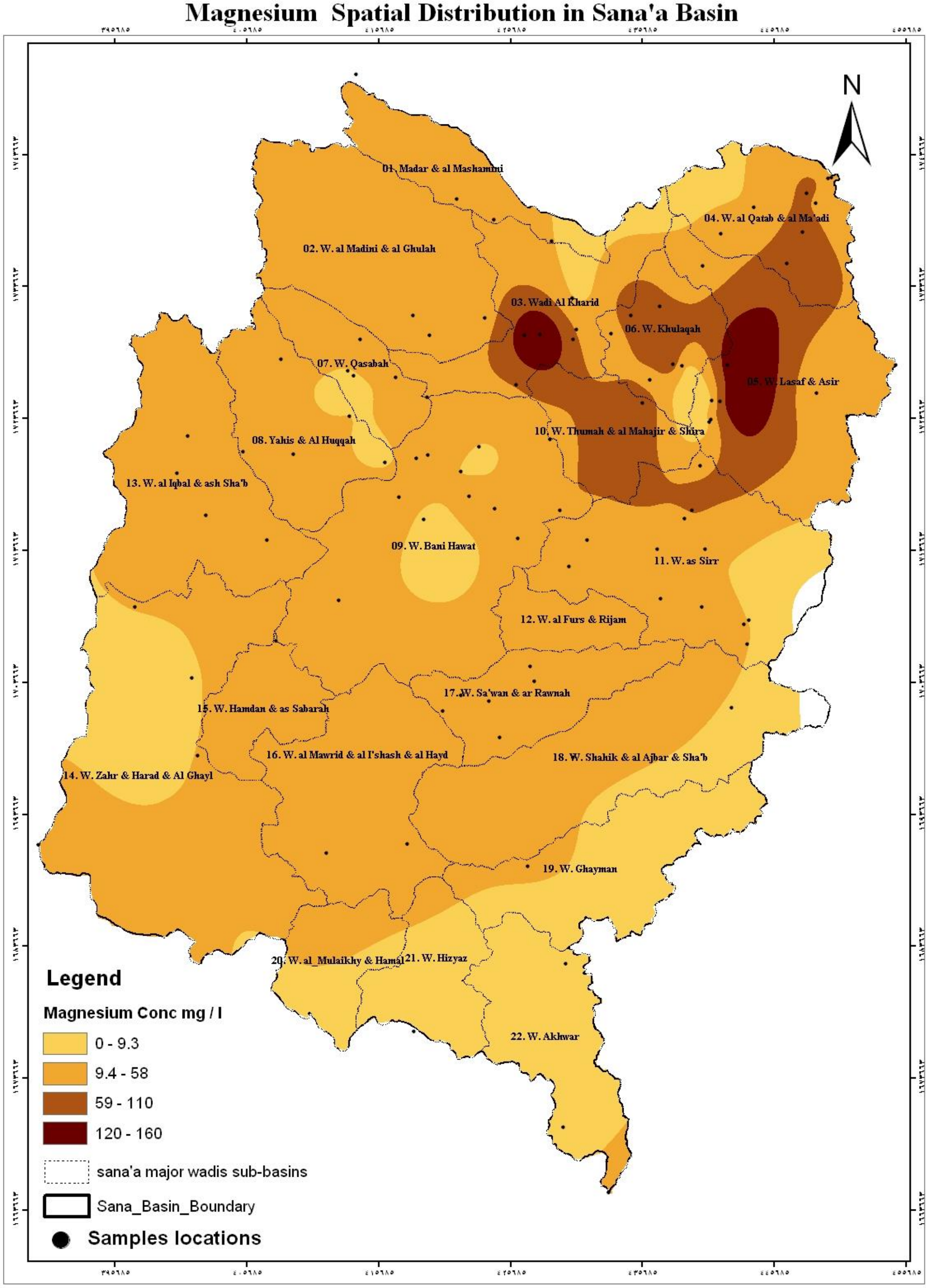


Figure (3.7) Distribution of Magnesium concentration (mg/l) over Sana’a Basin

Magnesium concentration in the **Volcanic aquifer** vary from few milligram per liter (2.9-4.5) at southern and south-western wadis (Akhwar, Shahik and Hyziz) indicating felsic rocks origin, and 46mg/l at Wadi Assir where mafic (basic) volcanic rocks. The least average concentration of Mg concentration found at Hizyz (4.5 mg/l) while the highest averaged at Sawan (20.4mg/l).

In the **alluvial aquifer** Magnesium concentrations vary between 8mg/l (HSA95) of Bani Huwat and 29 mg/l (HS69) of Wadi Assir. Exceptionally one sample show high Mg concentration of 133mg/l (HSA74) at Al Kharid with high TDS value of 1611mg/l. This sample is Mg dominant water type with high concentration of all major ions, and phosphorous of 0.4mg/l.

It is worth to noting that chemical analyses for samples taken from boreholes which tap both the Volcanic and the Cretaceous sandstone, show enhanced Mg/Ca ratio. This implies that the volcanic rocks are draining into the Cretaceous sandstone.

3.2.4. Sodium

The distribution of sodium over Sana'a Basin is shown in Figure (3.8)

The least Na concentration in **Limestone aquifer** is 20 mg/l (HSA66) in Wadi Al Mashami while the highest is 423 mg/l (HSA129) at Al Kharid. All samples with Na concentration >100 mg/l are brackish water (TDS>1000), but sample (HSA68) with fresh water (TDS=680mg/l) at Al Mashami. It is probably of different origin than other samples. The ratio of Na/(Na+Cl) for this sample is 0.6 which indicate sodium source other than halite – albite. While its Ca/(Ca+SO_4) is 0.302 (i.e. <0.5) with neutral PH indicate calcium removal due to ion exchange or calcite precipitation. The sample is oversaturated with respect to calcite (SI=0.7). The other (13) samples apparently resulted from evaporates, recycling of irrigated water, cation exchange process as indicated from the Na/Cl ratios which are in the range of 3.2 – 8.5. Human impact to shallow groundwater manifested by the 8 samples which drawn from shallow aquifer. The least Na concentration averaged over Al Mashami and Bani Huwat (60mg/l), while the exceptionally highest concentration is 209.6mg/l at Wadi Al Kharid sub-catchment.

Within the **Sandstone aquifer** the concentration ranges from 18mg/l (HS31 - dugwell) at Lafaf & Alsir and 178mgl (HS112) at Khulaqa. Exceptionally high Na concentration of 355mg/l measured at sample collected from dugwell at Bani Huwat, with TDS of 2841 mg/l and the water dominant by SO_4 with high concentration of Ca and Na. Pollution from the surface (human or animal waste disposal) is responsible from the chemistry of this sample. The least averaged Na averaged over Lafaf & Alsir 22mg/l, while the second highest at Thoma 00mg/l. Anomaly averaged at Bani Huwat is 235mg/l probably resulted from urban sewerage disposal.

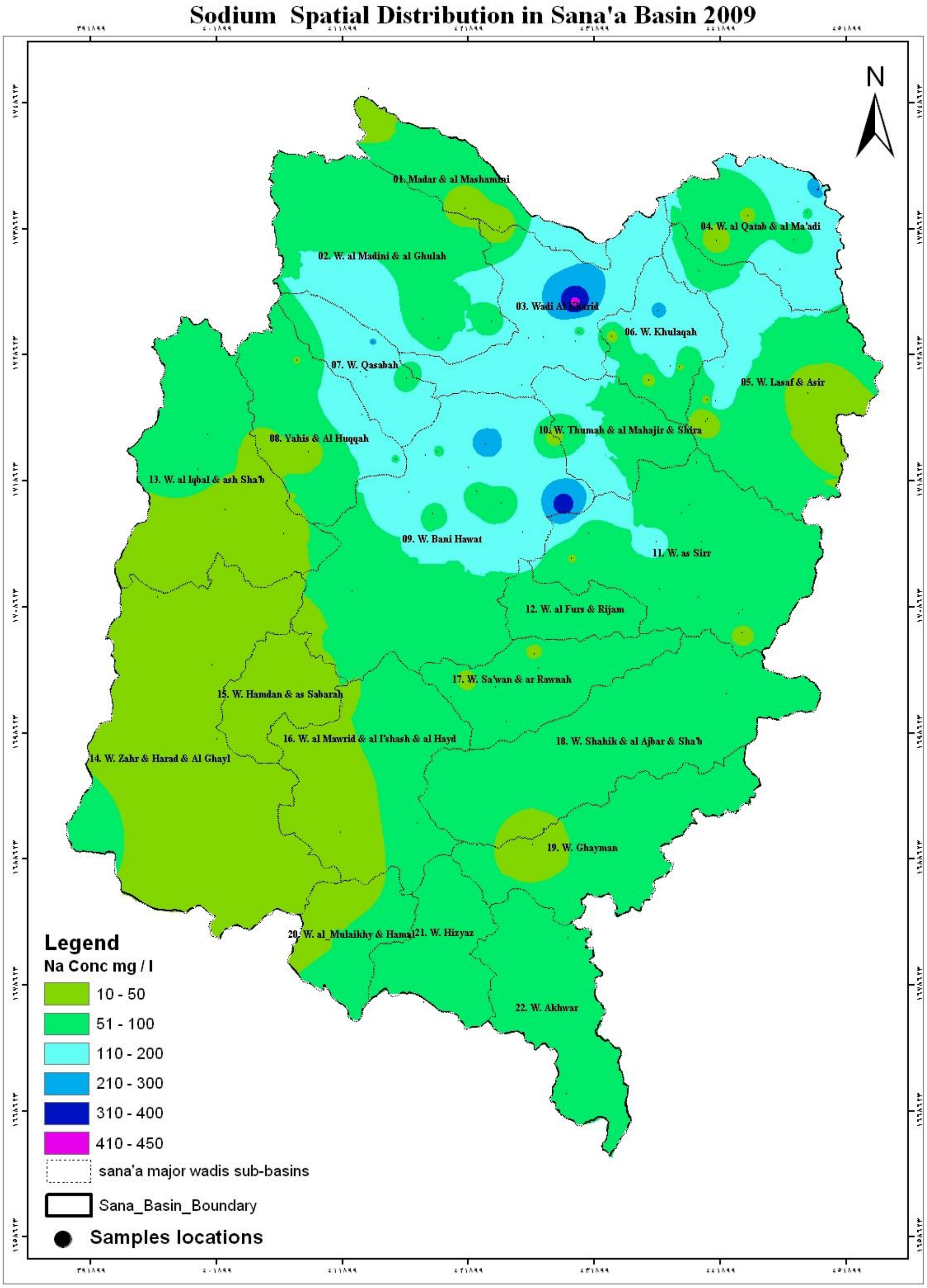


Figure (3.8) Distribution of Sodium concentration (mg/l) over Sana'a Basin

The sodium concentration in the **Volcanic aquifer** vary from 17mg/l in Wadi Zahr at the eastern plateau and 176mg/l at Wadi Qasabah. The major source of Na in natural waters from volcanic aquifer results from the weathering of feldspars. It is gradually released from rocks. This means, high concentrations indicate increase in residence time. Presence of sediments deposits layers within the Tertiary Volcanic, may lead Clay to contribute Na in this aquifer. In general, the distribution of Na in the volcanic aquifer appears to be controlled by the lithology rather than cation-exchange process. High Na/Cl ratio observed at three samples from Wadis Al Huqqah and Qasabah. The least averaged Na concentration is 30mg/l shown in Wadi Zahr where most of the volcanic rocks are mafic while the highest shown in 128 mg/l in W. Qasabah, Leachate from Al Azragin landfill may be suspected.

In the **Alluvium aquifer** the lowest Na concentration (41 mg/l) found in sample (HS101) at Al Maadi from shallow aquifer. The highest concentration is 250 mg/l (HSA95) at Bani Huwat.

3.2.5. Potassium

The distribution of Potassium over the entire Sana'a Basin is shown in Figure (3.9)

Potassium concentration in the **Limestone aquifer** vary between 1.4mg/l (HSA93) at Bani Huwat and 21mg/l (HSA92) at Al Kharid. Only four samples have K concentration >10 mg/l and probably related to application of K-fertilizer. Presence of K is of great importance for soil health, plant growth and animal nutrition. Potassium and (sodium) are often associated with chloride and bromide. In these forms, they readily dissolve in water. The lowest averaged 2.7 mg/l observed at wadi bani Huwat and the highest 14mg/l at Khulaqa.

In the **Sandstone aquifer** potassium concentration range between 1.2 – 36 mg/l. Only three samples shows K concentration >10 mg/l. They present in Wadi Khulaqa, Thoma and bani Huwat. The lowest averaged 2.4 mg/l observed at Lafaf &Alsir and the highest 23mg/l at Bani Huwat. The potassium released slowly upon dissolution of K-minerals, as potassium feldspars and mica minerals. This means that concentration increase as residence time in groundwater increases.

In the Volcanic Aquifer the K varies between 0.7 and 5.5 mg/l. As K is commonly associated with sedimentary rocks, no trend has been found in the volcanic aquifer.

In the **Alluvium aquifer** the lowest Na concentration (2.3 mg/l) found in sample (HS101) at Al Maadi from shallow aquifer. The highest concentration is 7.4 mg/l (HS69) at Wadi Assir from the shallow aquifer.

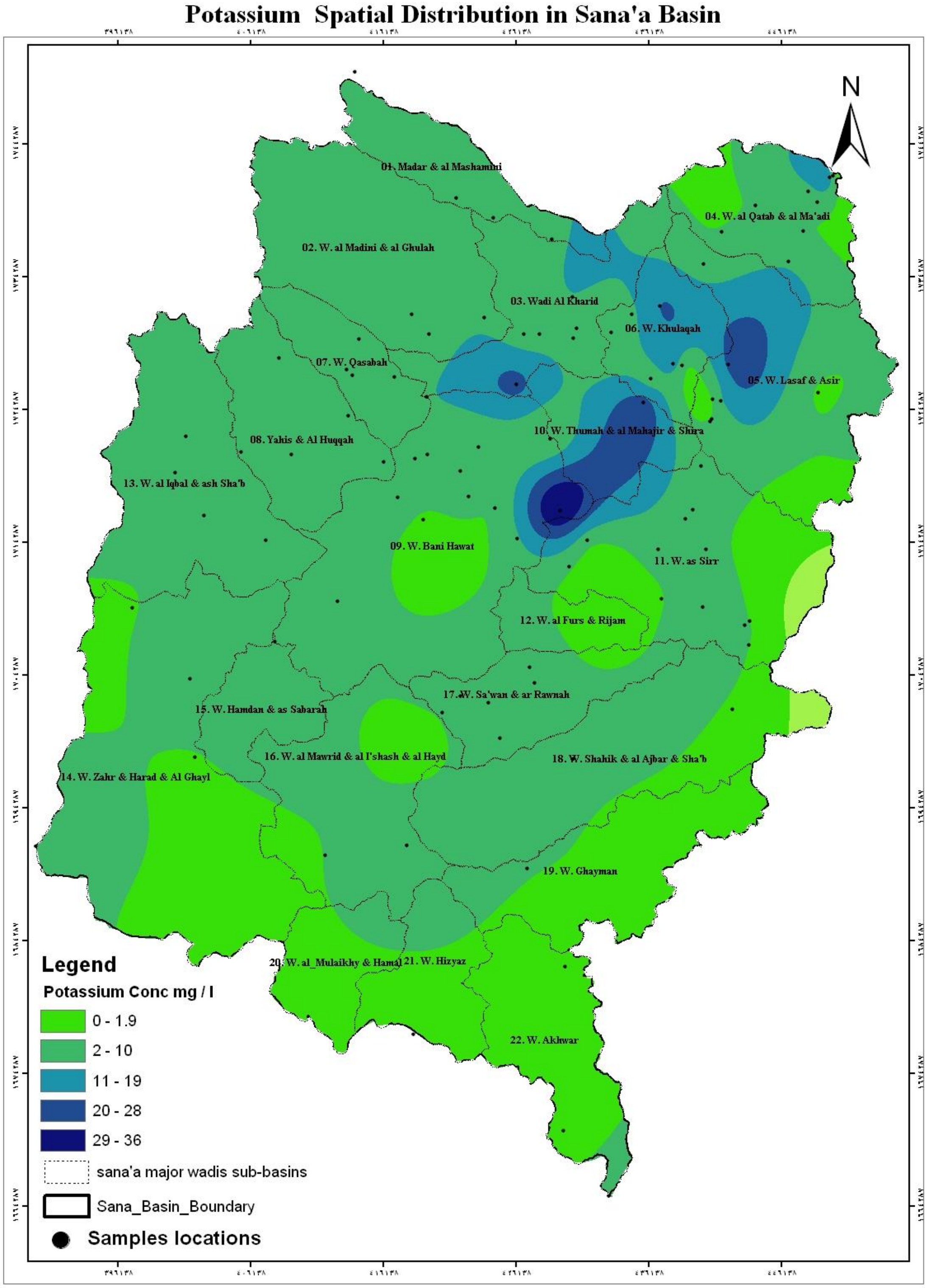


Figure (3.9) Distribution of Potassium concentration (mg/l) over Sana’a Basin

3.2.6. Chloride

Chlorine alone as Cl_2 is highly toxic, and it is often used in disinfectants, paper production (bleach), antiseptic, dyestuffs, solvents, and many other consumer products. Chloride (Cl-) is a salt compound resulting from the combination of the gas chlorine and metal (NaCl, $MgCl_2$). Almost all chloride salts are highly soluble in water. Chloride does not substitute for other anions (no water-rock interaction), so used in mass balance calculations for mixing of water bodies (conservative element). Chlorides may get into groundwater water from several sources including: rocks containing chlorides, percolated agricultural runoff, wastewater from industries, and effluent wastewater from treatment plants.

The conservative behaviour of the chloride ion in groundwater is described by Hem (1970). In hydrochemical groundwater evolution the chloride ion tends to be the most conservative in that it is readily removed from the matrix material but rarely precipitated under dilute solution conditions. The normal chloride concentration increases down the hydraulic gradient and with groundwater flow experience and residence. The normal chloride concentration increases is only disturbed where pollution or dilution occurs so that chloride is an excellent indicator of groundwater flow direction.

The evaporation process also affect the amount of the Cl, thus sometimes chloride may be used to calculate a precipitation surplus if it's concentration in a conservative manner (and not affected by other processes). For this property, chloride areal distribution have been used to define the groundwater flow direction in the Sana'a basin hydrogeological system.

The distribution of Potassium over the entire Sana'a Basin is shown in Figure (3.10).

Bulk of chloride concentrations results in **Limestone aquifer** vary between 8.8 mg/l (HS104) and 92.3 mg/l (HS96) at shallow aquifer of Wadi Al Maadi. Five brackish samples have Cl concentration >1000 mg/l. A borehole sample (HSA105) of wadi Al Qasabah, with almost unity Na/Cl ratio indicating dissolution of halite. The other four samples are representing shallow aquifer water of Al Maadi (2), Khulaqa and Al Kharid with ratio of Na/Cl less than unity and indiscriminate ions water type. Eight samples with Cl ion concentration <100 mg/l are dominant with SO_4 and TDS>1000 mg/l. The other sixteen samples are all fresh recharge water (TDS<1000) and HCO_3 dominant water type. No trend can be observed for Cl and depth to water table for shallow aquifer, however, a decrease in Cl concentration can be tracked with increase of water table for deeper aquifer part. No trend observed for other ions. The least average Cl is 20mg/l in wadi Al mashami and highest 189 mg/l at Khulaqa.

Chloride concentrations in **Sandstone aquifer** vary between 13 mg/l (HA110) at Lafaf and Alsir and 238 mg/l (HS148) at Wadi Assir. In general, the lower the Cl concentration the fresh the groundwater. The lower Cl concentration observed found at upper reaches of tributaries wadis and increases in downstream direction in areas just before these minor wadis discharge their water into the main channel. Average Cl concentration at Lafaf & Alsir, Hamdan, Khulaqa, Sawan and Bani Huwat shows <100 mg/l, while Al maadi, Assir and Thoma have Cl average concentration >100mg/l.

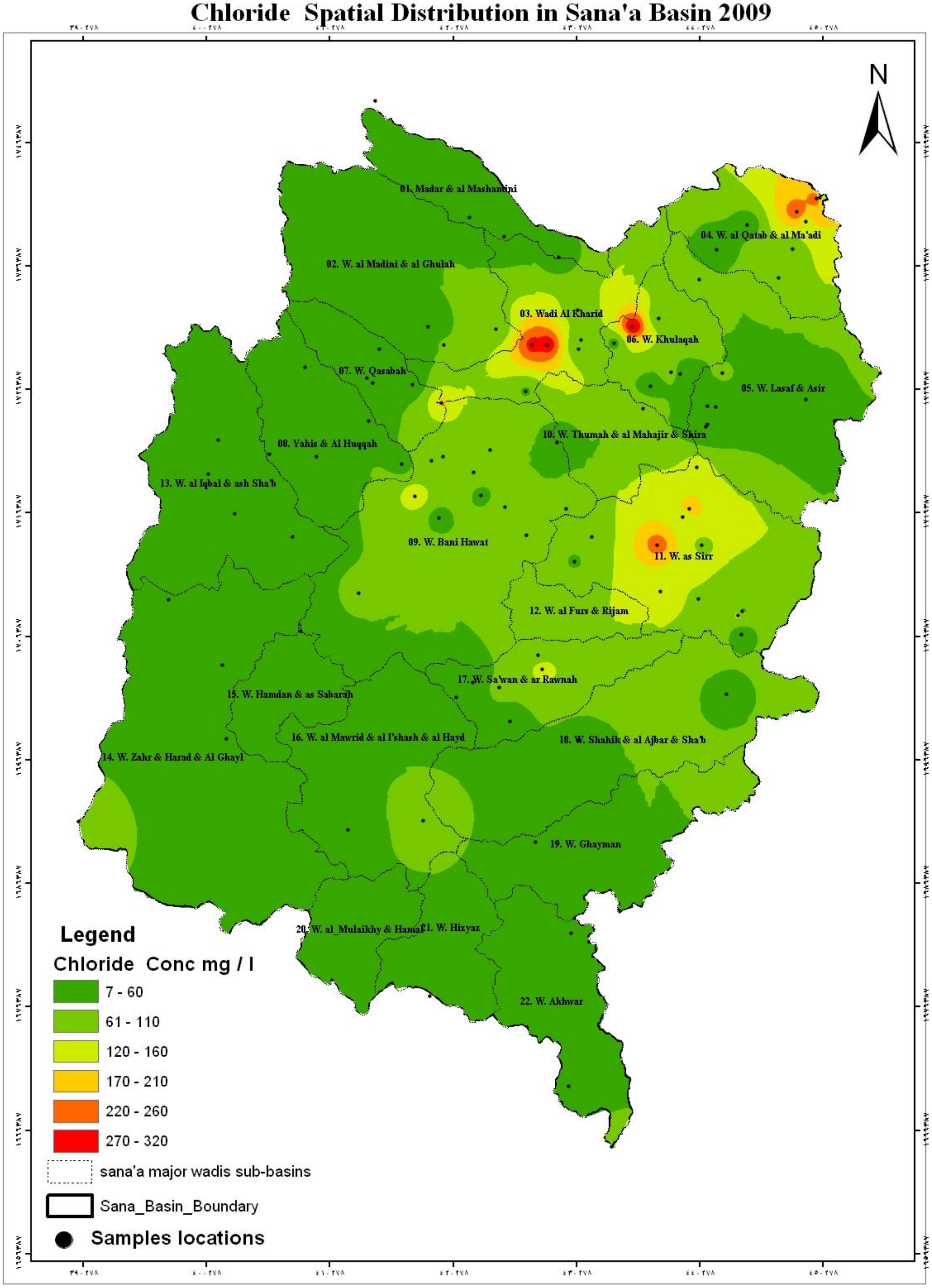


Figure (3.10) Distribution of Chloride concentration (mg/l) over Sana’a Basin

The control of the topography and the structures in the groundwater flow is well reflected in the distribution of the chloride ion concentration. Within the main wellfield areas, the chloride distribution is highly correlated with the depression of the peizometeric surface.

Within the **Volcanic aquifer** 25 samples show Cl concentration of less than 100mg/l and TDS <600mg/l. The four remaining samples with Cl >100mg/l and TDS>700mg/l are drawn from shallow aquifer of Assir (3) and Sawan(1). The least average Cl calculated for Wadi Hamadan 12 mg/l while highest 92mg/l at Assir. The variation of Cl concentration the distribution is well correlated to the piezometric data. Local anomaly may have been caused by evaporation, or anthropogenic effect. Relatively uniform value of chloride found at all the samples from boreholes at the southern part of the basin. The origin of this chloride might be related to presence of sodalite, or using of KCl (fertilizer). However is more likely to be a result of solution and precipitation of the least soluble salts.

Chloride distribution within the alluvium aquifer vary between 28mg/l (HS101), and 283 mg/l (HSA74) at Al Kharid. The lowest average concentration of Cl found at Wadi Maadi and the highest at Al Kharid.

3.2.7. Sulfate

The spatial distribution of the sulphate concentration is shown in Figure (3.11)

A wide range of sulphate concentrations found in the **Limestone aquifer**. The lowest is 23 mg/l found at HSA80 at Al Mashami. The highest concentration 1700 mg/l in sample HS120 at Wadi Lafaf and Alsir and may be related to the dissolution of anhydrite/ gypsum as well as oxidation of pyrite and probably has been exaggerated by recycling of irrigation water. A less extreme effect of evaporation and recycling of irrigated water is found Al Maadi (1175 mg/l). SO_4 concentrations range between 500-1000 mg/l present in brackish water from shallow and deep aquifer at Al Kharid and Khulaqa, which indicate hydraulic connection. Average minimum concentration per sub-basin estimated was 38 for Mashami while the maximum 1004 mg/l at Wadi Lasaf and Alsir.

In the **Sandstone aquifer** the sulphate levels vary over a wide range from 25 to 750mg/l. The exceptionally highest value of SO_4 (1325mg/l) is found at Bani Huwat (HS55) and related to irrigation return/surface pollution or dissolution of gypsum and anhydrite and this dug well is belong to limestone rather than Sandstone. The latter is more likely. High sulphate concentrations occur in Wadi Thoma (750 mg/l) and Khulaqa (725mg/l) and probably these boreholes are penetrating limestone aquifer. High sulphate (312mg/l) found in Wadi Khulaqa has also high NO_3 concentration and probably related to human waste pollution. Samples with medium sulphate concentration with TDS around 1000mg/l are probably related to oxidation of pyrite (sulphide minerals). In some cases sulphur gas in the volcanic region may affect the sulphate concentration (Hem, 1985).

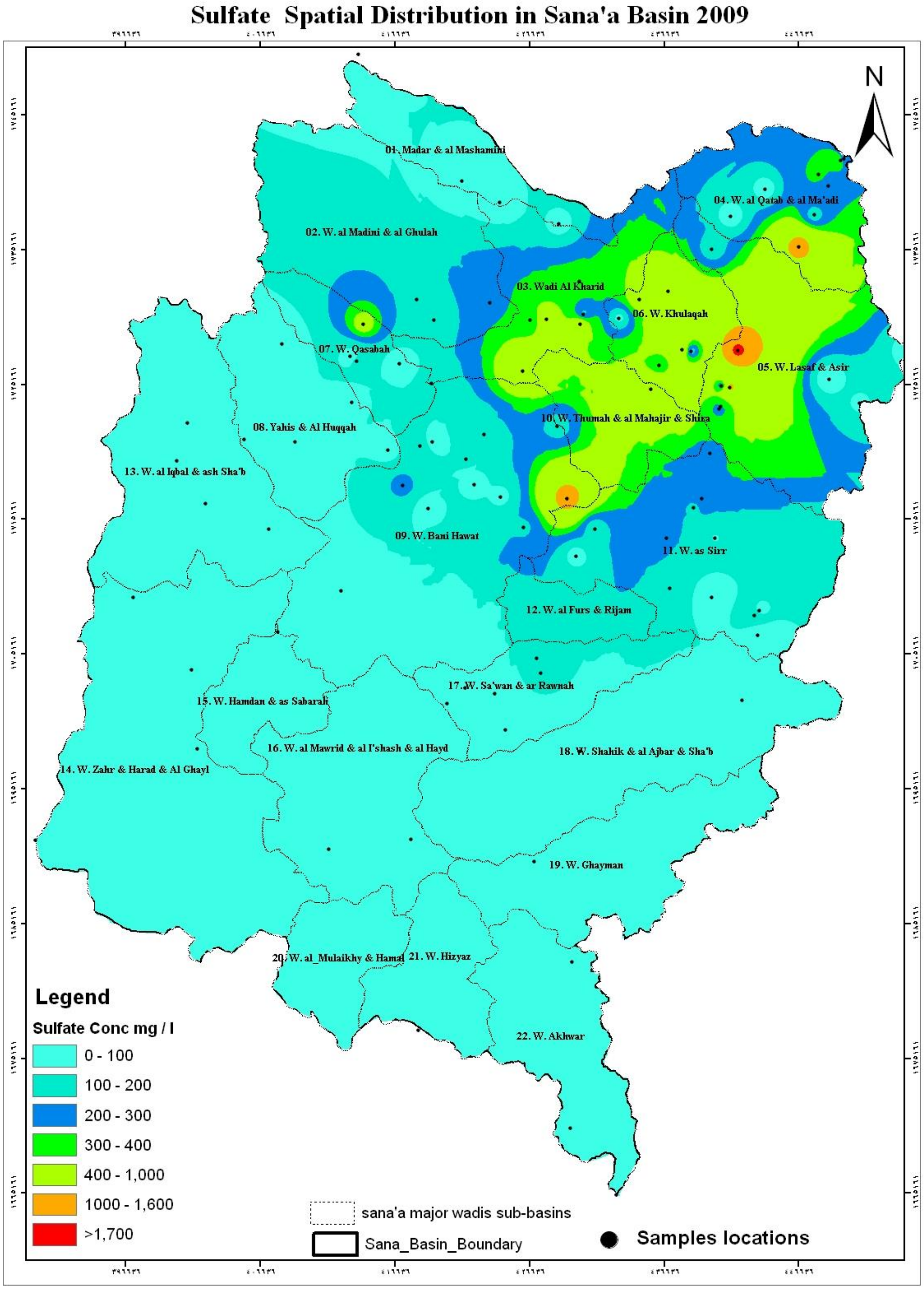


Figure (3.11) Distribution of Sulfate concentration (mg/l) over Sana’a Basin

In the **Volcanic aquifer** the sulphate concentrations range between 8mg/l at Zahr and 250 mg/l at Assir. High values of SO_4 of 200mg/l are found in shallow dug wells resulting from receive large inputs of sulfate from atmospheric deposition, fertilizer use and land application of animal wastes. High concentration of 113 mg/l found at deep borehole at Qasabah. The geological logs from borehole 2P which penetrates the volcanic, have shown the presence of pyrite within the clay layers Mos. 1986. This means the high SO_4 in deep volcanic aquifer may be related to oxidation of pyrite. Lowest average sulphate concentration at sub-basin level estimated for wadi Zahr 17 mg/l while highest at Wadi Assir.

Within the **Alluvial aquifer** the sulphate concentrations vary widely, the lowest value at shallow dugwell at Wadi Assir 25mg/l and the highest levels of 350 mg/l is found in shallow dugwell at Al Kharid.

3.2.8. Bicarbonate

The distribution of the bicarbonate ions in the Sana'a basin is shown in Figure (3.12).

In the **Limestone aquifer,** the bicarbonate vary widely between 112 and 905 mg/l. The highest found at Wadi Khulaqa. Bicarbonate is dominant ions in most samples of this aquifer. The sixteen fresh water of this aquifer has HCO_3 concentration range between 112 and 434mg/l. The lowest average of bicarbonate at sub-basin level is 229 at Bani Huwat while the highest is 634 mg/l at Khulaqa.

The values of the bicarbonate in the **Sandstone aquifer** range from 205mg/l (HS141) at Assir, to 599mg/l (HS55) at dugwell in Bani Huwat. Water dominant by HCO_3 is commonly fresh recharge water. The lowest average concentration of bicarbonate is 266 mg/l at Hamdan, where fresh water is available. The highest is 446 mg/l at Bani Huwat. A slight increase along the local flow path within wadi Rujam have been observed and probably implies that, as groundwater moves in down gradient direction, it consumes more H_2CO_3 in the process of dissolution of minerals.

The bicarbonate in the **Volcanic aquifer** is the dominant ion in the most of the samples. This is because dissolution of silicate minerals except quartz, consumes hydrogen ion during the incongruent dissolution and result in arise in pH and alkalinity. The highest HCO_3 concentration 319mg/l is found at dugwell (HS131) at wadi Assir. The lowest concentration is 109 mg/l at Shahik. The highest average concentration at sub-basin level is 212 mg/l at Iqbal.

In the **alluvial aquifer** the bicarbonate concentrations vary between 162mg/l (HS103) at Bani Huwat and 537 (HS69) at Wadi Assir.

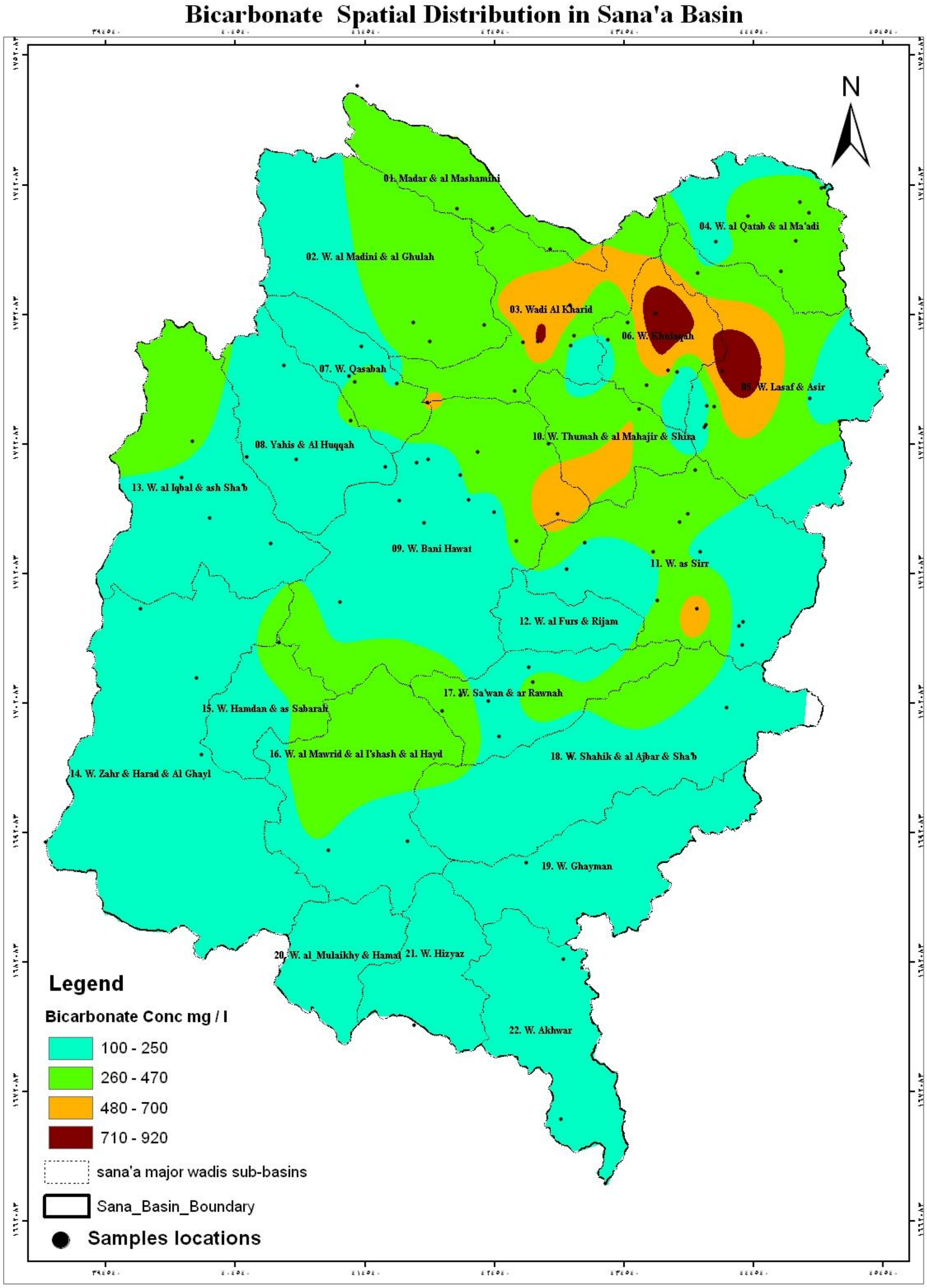


Figure (3.12) Distribution of Bicarbonate concentration (mg/l) over Sana’a Basin

3.2.9. Nitrate

The distribution of Nitrate concentration in Sana'a Basin is shown in Figure (3.13).

Nitrate in **Limestone aquifer** varies between 0.44 mg/l to 67.7 mg/l. The highest value found at dug well (HS115) of wadi Khulaqa with TDS of 1774mg/l. Nine samples have nitrate concentration of higher than 10mg/l. The high concentrations of nitrate are the result of contamination of groundwater supplies by septic systems, feed lots, and agricultural fertilizers. Out of these nine samples, three were drawn from deeper boreholes at Qasabah, Mashami and bani Huwat reflecting the depth reached by the contamination in these areas.

The nitrate in the **Sandstone aquifer** varies between none to 5.7 mg/l at Wadi Khulaqa. Only two samples: HS148 of Wadi Assir with nitrate concentration of 23mg/l and TDS of 1034mg/l. Sample HS21 of Wadi Khulaqa has nitrate concentration of 33 mg/l but TDS of 514mg/l. Both samples are drawn from deep boreholes with water table of more than 150 mbgs.

In the **Volcanic aquifer**, the nitrate concentration has wider range varying between 0.44mg/l and 42 mg/l. Eleven samples show nitrate concentration of more than 10mg/l. Only two of these samples are drawn from shallow aquifer. The rest of the samples are drawn from boreholes with water table greater than 200mg/l. This reflects depth of contamination. Nitrate comes into water through the nitrogen cycle rather than via dissolved minerals. In aerobic condition, NO_3 is stable and tends to be conservative in most groundwater environments. It seems the depth of NO_3 in this aquifer is due to poor construction of borehole which allows (act as conduits) entry of contaminated water from surface to the deeper part of the aquifer.

In the **alluvial aquifer**, 50% of the samples have nitrate concentration of less than 10 mg/l. samples with higher nitrate concentration are present in Wadi Bani Huwat.

3.2.10 Phosphates

Phosphorus is usually present in natural water as phosphates.

Only three samples from **Limestone aquifer** shows phosphate concentration of 0.15, (HSA107) at dugwell in Al Kharid, 0.21 mg/l (HSA68) at borehole in Al Mashami, and 0.28 mg/l (HSA77) at dugwell in Bani Huwat. The presence of phosphate is affected by wastewater and septic system effluent, detergents & fertilizers and/or animal waste.

All samples from **Sandstone aquifer** are free of phosphate.

Only one sample in the **Volcanic aquifer** show concentration of phosphate of 0.07 mg/l (HSS40) at Wadi Hizyaz.

In the **alluvial aquifer**, only two samples show concentration of phosphate of 0.32 mg/l (HSA7) of Bani Huwat and 0.4mg/l (HSA74) of wadi Al Kharid

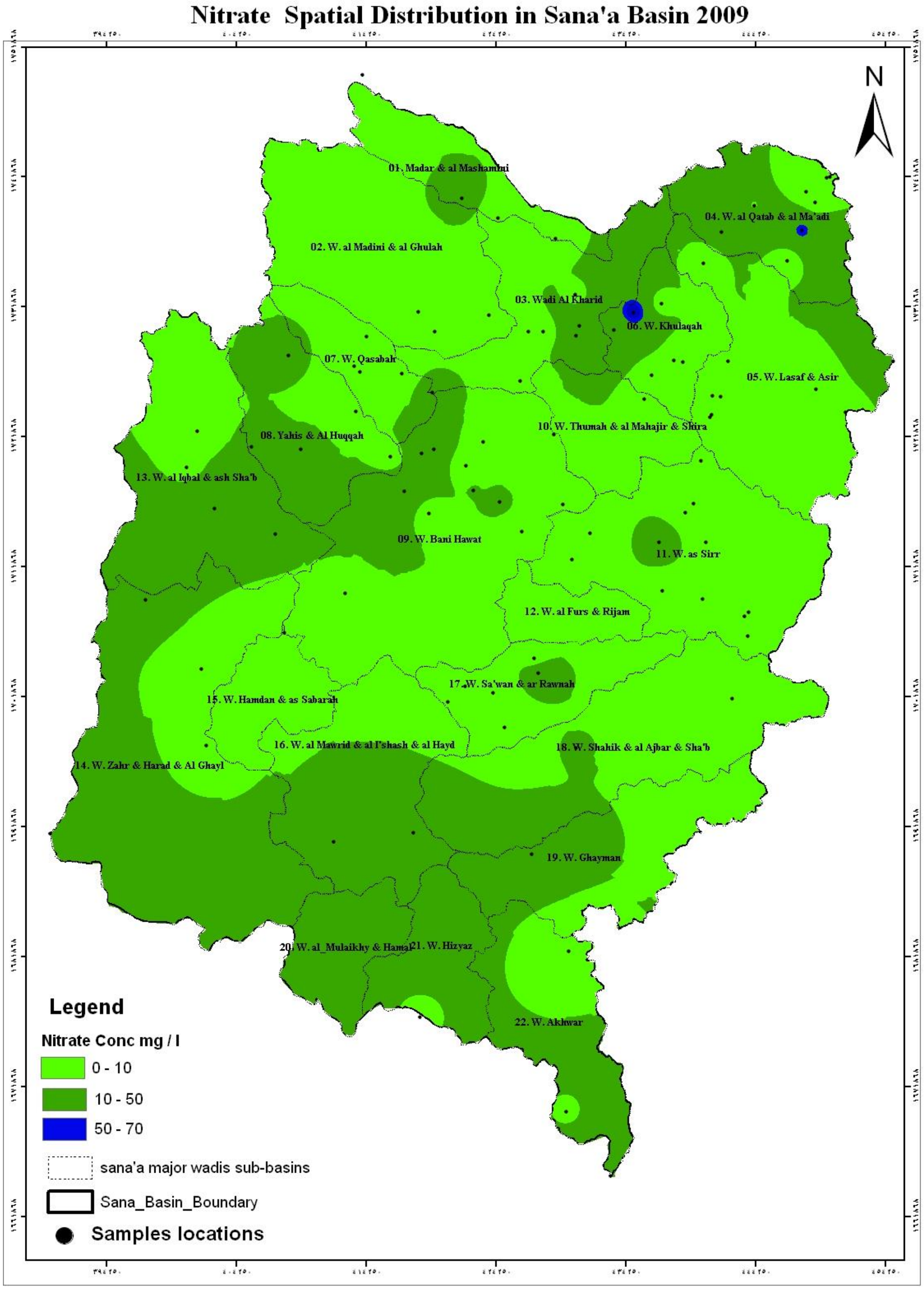


Figure (3.13) Distribution of Nitrate concentration (mg/l) over Sana’a Basin

3.3. TEMPORAL HYDROCHEMICAL VARIATION

Variation between 2007 and 2009 were undertaken at sample level for each aquifer. However, there are several samples analyzed during 2007, their results were not available for this study. Other samples were changed due to not existing of borehole/dugwell used during 2007.

Variation between 1986, 1995, 2007 and 2009 were undertaken at two levels: at each sub-basin and each aquifer level. This is because not the same samples were analyzed by all studies. Only numerical variation was assessed as the spatial distribution may not be accurate enough.

3.3.1. LIMESTONE AQUIFER

3.3.1.1. Temporal hydrochemical variation during 2007-2009

58 samples were compared; 29 samples for each study of 2007 and 2009 were used. Three levels were identified: decrease in the TDS values, increase in TDS, Almost means the difference is less than 50mg/l.

18 samples show increase in their TDS values ranges between 64mg/l (HS86) of Al Maadi and 1103 mg/l (HS120) of wadi lasaf & Alsir.

Three samples show decrease during 2007-2009 of their TDS values range between 52mg/l (HS117) of Lasaf &Alsir and 405 mg/l (HSA108) of Wadi Al Kharid.

8 samples show almost little changes either decrease or increase in TDS values.

Wadi lasaf consist samples of highest increase of TDS (HS120) and lowest decrease in TDS value (HS117) among samples of all sub-basin. This indicates there is no dilution occurring in this sub-basin and water quality is worsen by time.

If samples analyzed correctly, this variation may be related to amount of recharge/discharge of the sub-basin (sample). While increase in TDS value indicate deterioration of water quality of the sample which may be results from higher discharge and/or putting more pollution locad to the aquifer. The decrease of TDS which noticed only on sample (HSA108) by 405 mg/l resulting from dilution of water quality as result of recharge pulses.

Table (3.5) Temporal hydrochemical variation on Limestone aquifer during 2007-2009

Well Name	year	Sub-Basin	PH	TDS	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	Cal TDS	Difference	status
HS100	2007	Al Maadi	7.6	733	83	50	100	9	16	225	191	171	846		
HS100	2009	Al Maadi	8.03	650	63	71	67	2	0	332	69	150	754	-92	**decrease**
HS104	2007	Al Maadi	7.7	299	70	17	16	3	16	241	36	20	419		
HS104	2009	Al Maadi	7.68	334	62	24	25	2	23	230	9	36	410	-9	**almost**
HS115	2007	Khulaqa	7.4	1231	206	80	90	8	16	273	306	389	1368		
HS115	2009	Khulaqa	6.85	1489	284	98	125	9	0	363	315	512.5	1705	338	**increase**
HS117	2007	Wadi A'sir	7.6	655	63	27	132	5	24	233	153	135	771		
HS117	2009	Wadi A'sir	7.4	600	67	28	94	6	16	297	74	137.5	719	-52	**decrease**
HS120	2007	Wadi A'sir	7.3	2213	401	117	130	10		201	105	1350	2314		
HS120	2009	Wadi A'sir	7.1	2152	579	128	143	21	0	783	64	1700	3417	1103	**increase**
HS122	2007	Wadi A'sir	7.4	1414	240	64	130	8	16	241	86	750	1534		
HS122	2009	Wadi A'sir	6.87	1515	300	80	190	9	0	378	59	1175	2192	657	**increase**
HS78	2007	Khulaqa	7.2	1339	270	67	100	18	24	618	81	470	1648		
HS78	2009	Khulaqa	7.36	1456	332	74	215	19	0	905	64	775	2384	736	**increase**
HS85	2007	Al Maadi	7.8	1285	86	44	320	11	24	249	297	380	1410		
HS85	2009	Al Maadi	7.58	1253	95	39	352	12	32	263	298	425	1516	106	**increase**
HS86	2007	Al Maadi	7.9	509	101	23	52	4	8	209	89	128	613		
HS86	2009	Al Maadi	7.99	616	107	25	63	6	10	236	80	150	677	64	**increase**
HS91	2007	Al Maadi	7.7	735	70	44	120	5	16	160	220	180	816		
HS91	2009	Al Maadi	7.33	1053	181	61	136	8	0	321	258	325	1290	475	**increase**
HS96	2007	Al Maadi	7.5	1420	270	64	100	9		225	115	750	1533		
HS96	2009	Al Maadi	7.5	1430	350	82	180	9	23	266	92	1225	2228	695	**increase**
HSA105	2007	Qasabah	7.9	800	65	44	168	6	32	377	211	86	989		
HSA105	2009	Qasabah	7.5	943	102	49	162	9	0	489	166	125	1102	114	**increase**
HSA106	2007	al Madini	8.3	416	21	11	122	3	32	225	45	70	529		
HSA106	2009	al Madini	7.5	627	65	37	95	6	25	290	60	120	697	169	**increase**
HSA107	2007	Al karid	7.7	1150	154	82	105	5	16	184	96	600	1242		
HSA107	2009	Al karid	8.03	997	120	70	176	6	22	237	73	550	1253	11	**almost**
HSA108	2007	Al karid	7.9	1011	31	26	290	4	32	321	148	320	1172		
HSA108	2009	Al karid	7.72	681	86	52	75	4	0	314	59	175	766	-405	**decrease**
HSA10	200	Al karid	7.9	655	91	45	60	6	16	233	22	300	771		

9	7														
HSA109	2009	Al karid	7.11	1034	11	10	423	10	3	558	76	325	1416	645	**increase**
HSA65	2007	Mashami	7.5	290	62	22	18	3	24	205	29	30	392		
HSA65	2009	Mashami	7.4	380	60	24	34	5	0	308	31	33	495	102	**increase**
HSA66	2007	Mashami	7.7	340	86	24	12	3	20	281	26	29	481		
HSA66	2009	Mashami	7.56	403	67	30	20	3	21	325	13	33	511	31	**almost**
HSA68	2007	Mashami	8.3	419	26	12	120	9	28	297	29	47	567		
HSA68	2009	Mashami	7.8	477	11	10	170	8	19	380	20	62.5	682	114	**increase**
HSA71	2007	al Madini	7.7	383	77	24	30	5	16	241	31	80	503		
HSA71	2009	al Madini	7.78	569	78	35	68	7	0	345	22	180	736	232	**increase**
HSA73	2007	al Madini	7.7	520	105	29	36	4	16	257	36	166	648		
HSA73	2009	al Madini	8.09	753	137	39	72	8	0	434	61	237.5	990	342	**increase**
HSA75	2007	Al karid	7.4	1440	193	135	130	6	24	433	316	420	1657		
HSA75	2009	Al karid	7.94	1625	209	154	190	6	0	712	301	512.5	2085	428	**increase**
HSA77	2007	B.Huwat	7.7	370	87	26	20	3	16	329	31	23	535		
HSA77	2009	B Huwat	7	523	99	35	34	4	0	371	22	141.1	706	172	**increase**
HSA80	2007	Mashami	7.6	264	63	17	14	2	8	249	22	15	389		
HSA80	2009	Mashami	8.1	317	51	23	21	2	12	254	18	23	403	14	**almost**
HSA88	2007	Qasabah	8.3	361	17	15	96	4	24	217	31	66	469		
HSA88	2009	Qasabah	7.3	857	74	42	203	7	8	198	30	500	1061	592	**increase**
HSA92	2007	Al karid	7.7	1344	159	54	180	19	24	233	72	720	1460		
HSA92	2009	Al karid	7.83	1236	147	63	184	21	35	286	53	710	1499	38	**almost**
HSA93	2007	B Huwat	7.9	301	11	2	100	1	8	120	55	64	361		
HSA93	2009	B Huwat	8.54	358	6	5	88	1	13	112	42	60	327	-33	**almost**
HSA94	2007	B Huwat	8.1	426	65	14	72	3	32	168	84	72	510		
HSA94	2009	B Huwat	7.96	525	85	14	61	3	25	203	75	75	540	30	**almost**
HSA97	2007	Qasabah	8.2	347	43	16	66	3	32	168	38	64	431		
HSA97	2009	Qasabah	8.14	380	37	20	69	4	11	241	30	40	452	21	**almost**

3.3.1.2. Temporal hydrochemical variation during 1986, 1995, 2007, and 2009

Table (3.6) Hydrochemical variation of Limestone at aquifer level

year	**pH**	**Ca**	**Mg**	**Na**	**K**	**CO3**	**HCO3**	**Cl**	**SO4**	**Hardness**	**Cal TDS**	**Difference**	**status**	**Number of samples**	**Sub basin**

1986	7.9	150	34	169	6.6	1.9	183	120	539	515	1205	-		19	5
2007	7.8	114	41	126	8.0	21	274	100	320	456	1007	-198.1	decrease	33	9
2009	7.6	144	49	125	7.8	9	378	86	377	565	1189	182.2	increase	29	8

In 1986, 19 samples covers the limestone and five sub-basin, while in 2007 33 samples covered 9 sub-basin and in 2009 29 samples covers 8 sub basin.

Water quality show dilution following a decrease in TDS value between 1986 and 2007 by 198mg/l and general decrease of most of major constituents of water. Slight change in TDS values of water samples collected from this aquifer is observed between 2007 and 2009 by 182. mg/l.

Table (3.7) Hydrochemcial variation of limestone aquifer at sub-basin level

Sub-basin	**Year**	**pH**	**Ca**	**Mg**	**Na**	**K**	**CO3**	**HCO3**	**Cl**	**SO4**	**hardness**	**Cal TDS**	**Difference**	**Status**	**Number of samples**
Al maadi	1986	8.0	140	47	77	6	6	152	170	331	544	929			4
Al maadi	2007	7.7	113	40	118	7	13	218	158	272	450	939	10	**almost**	6
Al maadi	2009	7.7	143	50	137	6	15	275	134	385	564	1160	221	**increase**	6
bani huwat	1986	8.2	88	20	190	5	2	207	91	373	302	975			6
bani huwat	2007	7.9	45	11	72	2	14	186	60	56	159	447	-528	**decrease**	4
bani huwat	2009	7.8	63	18	61	3	13	229	46	92	232	530	84	**increase**	3
khulaqa	1986	7.4	78	41	411	10	0	225	138	853	361	1756			4
khulaqa	2007	7.3	238	74	95	13	20	445	194	430	897	1508	-248	**Decrease**	2
khulaqa	2009	7.1	308	86	170	14	0	634	189	644	1122	2079	571	**Increase**	2
lasaf asir	1986	8.1	70	35	98	5	2	225	98	201	316	733			3
lasaf asir	2007	7.4	234	69	131	8	13	225	115	745	870	1540	807	**increase**	3
lasaf asir	2009	7.1	315	79	142	12	5	486	66	1004	1111	2112	572	**increase**	3
Thoma	1986	8.1	376	29	69	8	0	107	106	940	1056	1633			2
Thoma	2007	8.2	116	52	350	21	39	345	96	750	504	1769	136	**increase**	1
Al kharid	2007	7.8	108	58	160	8	22	283	122	408	507	1169			6
Al kharid	2009	7.7	115	70	210	9	12	421	113	455	573	1414	245	**increase**	5
madini	2007	7.8	77	24	62	5	20	255	38	125	293	606			4
madini	2009	7.8	94	37	78	7	8	356	48	179	386	812	205	**increase**	3
qasabah	2007	8.1	42	25	110	4	29	254	93	72	207	630			3

qasabah	2009	7.6	71	37	145	7	7	309	75	222	329	880	250	**increase**	3
mashami	2007	7.8	59	19	41	4	20	258	26	30	225	457			4
mashami	2009	7.7	48	22	61	5	13	317	20	38	208	529	72	**increase**	4

Al Maadi shows slight change between 1986 and 2007 however, an increase of >200 mg/l observed between 2007 and 2009. While at Bani Huwat high decrease in TDS observed between 1986 and 2007 with slight increase between 2007 and 2009. For Khulaqa a decrease of 248 in TDS value noticed between 1986 and 2007, however this trend has been reversed and double increase of TDS 571 mg/l noticed between 2007 and 2009. The increasing trend observed in Wadi Lasaf & Alsir since 1986 when TDS was 733 mg/l, in 2007 1508 mg/l, then to 2079 mg/l in 2009. For the rest of the five sub-basin, information available for 2007 and 2009. All sub-basin show an increasing trend of TDS varies between 72mg/l in Mashami and 245mg/l in Al Kharid between 2007 and 2009. In fact, the deterioration of water quality according to TDS values has been observed for all sub-basin during 2007-2009 over this aquifer.

3.3.2. SANDSTONE AQUIFER

3.3.2.1. Temporal hydrochemical variation during 2007-2009

24 samples during 2009 while during 2007 only 19 samples results are available. Comparable samples are 18 for each survey which makes 36 samples were temporal variation between 2007 and 2009. Three levels were identified: decrease in the TDS values, increase in TDS, Almost means the difference is less than 50mg/l.

25 water points show increase in their TDS value between 2007 and 2009 ranges between 71 mg/l (HS21) of W. Khulaqa and 1424 mg/l (HS55) of Bani Huwat. These water points shows deterioration in water quality with various degree. The highest is of the dugwell of Khulaqa with an increase in all major constituent but Cl. Decrease of TDS value observed only at borehole (HS31) of Wadi Assir with amount of 259 mg/l. Two boreholes at Wadi Assir (HS141 and HS147) shows slight change in their TDS values between 2007 and 2009.

Table (3.8) Temporal variation on Sandstone aquifer during 2007-2009

Well Name	**year**	**Sub-Basin**	**PH**	**TDS**	**Ca**	**Mg**	**Na**	**K**	**CO3**	**HCO3**	**Cl**	**SO4**	**Cal TDS**	**Difference**	**Status**
HS105	2007	khulaqa	7.6	587	131	35	26	6	16	241	65	189	708		
HS105	2009	khulaqa	7.3	684	161	40	35	7	0	316	29	313	900	192	**increase**
HS110	2007	lasaf	7.9	193	40	10	18	1	8	160	22	14	273		
HS110	2009	lasaf	7.64	259	49	16	25	1	0	229	13	25	359	86	**increase**
HS112	2007	khulaqa	7.5	1267	155	78	160	10	16	329	134	550	1432		
HS112	2009	khulaqa	7.12	1198	215	79	178	15	0	537	84	725	1832	400	**increase**
HS113	2007	khulaqa	7.5	300	62	20	16	2	8	168	34	73	383		
HS113	2009	khulaqa	6.25	463	88	25	32	5	0	224	33	138	543	160	**increase**
HS124	2007	lasaf	7.5	303	67	20	14	7	24	160	24	67	383		
HS124	2009	lasaf	7.3	490	124	17	23	3	0	209	17	200	592	209	**increase**
HS125	2007	lasaf	7.4	324	85	12	12	2	16	160	24	93	404		
HS125	2009	lasaf	7.49	485	110	17	22	3	0	208	15	215	590	186	**increase**
HS126	2007	lasaf	7.5	580	144	24	24	2	16	225	29	230	692		
HS126	2009	lasaf	7.82	619	154	30	20	2	0	249	18	338	810	118	**increase**
HS127	2007	thoma	7.4	1196	215	78	70	11	16	321	96	550	1356		
HS127	2009	thoma	7.5	1201	299	88	100	22	0	438	100	750	1798	441	**increase**
HS132	2007	assir	7.2	851	145	48	80	6	32	225	259	170	963		
HS132	2009	assir	6.63	896	136	61	88	5	0	354	191	275	1110	147	**increase**
HS133	2007	assir	7.5	590	107	34	50	5	24	249	101	146	715		
HS133	2009	assir	6.78	733	119	49	67	5	0	360	116	188	905	190	**increase**
HS141	2007	assir	7.4	475	86	18	56	4	24	184	110	84	567		
HS141	2009	assir	7.17	561	87	20	72	4	0	205	101	100	588	22	**almost**
HS147	2007	assir	7.5	379	69	16	44	4	24	56	98	96	407		
HS147	2009	assir	7.38	404	61	19	47	3	0	208	54	63	455	48	**almost**
HS148	2007	assir	7.3	823	140	33	100	5	24	176	249	184	911		
HS148	2009	assir	7.23	949	157	43	113	6	0	265	238	213	1034	124	**increase**

HS152	2007	bani huwat	7.9	571	73	15	95	9	16	168	74	205	656		
HS152	2009	bani huwat	7.38	653	86	21	116	10	0	295	78	188	792	137	**increase**
HS21	2007	khulaqa	7.4	354	66	20	30	6	32	176	50	62	442		
HS21	2009	khulaqa	7.3	463	82	25	32	6	0	251	43	75	514	71	**increase**
HS31	2007	assir	7	602	86	58	45	4	16	257	74	190	730		
HS31	2009	assir	7.63	377	65	28	18	4	0	250	19	88	471	-259	**decrease**
HS4	2007	Al maadi	7.5	896	129	54	95	9	32	168	259	235	981		
HS4	2009	Al maadi	7.32	866	159	54	90	6	0	373	146	263	1091	110	**increase**
HS55	2007	bani huwat	7.9	1338	275	31	110	8	16	160	67	750	1418		
HS55	2009	bani huwat	7.9	1931	414	52	355	36	0	599	60	1325	2841	1424	**increase**

3.3.2.2. Temporal hydrochemical variation during 1986, 1995, 2007, and 2009

Table (3.9) Hydrochemical variation of Sandstone at aquifer level

Year	PH	TDS	Ca	Mg	Na	K	CO3	HCO3	Cl	SO4	Hardness	Cal TDS	Difference	Status	number of samples	sub-basin
1986	7.9	534	85	20	68	3	2	152	75	206	295	611			49	5
1995	8.0	558	89	21	45	4	0	245	57	89	307	558	-53	almost	30	5
2007	7.5	766	134	40	67	7	20	209	109	285	501	871	313	increase	19	6
2009	7.4	757	148	41	86	9	5	327	73	318	539	1010	139	increase	24	8

At aquifer level, there is almost no changes in TDS between 1986 and 1995, however, an increasing trend in TDS value has been noticed between 1995 and 2007 (by 313mg/l) and between 2007 and 2009 (139 mg/l). this means by year 2009 the water o this aquifer became brackish water with TDS value of 1010mg/l. Water is also becoming harder.

Table (3.10) Hydrochemcial variation of Sandstone aquifer at sub-basin level

sub-basin	year	PH	TDS	Ca	Mg	Na	K	CO3	HCO3	Cl	SO4	Hardness	Cal TDS	Difference	status	number of samples
almaadi	1986	7.8	806	173	29	36	2	0	104	29	485	553	858			1
almaadi	1995	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
almaadi	2007	7.5	896	129	54	95	9	32	168	259	235	544	981	123	**increase**	1
almaadi	2009	7.3	866	159	54	90	6	0	373	146	263	618	1091	110	**increase**	1
B huwat	1986	8.0	636	59	19	129	3	4	139	108	232	227	695			8
B huwat	1995	9.5	531	90	17	46	3	0	226	59	90	295	531	-164	**decrease**	1

B huwat	2007	7.9	955	174	23	103	9	16	164	71	478	530	1037	506	**increase**	2
b huwat	2009	7.6	1292	250	37	235	23	0	447	69	756	776	1819	782	**increase**	2
Assir	1986	7.5	525	86	30	60	3	0	196	105	157	338	638			25
Assir	1995	7.7	685	113	27	58	4	0	234	99	130	391	685	47	**almost**	9
Assir	2007	7.4	575	99	32	57	4	24	194	133	128	381	672	-13	**almost**	7
Assir	2009	7.1	641	101	35	68	5	0	269	115	152	397	750	78	**increase**	7
Lasaf	1986	7.9	306	35	7	70	3	0	189	44	52	116	400			2
Lasaf	1995	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
Lasaf	2007	7.6	350	84	16	17	3	16	176	25	101	277	438	38	**almost**	4
Lasaf	2009	7.6	463	109	20	23	2	0	224	16	194	355	590	151	**increase**	4
Rujam	1986	8.3	396	72	15	45	3	3	134	89	105	243	466			13
Rujam	1995	8.1	508	79	17	43	4	0	231	49	77	268	508	42	**increase**	7
Rujam	2007	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
Rujam	2009	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
Sawan	1986	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
Sawan	1995	7.5	523	86	18	40	3	0	238	46	82	288	523			7
Sawan	2007	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
Sawan	2009	7.4	455	68	22	58	4	0	269	50	81	259	554	31	**almost**	4
Zahar	1986	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
Zahar	1995	7.3	543	76	26	38	4	0	296	32	65	296	543			6
Zahar	2007	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
Zahar	2009	7.9	434	61	31	49	4	39	266	37	38	279	524	-19	**almost**	1
Khulaqa	1986	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
Khulaqa	1995	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
Khulaqa	2007	7.5	627	104	38	58	6	18	229	71	219	416	741			4
Khulaqa	2009	7.0	702	136	42	69	8	0	332	47	313	515	957	216	**increase**	4
Thoma	1986	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
Thoma	1995	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
Thoma	2007	7.4	1196	215	78	70	11	16	321	96	550	856	1356			1
Thoma	2009	7.5	1201	299	88	100	22	0	438	100	750	1110	1798	441	**increase**	1

Al maadi show an increasing trend between 1986 and 2009. Water quality in Wadi Bani huwat show decreasing trend of TDS values between 1986 and 1995, then an increasing trend of TDS value continued to 2007 (1037mg/l), and 1819 mg/l in 2009 survey. An increase of salinity of the Sandstone aquifer also was observed in Wadi Khulaqa and Thoma during 2007-2009. During the same period slight increase of TDS value is shown in wadi Lasaf & Alsir. Interestingly the salinity increase is coincide with the cone of depression (reducing of groundwater table) as simulated in the numerical model

Almost stable water chemistry noticed in Wadi Assir during 1986 and 2009, in wadi Rujam during 1986 and 1995 and in wadi Sawan 1995 and 2007.

3.3.3. VOLCANIC AQUIFER

3.3.3.1. Temporal hydrochemical variation during 2007-2009

30 samples available during 2009 while during 2007 results of 14 samples are available for present analysis. Comparable samples are 12 from each survey. This means only 24 samples their temporal variation between 2007 and 2009 were assessed. Three levels were identified: decrease in the TDS values, increase in TDS, Almost means the difference is less than 50mg/l.

Three water points show increase in their TDS values during 2007-2009 ranges between 56 mg/l (HSA99) and 250 mg/l (HSA86) both in Wadi Qasabah. Four water points show decreases in their TDS values that ranges between 71mg/l (HS144) and 1118 mg/l at dug well (HS131) of Wadi Assir. This indicate dilution due to fresh recharge water. Five samples show slight change in their TDS values (+-50mg/l).

Table (3.11) Temporal hydrochemical variation on Volcanic aquifer during 2007-2009

Well Name	year	Sub-Basin	PH	TDS	Ca	Mg	Na	K	CO3	HCO3	Cl	SO4	Cal TDS	Difference	Status
HS131	2007	Assir	8.0	1898	158	35	480	9	47	385	326	650	2090		
HS131	2009	Assir	6.6	790	137	46	77	5	0	320	138	250	972	-1118	**decrease**
HS142	2007	Assir	7.6	288	33	3	68	1	8	104	69	54	340		
HS142	2009	Assir	8.2	340	38	5	67	1	0	133	47	69	361	20	**almost**
HS143	2007	Assir	7.2	843	118	35	136	8	8	337	110	260	1012		
HS143	2009	Assir	7.8	675	113	19	89	4	0	173	124	200	722	-289	**decrease**
HS144	2007	Assir	8.2	322	10	1	110	1	16	120	62	62	382		
HS144	2009	Assir	7.9	283	44	11	34	2	0	146	31	43	311	-71	**decrease**
HS145	2007	Assir	7.6	707	101	29	105	1	24	176	170	189	795		
HS145	2009	Assir	7.9	731	119	29	90	2	0	260	123	200	823	28	**almost**
HSA84	2007	alhuqqah	8.2	311	21	10	80	3	32	152	38	51	388		
HSA84	2009	alhuqqah	8.3	436	12	9	132	3	0	260	24	88	527	140	**increase**
HSA85	2007	qasabah	8.2	448	20	11	132	3	24	233	45	97	564		
HSA85	2009	qasabah	8.3	379	16	8	109	3	16	223	30	72	477	-87	**decrease**
HSA86	2007	qasabah	8.1	325	12	6	104	3	16	201	31	52	425		
HSA86	2009	qasabah	8.1	514	18	7	176	3	16	306	37	113	675	250	**increase**

HSA87	2007	alhuqqah	8.1	217	18	21	32	5	24	136	31	18	285		
HSA87	2009	alhuqqah	7.0	272	17	20	49	5	6	197	18	13	324	39	**almost**
HSA99	2007	qasabah	8.1	265	10	2	88	2	8	160	43	32	346		
HSA99	2009	qasabah	8.2	354	10	7	99	2	10	162	40	72	402	56	**increase**
HSH10	2007	alhuqqah	8.1	209	32	15	22	3	16	120	26	34	269		
HSH10	2009	alhuqqah	7.6	263	29	18	34	3	0	186	18	29	317	47	**almost**
HSH11	2007	alhuqqah	7.9	214	30	12	32	3	24	128	31	18	278		
HSH11	2009	alhuqqah	7.4	260	26	17	35	4	0	184	17	26	310	32	**almost**

3.3.3.2. Temporal hydrochemical variation during 1986, 1995, 2007, and 2009

Table (3.12) Hydrochemical variation of Volcanic at aquifer level

Years	PH	TDS	Ca	Mg	Na	K	CO3	HCO3	Cl	SO4	Hardness	cal TDS	Difference	status	No. of samples	Sub-basin
1986	8.0	348	52	20	47	1	2	182	72	60	213	437			100	12
2007	8.0	427	42	14	96	3	20	179	66	97	161	517	80	**increase**	14	3
2009	8.0	368	41	13	68	3	3	212	40	53	158	442	-75	**decrease**	30	12

According to the available samples for this aquifer from previous studies, there is slight increase in TDS between 1986 and 2007 and slight decrease trend in TDS values between 2007-2009. This implies there are no changes in water quality of the volcanic aquifer between 1986 and 2009. As the volcanic aquifer composes material with least solubility in groundwater, this means there is no active contamination sources over this aquifer.

Table (3.13) Temporal variation in volcanic aquifer at sub-basin level

sub-basin	year	PH	TDS	Ca	Mg	Na	K	CO3	HCO3	Cl	SO4	Hardness	cal TDS	Difference	Status	No. of samples
Akhwar	1986	8.1	303	40	20	42	1	3	150	71	46	182	373			14
Akhwar	2007	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
Akhwar	2009	8.3	274	31	6	56	1	0	166	28	28	101	326	-47	Almost	3
Assir	1986	7.8	347	45	31	39	2	1	203	71	58	241	450			8
Assir	2007	7.7	698	87	20	137	4	19	206	128	201	298	801	352	increase	7
Assir	2009	7.5	831	117	36	136	9	0	497	95	185	441	1087	286	increase	6
Hamdan	1986	8.0	331	51	16	45	3	2	141	82	61	191	401			4
Hamdan	2007	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
hamdan	2009	7.9	248	31	13	42	3	0	188	16	22	130	322	-79	decrease	2
hizyaz	198	8.	303	37	14	58	2	2	142	85	35	148	374			2

	6	2														
hizyaz	2007	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
hizyaz	2009	8.2	246	19	4	59	1	0	131	27	37	66	279	-96	decrease	1
sawan	1986	8.0	397	60	34	39	2	5	206	102	52	290	500			10
sawan	2007	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
sawan	2009	7.8	539	89	20	62	5	0	246	88	89	307	613	113	increase	2
shahik	1986	8.0	252	44	23	18	1	1	174	46	34	204	340			11
shahik	2007	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
shahik	2009	9.2	304	2	3	94	1	13	109	39	43	18	304	-35	Almost	1
zahar	1986	8.0	217	35	24	12	1	1	158	38	28	186	297			30
zahar	2007	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
zahar	2009	8.1	212	30	8	30	2	0	165	12	17	109	273	-24	Almost	2
huqqah	1986	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
huqqah	2007	8.1	238	25	15	42	4	24	134	32	30	124	305			4
huqqah	2009	7.6	308	21	16	62	4	2	207	19	39	119	380	75	increase	4
Qasabah	1986	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm			
Qasabah	2007	8.1	346	14	6	108	3	16	198	40	60	61	445			3
Qasabah	2009	8.2	415	15	8	128	2	14	230	36	86	68	520	75	increase	3

Analysis results of 2007 available only for 3 sub-basin. Several sub-basin of the volcanic aquifer is not covered by analysis of 2007 or 1986 surveys.

Wadi Assir, exceptionally shows the highest increase of TDS values between 1986-2007 (+352mg/l) and between 2007-2009 (286mg/l). In other word the average TDS of volcanic aquifer in Assir sub-basin in 1986 was 450mg/l. This value increased to 801 mg/l by 2007 and to 1087mg/l in 2009. Increasing of salinity is related to irrigation return water.

Sawan, Al Huqqah and Qasabah show increasing trend of TDS of less than 120mg/l. This increase is probably resulted from surface activities.

Hamdan, Hizyaz shows decreasing trend of TDS between 1986 and 2009. This confirms fresh recharge water is taking places in these sub-basins. These sub-basin are located where highest rainfall occurs in the basin.

Akhwar, Shahik and Zahar shows little changes in TDS values between 1986 and 2009. These sub-basin located in the south west and south east where high recharge values are expected.

3.3.4. ALLUVIAL AQUIFER

3.3.4.1. Temporal hydrochemical variation during 2007-2009

10 samples available from survey carried out during 2009 and results of 10 comparable samples drawn from the same water point during 2007 are available. Three levels were identified: decrease in the TDS values, increase in TDS, Almost means the difference is less than 50mg/l.

Six water points show increase in their TDS values between 2007 and 2009 which ranges between 57 mg/l (HSA103) of Bani Huwat and 533 mg/l (HS69) wadi Assir. Increase of TDS indicate deterioration of water quality at these water points which results from increase of discharge or addition of contamination load to the aquifer. Only borehole show reduction in calculated TDS value by 680 mg/l (HSA16) of Bani Huwat between 2007 and 2009. Rest of the samples (3 samples) show slight to no change in their TDS values between the two surveys undertaken during 2007 and 2009

Table (3.14) Temporal hydrochemical variation on Alluvial aquifer during 2007-2009

Well Name	year	Sub-Basin	PH	TDS	Ca	Mg	Na	K	CO3	HCO3	Cl	SO4	cal TDS	Diff erene	**status**
HS101	2007	al Ma'adi	7.6	346	69	19	34	3	16	265	43	30	478		
HS101	2009	al Ma'adi	6.69	397	78	19	41	2	16	288	28	47	518	40	**almost**
HS69	2007	as Sirr	7.7	282	48	8	46	1	16	176	43	32	370		
HS69	2009	as Sirr	7.89	699	115	28	86	7	0	537	106	25	904	533	**increase**
HSA101	2007	B Huwat	8	404	34	12	100	2	16	120	108	72	464		
HSA101	2009	B Huwat	7.6	580	17	17	164	4	5	188	80	188	663	199	**increase**
HSA103	2007	B Huwat	8.1	338	42	14	60	3	8	136	91	52	406		
HSA103	2009	B Huwat	7.33	495	37	23	86	4	10	162	92	50	463	57	**increase**
HSA104	2007	B Huwat	8	377	55	13	60	3	16	184	60	78	470		
HSA104	2009	B Huwat	7.69	434	50	16	70	4	0	239	49	66	493	23	**almost**
HSA16	2007	B Huwat	7.7	1460	297	67	110	4	16	136	498	400	1528		
HSA16	2009	B Huwat	7.59	782	96	26	138	4	0	190	145	250	848	-680	**decrease**
HSA7	2007	B Huwat	8.3	476	23	7	142	2	24	193	86	96	572		
HSA7	2009	B Huwat	7.55	575	21	9	182	3	20	244	83	113	675	102	**increase**
HSA74	2007	al Kharid	7.6	1069	149	81	115	4	24	457	249	220	1298		
HSA74	2009	al Kharid	7.13	1227	141	133	170	5	60	464	283	350	1605	307	**increase**
HSA90	2007	B Huwat	8	398	61	17	60	4	24	160	77	76	478		
HSA90	2009	B Huwat	7.34	467	72	21	52	4	0	229	68	63	507	29	**almost**

HSA95	2007	B Huwat	8.3	563	42	14	152	3	32	233	79	124	679		
HSA95	2009	B Huwat	8.17	725	16	9	250	3	76	298	66	125	843	164	**increase**

3.3.4.2. Temporal hydrochemical variation during 1986, 1995, 2007, and 2009

Table (3.15) Hydrochemical variation of Alluvial at aquifer level

years	**PH**	**TDS**	**Ca**	**Mg**	**Na**	**K**	**CO3**	**HCO3**	**Cl**	**SO4**	**hardness**	**cal TDS**	**difference**	**status**	**number of samples**	**number of sub-basin**
1986	7.8	383	46	24	62	2	2	195	95	55	215	481			38	8
1995	7.4	879	152	28	86	4	0	229	178	172	494	879	398	**increase**	18	4
2007	7.7	568	86	32	73	3	19	266	119	103	347	701	-178	**decrease**	10	4
2009	7.3	726	94	49	108	5	23	378	125	136	437	921	220	**increase**	10	4

According to the available samples for this aquifer from previous studies, there is increasing TDS values between 1986 and 1995. This trend reversed during 1995 and 2007 to decreasing trend and returned to increased trend between 2007 and 2009. There in effect of samples locations to this trend. To check that out, we used shared sub-basin between all studies (i.e. Assir and Bani Huwat). The TDS values were: 523, 724, 513 and 779 mg/l for 1986, 1995, 2007 and 2009, respectively. These trends probably is related to amount of fresh recharge this aquifer receives.

Table (3.16) Temporal variation in Alluvial aquifer at sub-basin level

sub-basin	**Year**	**PH**	**TDS**	**Ca**	**Mg**	**Na**	**K**	**CO3**	**HCO3**	**Cl**	**SO4**	**Hardness**	**cal TDS**	**Difference**	**status**	**No. of samples**
B huwat	1986	8.0	491	77	29	62	3	0	193	150	74	310	587			17
B huwat	1995	7.2	593	59	14	105	4	0	182	111	95	205	593	5	almost	11
B huwat	2007	8.1	574	79	21	98	3	19	166	143	128	283	657	64	increase	7
B huwat	2009	7.6	580	44	17	135	3	16	221	83	122	180	655	-2	almost	7
Assir	1986	7.7	393	37	60	17	1	0	136	124	86	338	460			1
Assir	1995	7.2	856	168	30	59	3	0	198	183	182	541	856	396	increase	4
assir	2007	7.7	282	48	8	46	1	16	176	43	32	154	370	-485	decrease	1
assir	2009	7.9	699	115	28	86	7	0	537	106	25	401	904	533	increase	1

sawan	1986	7.8	287	51	28	13	1	0	184	45	57	244	379			4
sawan	1995	6.9	739	133	25	77	4	0	270	131	99	434	739	359	increase	1
sawan	2007	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm		
sawan	2009	nm	Nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm		
Alkharid	1986	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm		
Alkharid	1995	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm		
Al kharid	2007	7.6	1069	149	81	115	4	24	457	249	220	702	1298			1
Al kharid	2009	7.1	1227	141	133	170	5	60	464	283	350	895	1605	307	increase	1
Al maadi	1986	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm		
Al maadi	1995	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm		
al maadi	2007	7.6	346	69	19	34	3	16	265	43	30	251	478			1
al maadi	2009	6.7	397	78	19	41	2	16	288	28	47	271	518	40	almost	1

Wadi Assir shows highest fluctuation in TDS values during 1986 and 2009. An increase of TDS occurred during 1986 and 1995. This followed by a decreasing trend of TDS values (485mg/l). Then an increasing TDS value by 533mg/l was observed between 2007 and 2009.

During 1986 and 1995, Sawan shows an increasing trend of TDS value in the alluvial aquifer. Similar increase noticed during 2007-2009 in Wadi Al Kharid. While Al maadi show no change in TDS values. Samples from Bani huwat show slight increase only during 1995-2007 by 64mg/l

4. GROUND WATER QUALITY AND POLLUTION

4.1 INTRODUCTION

Understanding the quality of groundwater is important because it is the main factor determining its suitability for drinking, domestic, agricultural and industrial purposes. Water quality is a concept referring to the chemical, biological and physical characteristics of the water. The required water quality is determined by the purpose for which the water is to be used (domestic, urban, agricultural, or industrial). The evaluation of water for use purposes is based on the characteristics of the water compared to a required quality for that use. The required quality is defined by “standards” which mean concentrations of constituents, which causes no negative effect to the health of the consumer over the life of consumption, WHO, (1995). The quality of groundwater of any region is a result of influences from; geology, hydrologic, human activity. Each factor has its mark on the resulting water and these marks were used to assess the various influences on the groundwater quality in Sana’a Basin.

The baseline water quality has to be adequately defined, so the contamination and pollution can be recognized and related to a known condition. For groundwater in Sana’a basin aquifers, water quality baseline was defined using chemistry data from, Taiz (Alderwish, et al., 1998), and Hadramaut (Alderwish, 2008), to recognize and assess contamination. Parameters used for indication of pollution include: Total Dissolved solids, chloride ion concentration and nitrate ion concentration. While the TDS provide general indication of water salinity, the Cl- and NO3- were selected as indicators to biological contamination. The average approximate baseline values for Tawilah Sandstone estimated are 850 mg/l, 80 mg/l and 10 mg/l for TDS, Cl and NO_3, respectively.

4.2 HYDROCHEMICAL CRITERIA FOR DOMESTIC USE

Water used for drinking, cooking, bathing, cleaning for residential, institutional and public building is referred as domestic water. The suitability of its quality as domestic water is judged on the basis of physical, microbiological and chemical characteristics. Portable water is water that can be used safely for domestic purposes. It must have the following characteristics:

- Its turbidity, color, odor and taste must be within acceptable and permissible limits.
- It must be free of pathogens.
- Its content of hazardous chemicals must be within permissible limits.

In the study area the design parameters used for drinking water are the national standards for drinking water of National Water Resources Authority (NWRA). These standards generally apply to two limits, the Highest Desirable Limit (HDL) and the Maximum Permissible Limit (MPL), which relate to the major ions. All compiled samples were assessed for suitability as drinking water. This is mainly because the main use of well is for irrigation, farmers not connected to public mains, commonly use the water for domestic purposes. Summary of the quality classification of suitability for domestic/drinking use for all compiled (93) samples are given in Table 4.1.

Table (4.1) Suitability of water samples for drinking water

Element	HDL (mg/l)	Number of well with less than HDL	MPL (mg/l)	Number of wells within the MPL	Number of wells over MPL
Calcium	**75**	47	**200**	36	10
Magnesium	**30**	62	**150**	30	1
Sodium	**200**	86	**400**	5	2
Potassium	**8**	77	**12**	9	7
Bicarbonate	**150**	8	**500**	77	8
Chloride	**200**	87	**600**	6	0
Sulfate	**200**	64	**400**	16	13
Nitrate	**10**	66	**50**	25	2
Iron	**0.3**	78	**1**	10	5
Total Hardness	**100**	13	**500**	58	22
TDS	**650**	49	**1500**	31	13

Highest number of samples with beyond MPL is for the total hardness, with 22 samples, followed by Sulfate (13 samples) and TDS (13 samples). The highest number of samples within the MPL are 77 samples for HCO_3 ion, followed by total hardness (58 samples) and Ca (36 samples). The highest number of samples fall within the HDL are those of Cl with 87 samples, followed by Na (86 samples) and Iron (78 samples).

Hardness

Several definition of hardness are in common use, however, the more modern meaning has been associated with water type that causing difficulty of lathering with soap or cause scaling in boilers and kettles. Both are result of precipitation of insoluble salt that result from polyvalent cations in water with the salt in the soap or precipitation through degassing of carbon dioxide as water is heated. Therefore heating partially softens the water as the insoluble carbonates reduces the divalent cation concentration (monovalent has soluble carbonates), Lloyd and Heathcote (1985). The part of hardness removable through boiling is known as temporary hardness and the remained is permanent.

Hardness is conventionally expressed as total concentration of Ca and Mg milligrams per liter equivalent $CaCO_3$. Total hardness can be computed from the expression:

Total hardness = 2.5 (Ca) + 4.1 (Mg).

In which the cation are expressed in mg/l.

Water is designated as being soft or very hard if it is hardness is less than 1.2meq/l (60mg/l) and greater than 3.6meq/l (180mg/l), respectively, Hem (1985). As can be seen in Table (4.2), 100% of Sandstone aquifer, 86% of Limestone aquifer samples show very hard water, while only 30%of volcanic aquifers are of very hard water.

Table (4.2) Summarize the results of water hardness in various aquifer

Range of hardness mg/l of CaCO3	Limestone aquifer	Sandstone aquifer	Volcanic aquifer	Quaternary dep.
(0 – 60) Soft water	1	0	3	0
(61 – 120) Moderately hard	2	0	8	3
(121 – 180) Hard water	1	0	10	0
>180 Very hard water	25	24	9	7

4.3. HYDROCHEMICAL CRITERIA FOR IRRIGATION

The suitability of groundwater for irrigation is contingent on the effects of mineral constituents of the water on both the plant and the soil. The concentration of dissolved substances increases in the soil as part of the irrigation water is evaporated. Concentration increase can be limited when salts precipitate and accumulate in the soil. Salts may harm plant growth physically by restricting the uptake of water through modification of osmotic process (Todd, 1980). Common precipitates which occur when fresh water evaporates are Calcite, sepiolite, gypsum, chert (colloidal silica). The salts have been ordered here in their common sequence of precipitation from fresh water. At later stages Na-containing salts can precipitate, like trona ($NaCO_3$). The precipitation of sepiolite is not well documented. The loss of Mg+ might also occur to a clay mineral (chlorite). In many instances an inverse relationship has been found between Si-concentration and Mg , so that precipitation in a silicate (sepiolite or clay mineral) seemed probable. Indeed, Mg seems to be of primary importance for the formation of clay minerals at low temperature (Harder, 1976). The principle applied to evaporating fresh water has been discussed in section 5.2. However A general conclusion about irrigation water quality can be drawn from the evaporation model developed by (Harder et al, 1978). Calcite is often the first mineral to precipitate from irrigation water. When alkalinity is larger than

Ca and Mg, concentrations of these cations will decrease in the return flow- part of irrigation water. The return flow- percentage must be carefully guarded to prevent problems associated with sodification. If the cations Ca + Mg are initially present at higher equivalent concentrations than alkalinity, then these cations increase in concentration upon evaporation, the SAR ratio will not change dramatically. Such water type is favourable for irrigation. It occurs when gypsum has dissolved in water initially, or when acid anions (SO_4 or NO_3) are present and have caused calcite dissolution.

The suitability of irrigation water is usually estimated from calculation of an empirically derived parameter (SAR) Sodium Adsorption Ratio which is defined by

$$SAR = Na * (Ca + Mg)^{-.5}$$

where the concentration of the cations in meq/l.

It indicates the degree to which cation exchange reactions occur in the soil, because as the sodium replaces Ca and Mg on clays and colloids causes the expansion "swelling" of clay particles and leading to reduction in permeability and hardening of the soil. SAR should remain low enough, so that Na occupies a low portion of the exchange complex. The structure and drainage properties of most soil remain good when SAR value remain below 10.

Figure 4.1 shows the quality classification of irrigation water, based on electrical conductivity and SAR value.(Hem ,1985). It shows that most of the sample is suitable for irrigation with respect to sodium hazard except few wells that found at Amran Group. However several water indicate high salinity hazard for the soil.

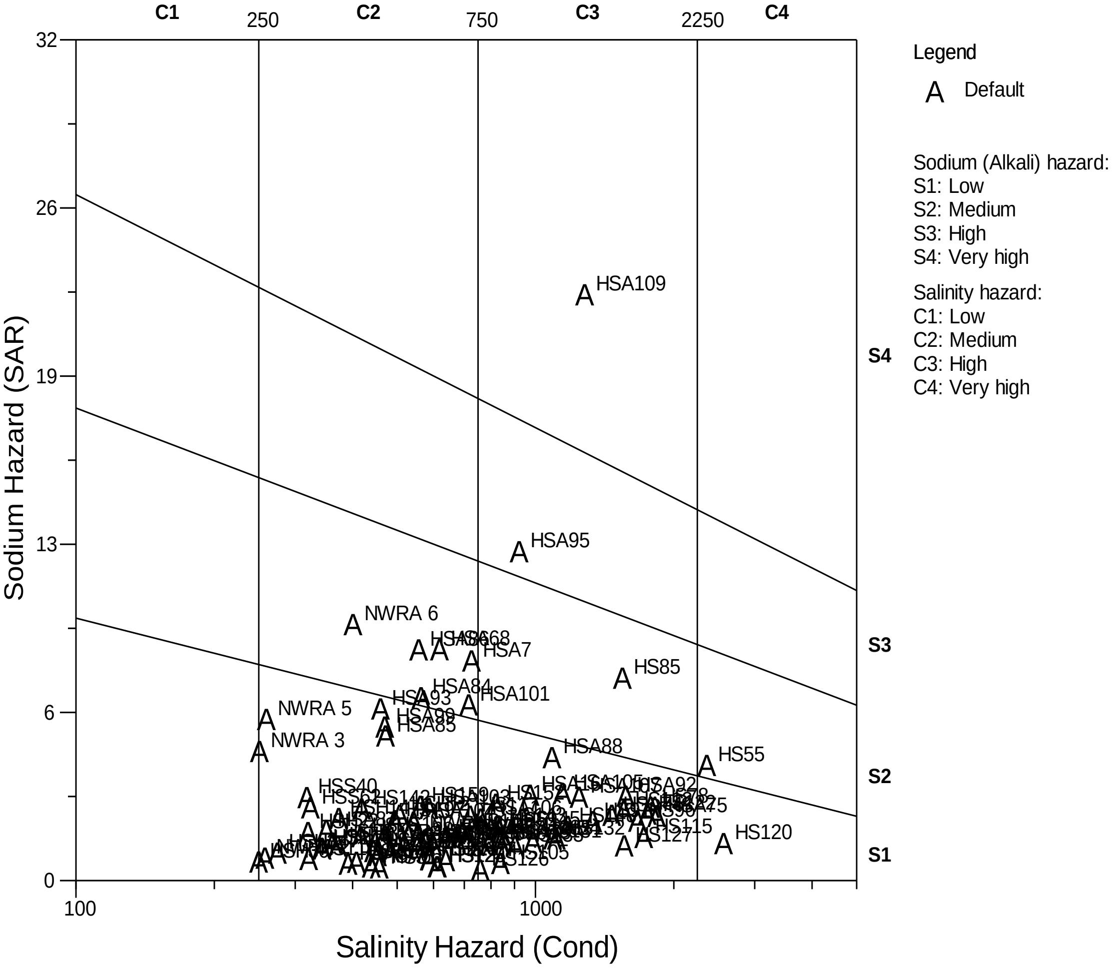


Figure (4.1) Wilcox distribution of samples

4.4. POLLUTION IN VICINITY OF SEWAGE PASSAGE.

4.4.1. Introduction

Sewage passage in Sana'a basin is started from the outlet of Sana'a city wastewater treatment plant at the Northern of Sana'a basin. The passage is running across the basin for about 20 km until reached the main stream of wadi Al-Kharid. Along the passage there are three dams that are Al-Mosyreka dam, Al-Masham dam and Al-Samena dam respectively. The passage runs across very critical geological configuration such as major faults and significant geological variation within volcanic and limestone outcrops. Figure (4.00.) presents a Google-Earth image that shows the passage marked by the black line. The difference of rocks colors on the east and west sides are very clear. Volcanic rocks outcrop is located on the west side while on the east side is located the limestone outcrop. Accordingly, it has been found that it is an important issue to have an intensive study for the ground water quality in the vicinity of the passage.

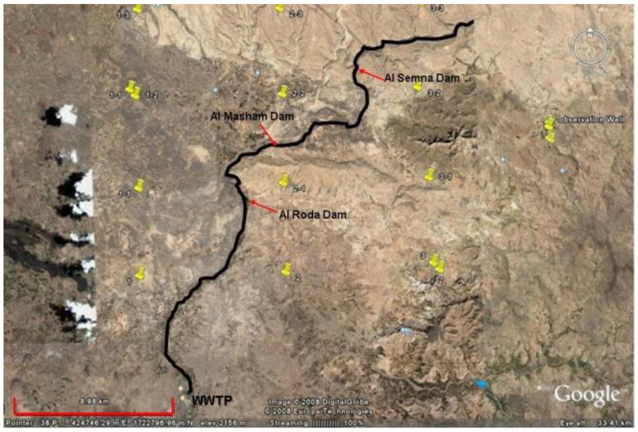


Figure (4.2) Google-Earth image for the wastewater passage showing the infrastructures along the passage (Hydrosult, 2008)

The objectives of this study is to assess the impact on of the passage on the different aquifers; assess the diffusion of the passage's water laterally; perform water quality basic cation and anion for the entire collected samples; perform microbiological analysis for the different collected samples to study the microbiological status for the groundwater aquifer(s) within the vicinity of the passage.

30 water samples were collected from the area under investigation. The samples were drawn from three aquifers: limestone, volcanic, and alluvial. These waters have been processed with the other samples. Two samples have ionic imbalance >5% and were removed from further analyses. The remaining correct samples are 28 samples. Location of these samples are shown in Figure (4.3)

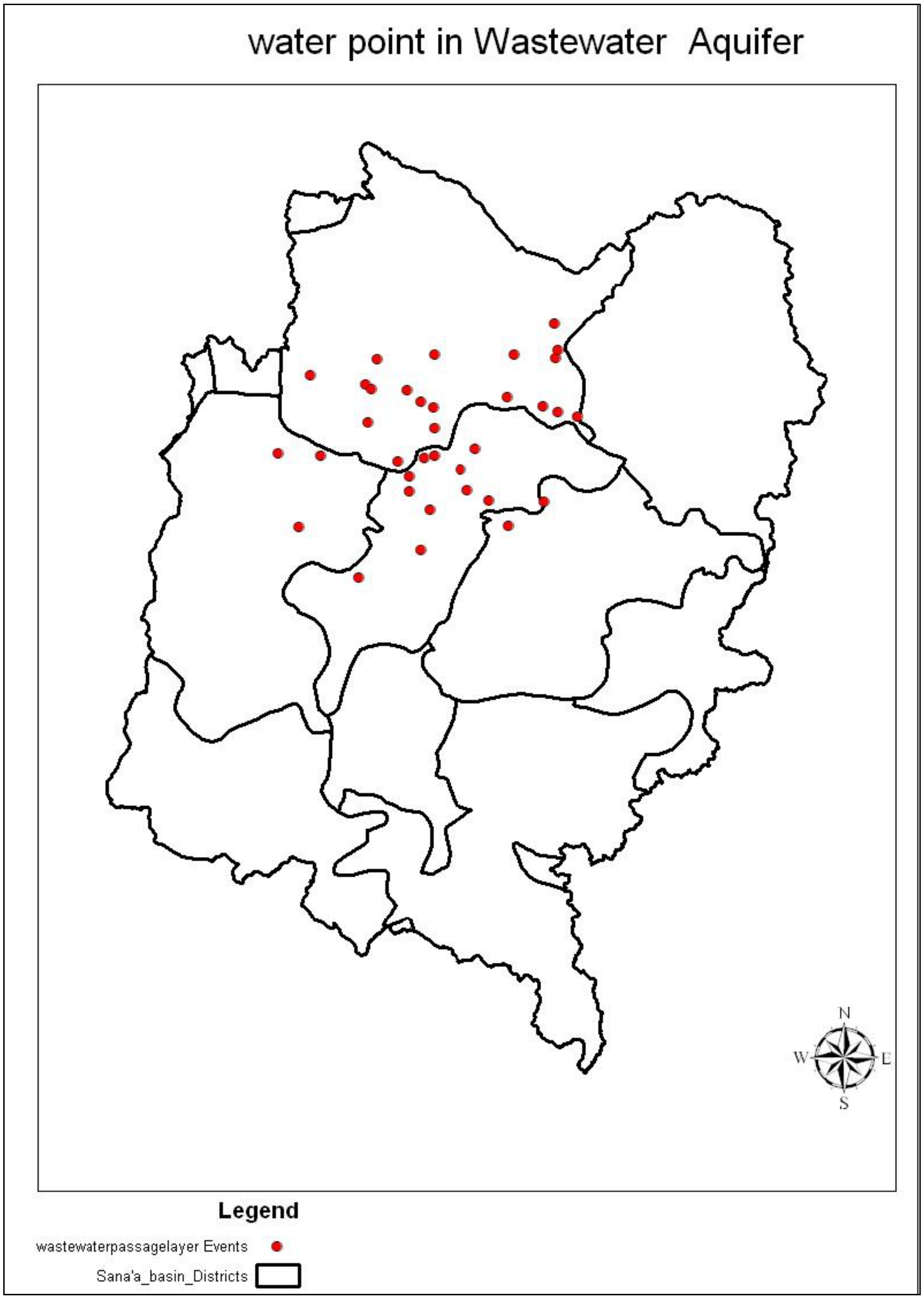


Figure (4.3) Location of water samples for pollution assessment

4.4.2. Results of the Collected Samples Water Quality Analysis

The following Figures (4.4 through 4.13) introduce developed maps for the water quality samples analysis in the vicinity of the treated water passage within the boundary of Sana'a basin.

Total Dissolved Solids

Varies between 324 mg/l and 2850 mg/l. Only six samples have TDS >1000mg/. Only one brackish sample from dug well (HS55) at Bani Huwat show biological contamination. Brackish samples from dug wells in Al kharid show no sign of biological contamination. No trend can be traced to related TDS distribution to the passage of the wastewater.

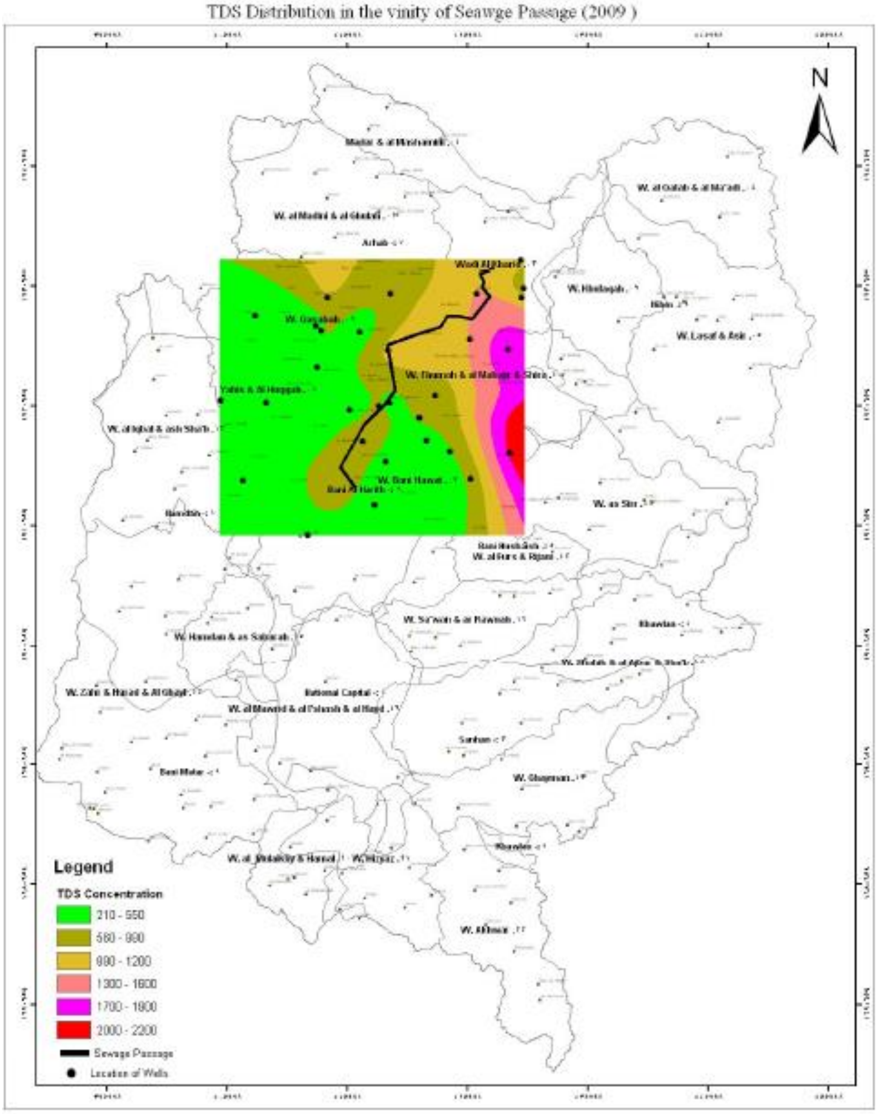


Figure (4.4) Distribution of TDS in the vicinity of sewage passage

Calcium

Varies between 9.8 mg/l at well (HSA99) and 414.1 mg/l at well HS55 with highest TDS and biological contamination. No trend can be traced related to passage of wastewater.

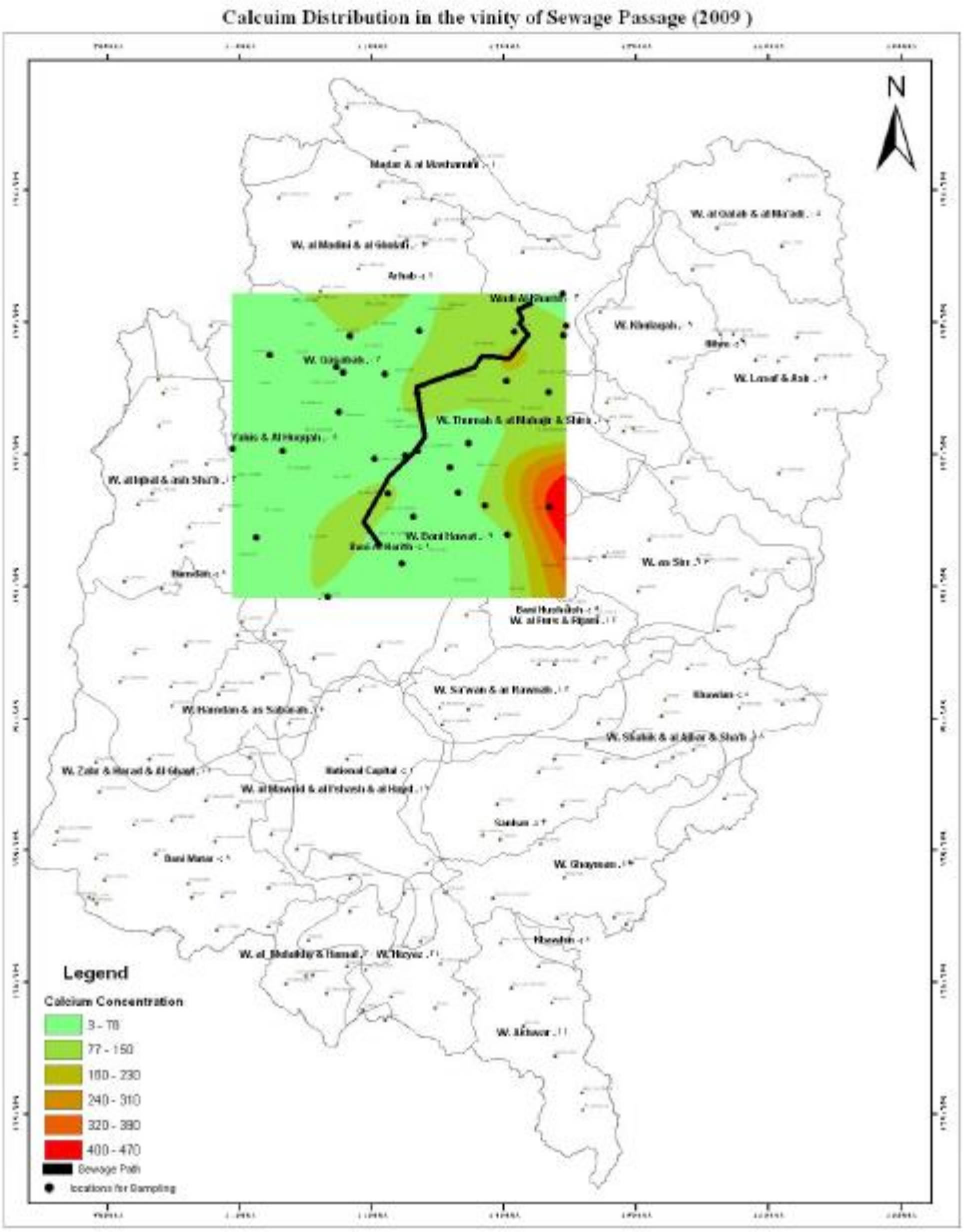


Figure (4.5) Distribution of Ca concentration in the vicinity of sewage passage

Magnesium

Varies between 7.3 mg/l at well (HSA99) and 132.6 mg/l at dug well (HSA74) at Al Kharid. A general an increasing trend of Mg concentration can be followed along the extend of the passage line toward the end of sewage passage line.

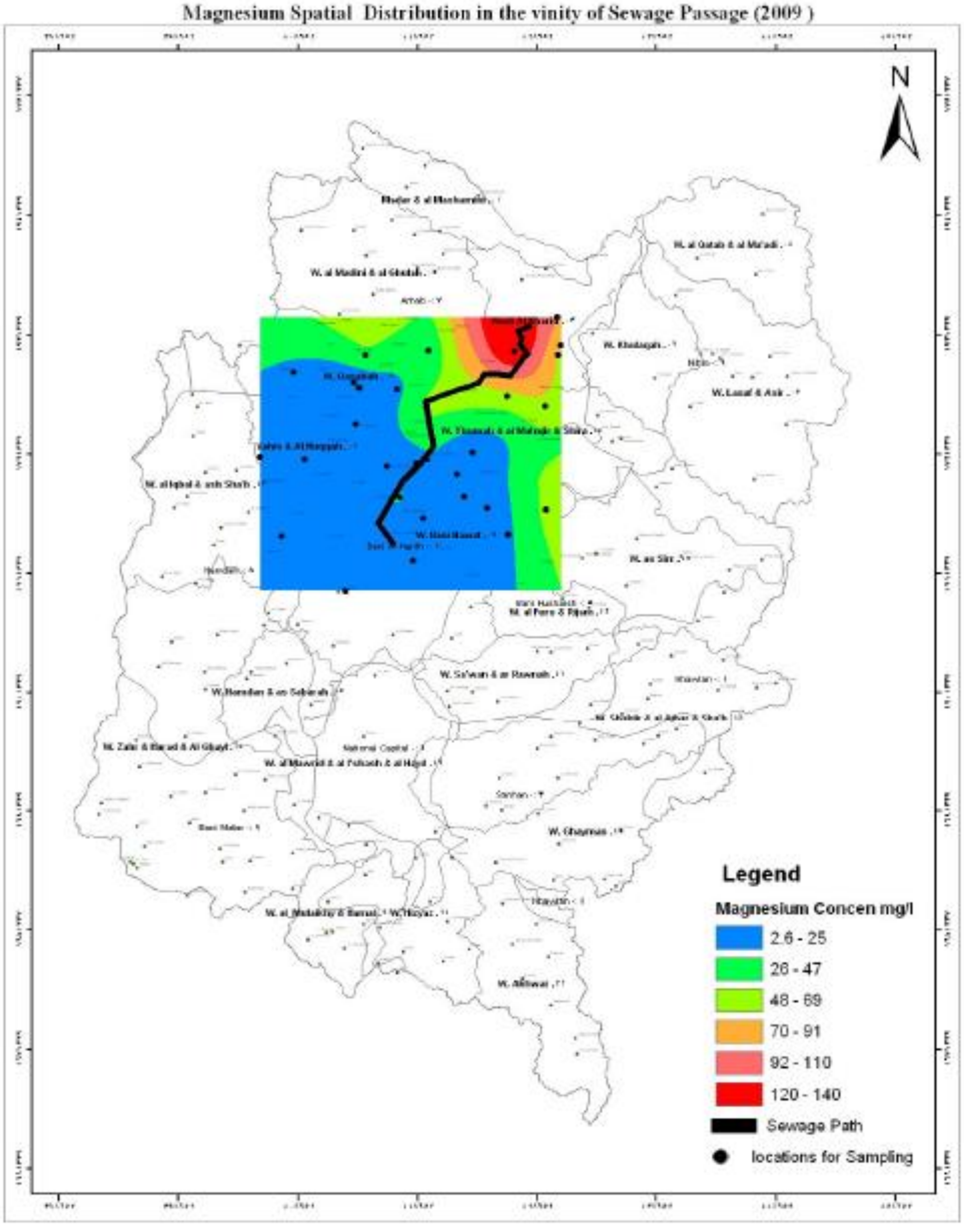
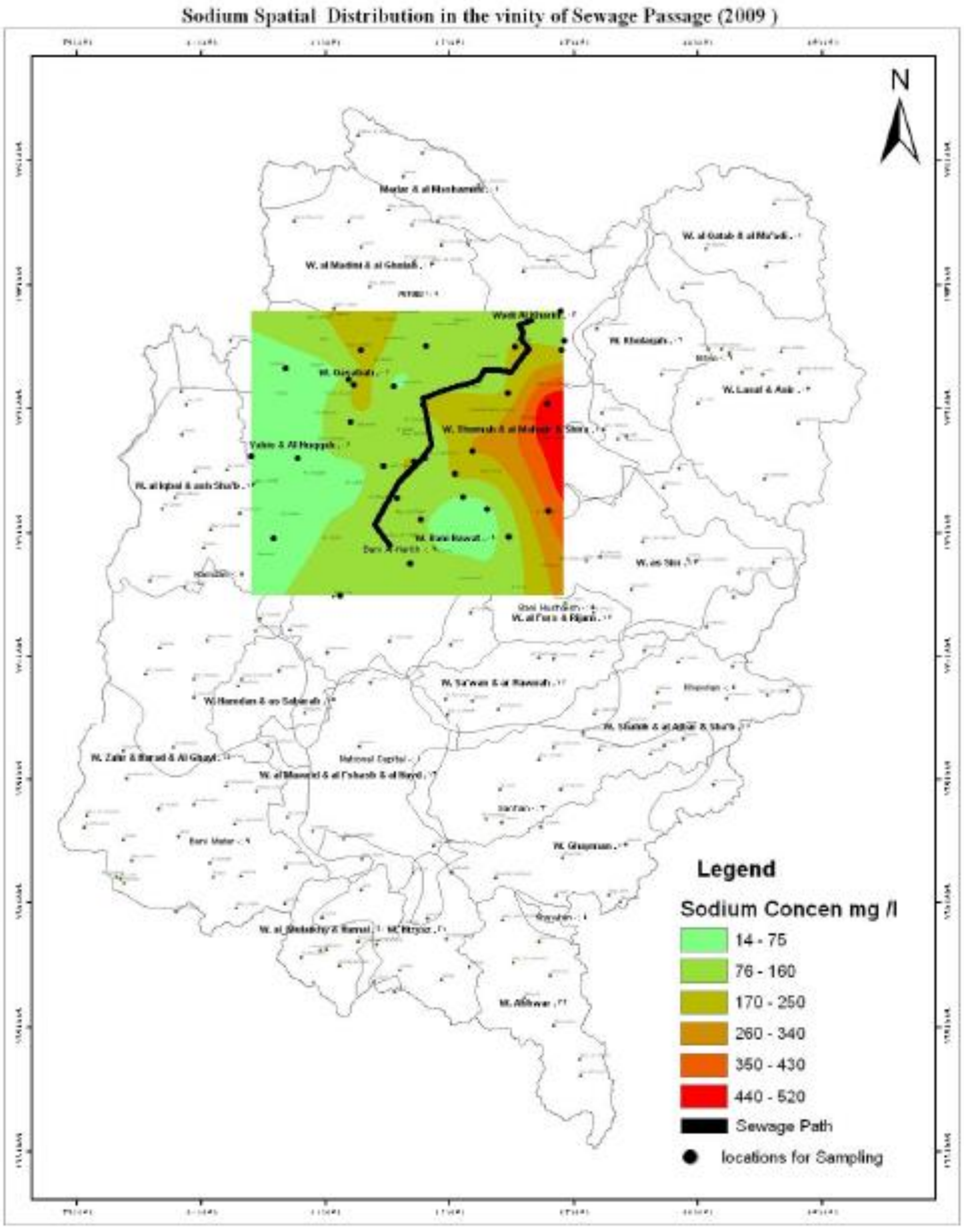


Figure (4.6) Distribution of Mg concentration in the vicinity of sewage passage

Sodium

Concentration varies between 25 mg/l measured at samples from wells (HS104) of Al maadi, and (HS110) of Assir ?? and 423 mg/l (HSA109) at wadi Al Kharid. No trend can be traced to be related to the sewage passage.



Sodium Spatial Distribution in the vinity of Sewage Passage (2009)

Figure (4.7) Distribution of Na concentration in the vicinity of sewage passage

Potassium

Concentration varies between 1.2 mg/l (HS110) and 36mg/l (HS55) with highest TDS 2850 mg/l and biological contamination. Difficult to assume any trend of K concentration relates to sewage passage.

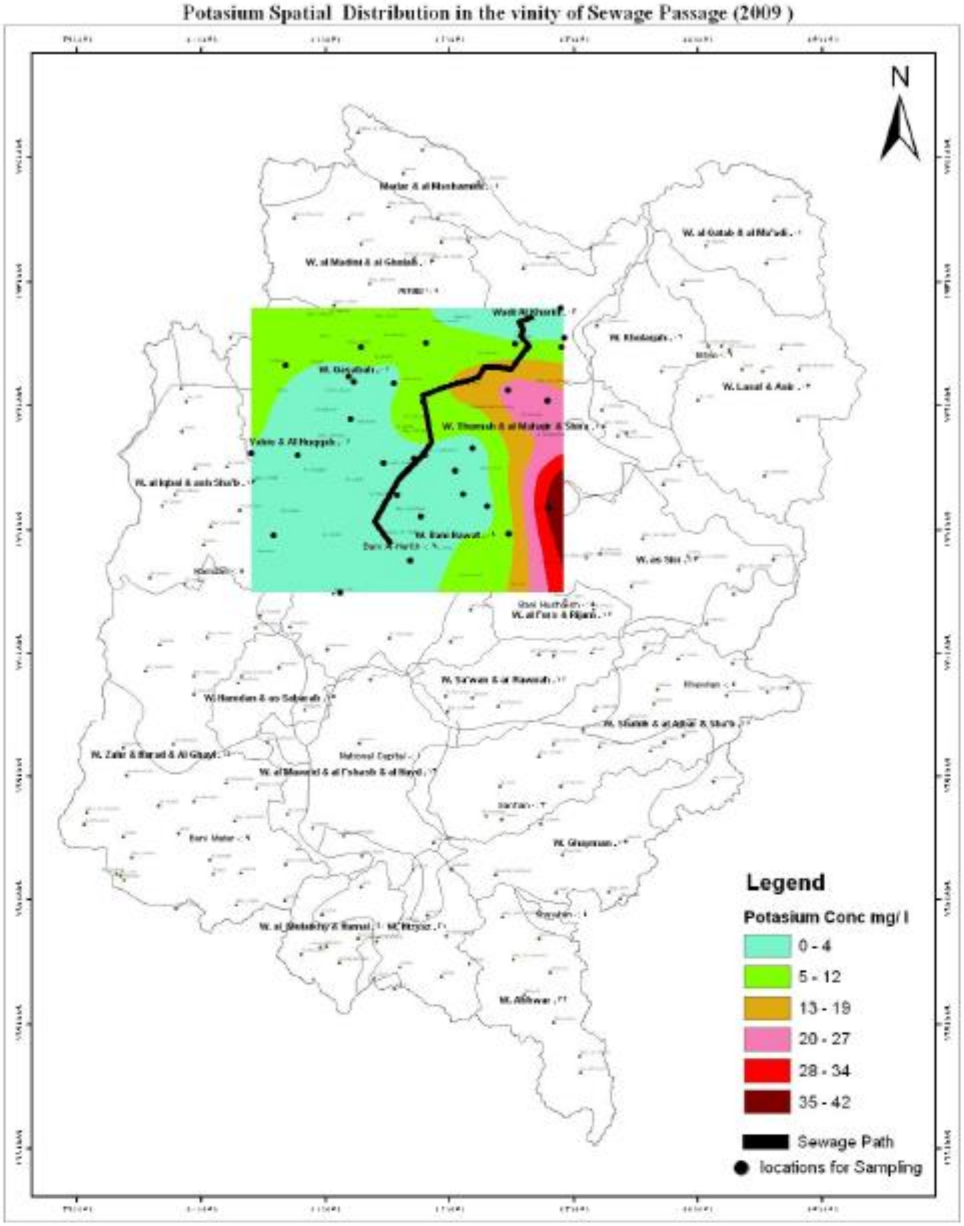


Figure (4.8) Distribution of K concentration in the vicinity of sewage passage

Chloride

Concentration varies between 8.8 mg/l (HS104) and 283 mg/l (HSA74) at Al Kharid. Two trend can be traced. The first is that high concentration of Cl ion observed along the sewage passage line and decrease away from that line. The second trend is an increasing trend as three anomalies exist along the sewage passage line, with highest at the end of the line (in the north).

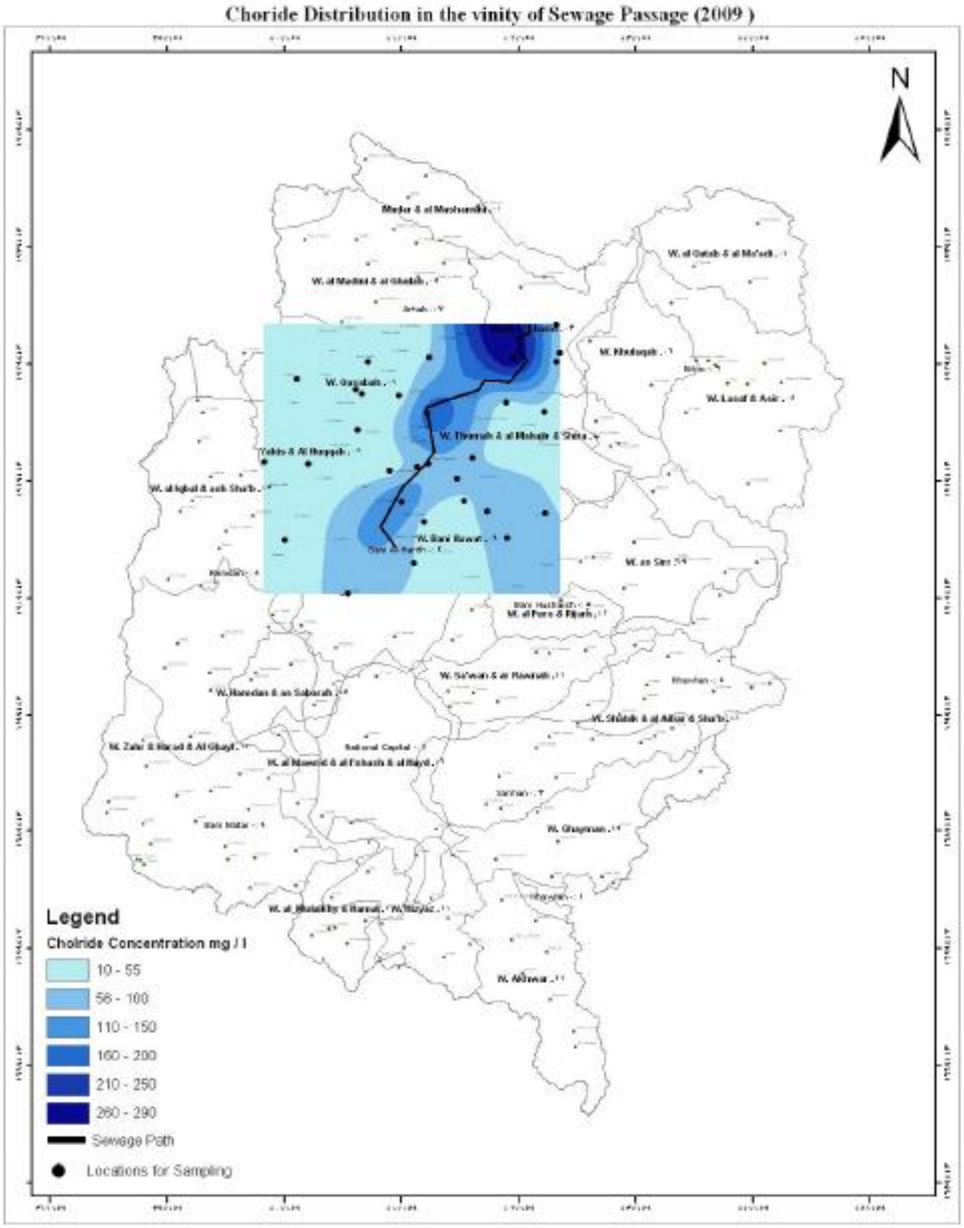

Choride Distribution in the vinity of Sewage Passage (2009)

Figure (4.9) Distribution of Cl concentration in the vicinity of sewage passage

Sulfate

Varies between 12.5mg/l (HSA87) and 1325 mg/l (HS55) with highest TDS of 2850mg/l and biological contamination. No trend can be traced to relate SO_4 concentration with sewage passage.

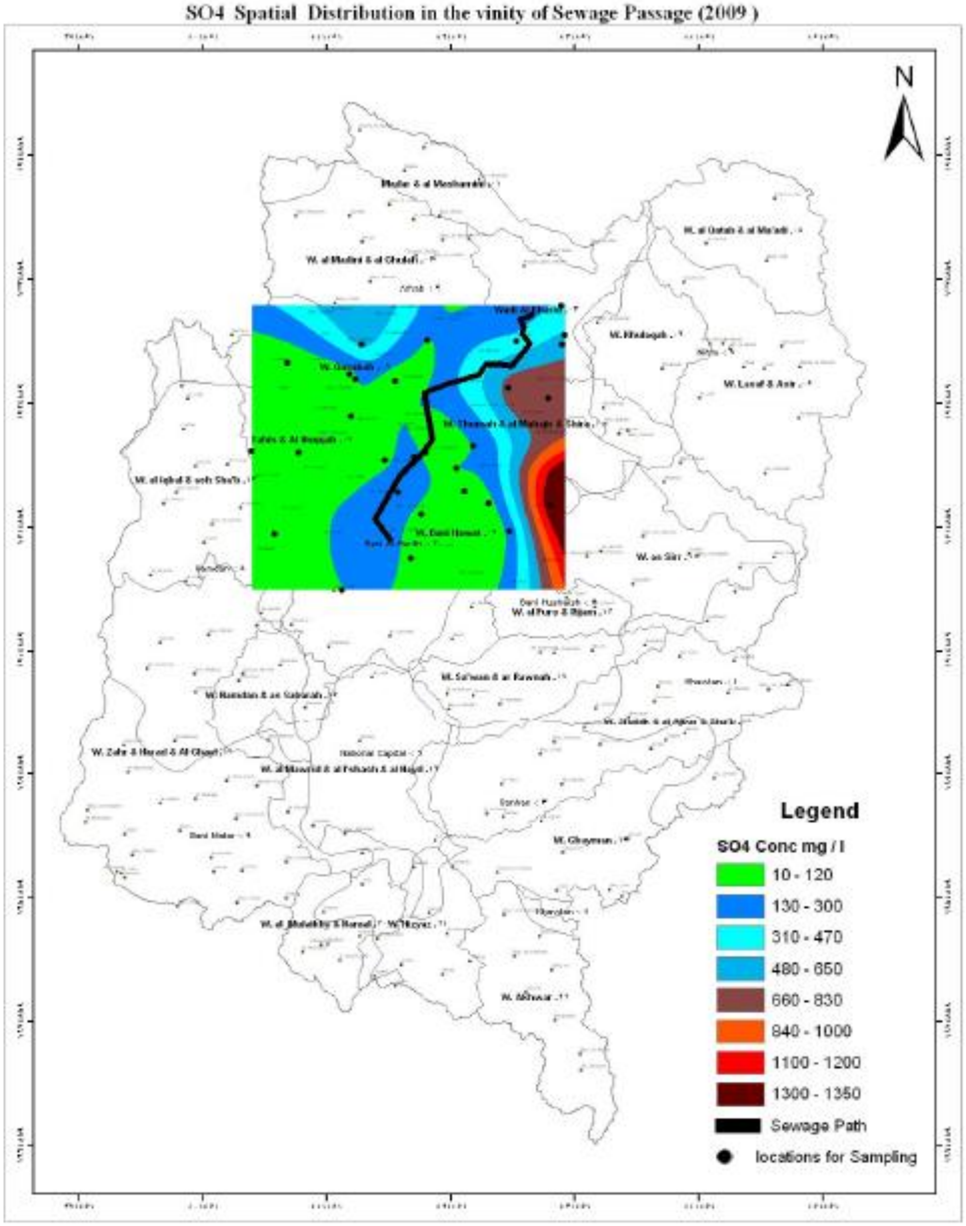


Figure (4.10) Distribution of SO_4 concentration in the vicinity of sewage passage

Bicarbonate

Concentration varies between 161.6 mg/l at wells (HSA103) and (HSA99) and 598.8 mg/l at the highly contaminated well (HS55) at Bani Huwat. No trend can be traced along the sewage passage.

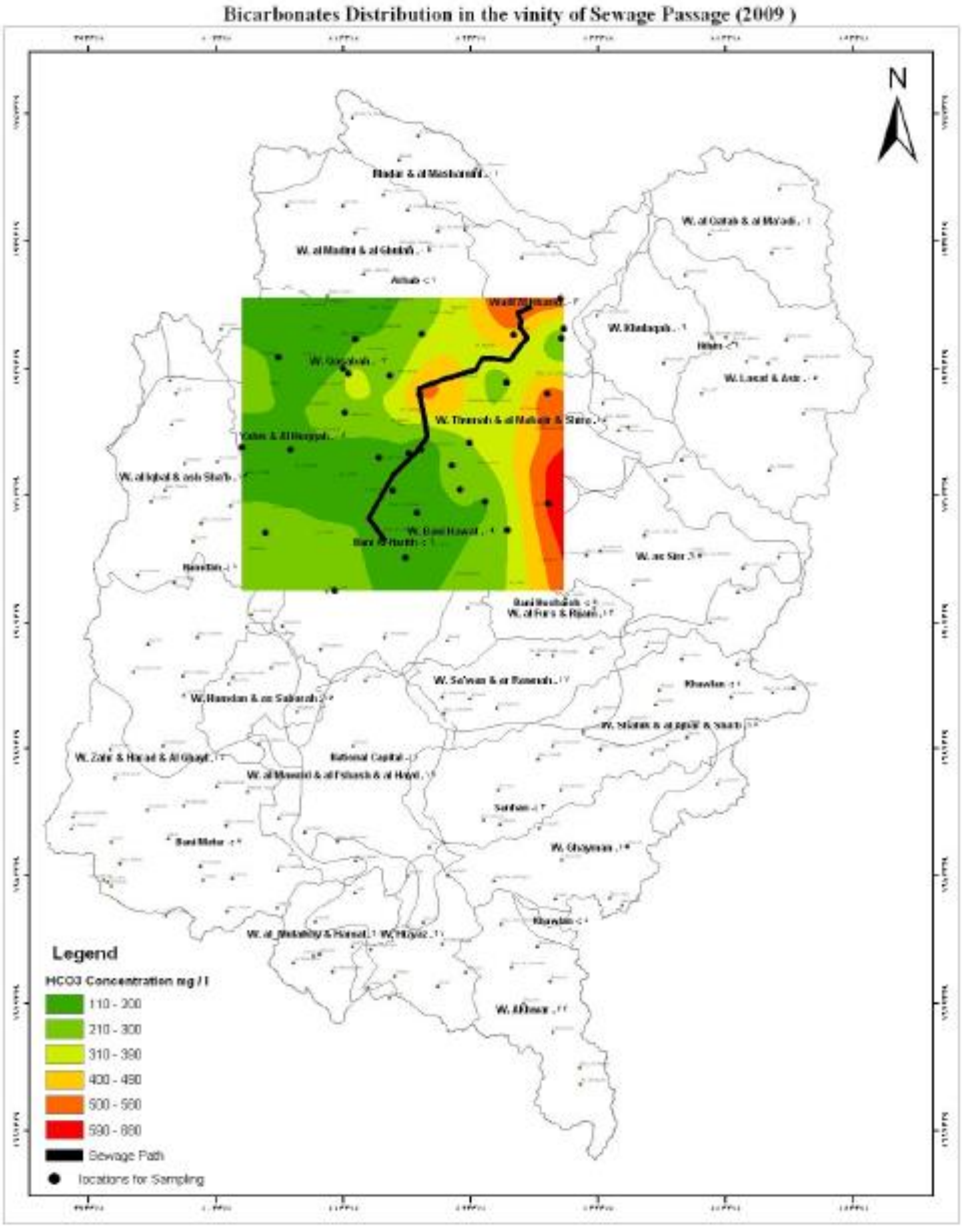


Figure (4.11) Distribution of HCO_3 concentration in the vicinity of sewage passage

Nitrate

Concentration varies between less than 1 mg/l at (HSA86) and 32.2 mg/l at borehole (HSA16) at Bani Huwat. 13 samples with NO_3 >10mg/l with two samples (HSH10) and (HSH11) shows biological contamination. A trend along the first half of sewage passage can be traced where the highest NO_3 observed under the passage and fate away from it.

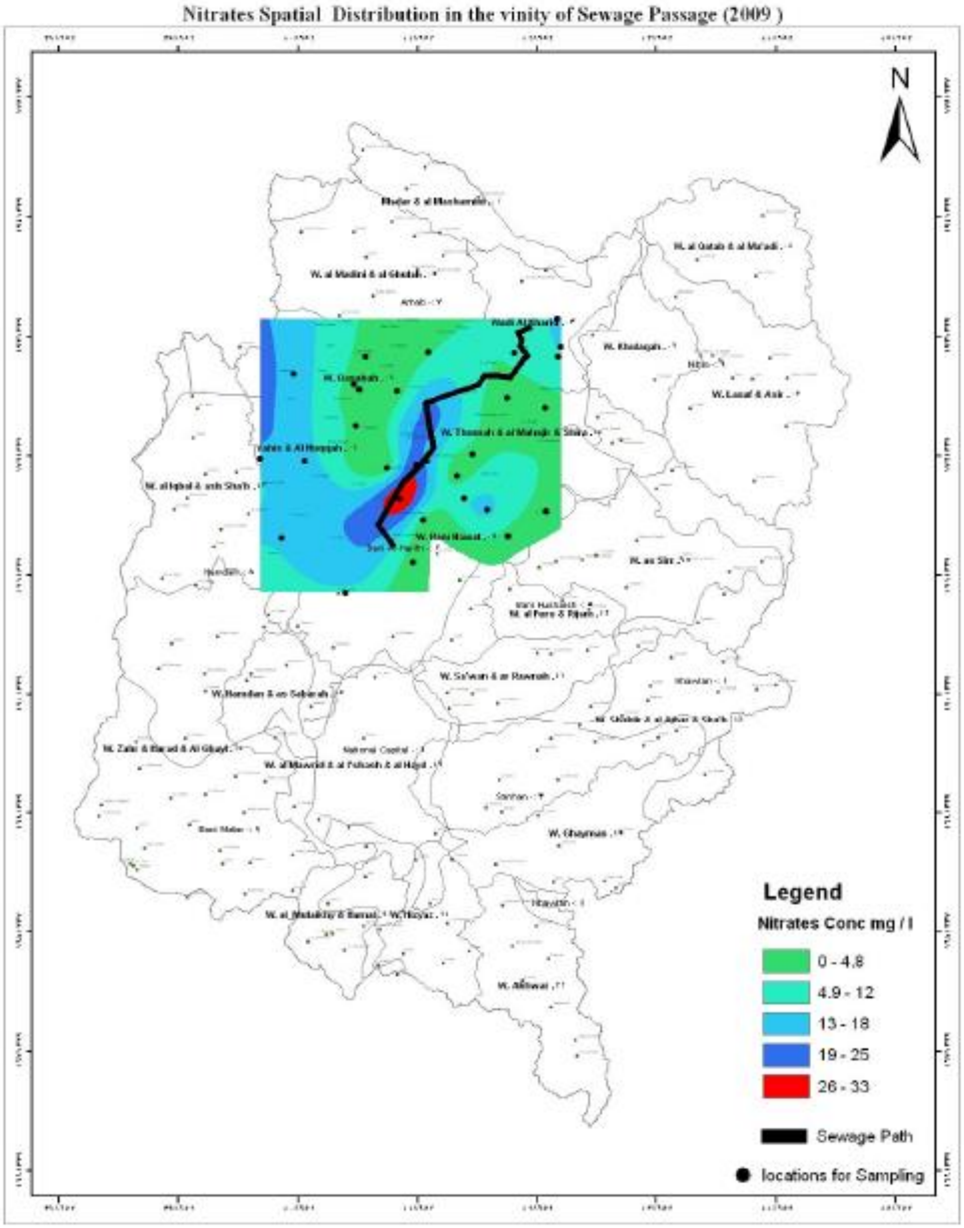


Figure (4.12) Distribution of NO_3 concentration in the vicinity of sewage passage

Iron

Concentration varies between not detected at (HAS 103) and (HSA107) and 0.54 mg/l at deep borehole (HSA84) at Al Huqqah. No trend can be traced to relate iron concentration to sewage passage.

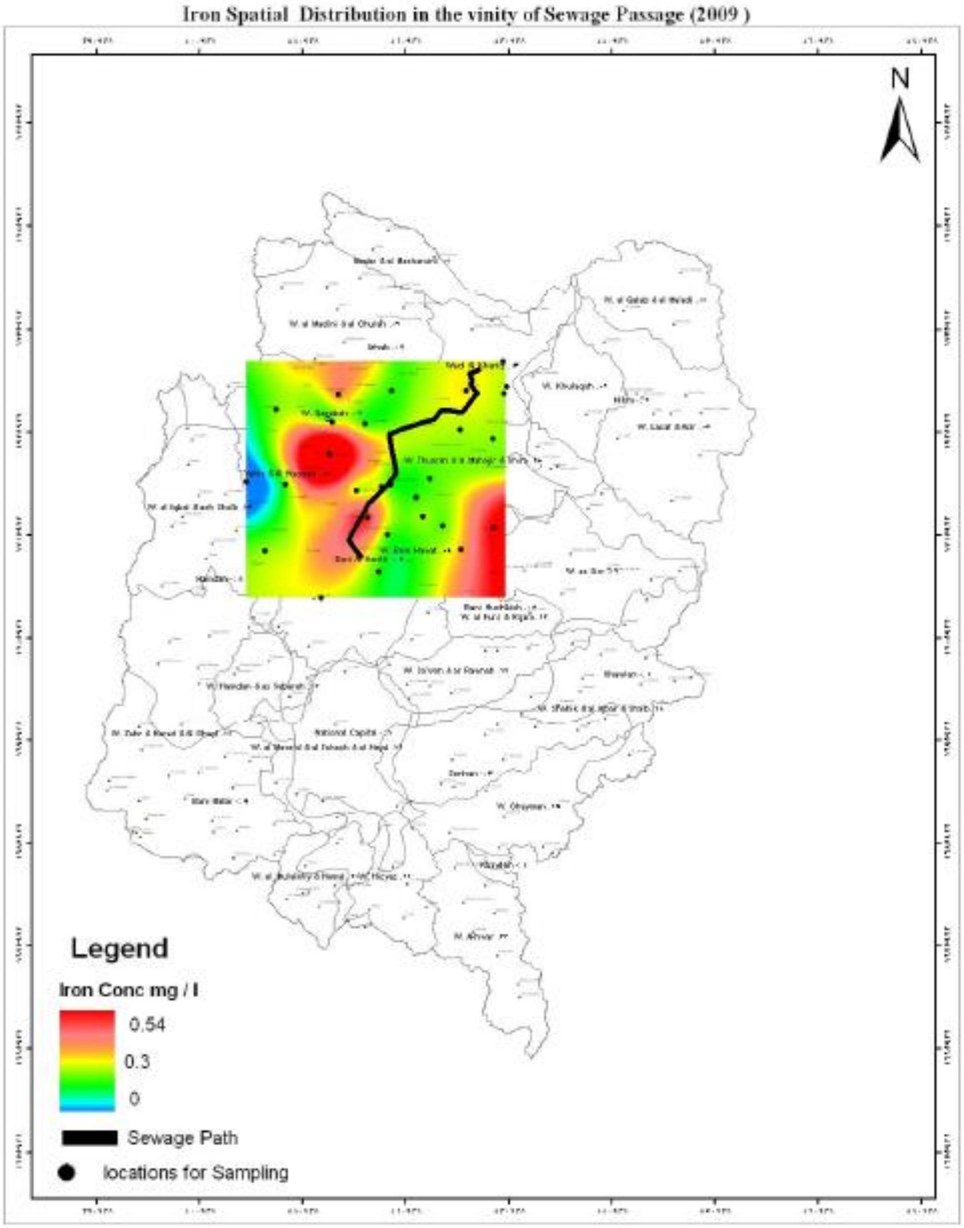


Figure (4.13) Distribution of Fe concentration in the vicinity of sewage passage

4.4.3. Biological and Trace element analysis:

The 28 samples were analyzed for biological contamination through evaluation of Coliform. Fecal No./100mL and Group No./100mL. Only four samples show biological contamination and these are:

Sample ID	Coliform: Fecal No./100mL	Coliform: Group No./100mL
HS55	6	10
HSA90	1	4
HSH10	0	10
HSH11	5	20

It is difficult to relate the biological contamination of these samples to the sewage passage.

The 28 samples also were analyzed for Arsenic and Chromium and Phosphate. Although none samples show sign of Ar and Cd, three samples shows phosphate presence in water samples. These samples are:

HSA107	Wadi al Kharid	0.15
HSA7	Wadi bani Huwat	0.32
HSA74	Wadi al Kharid	0.4

It is difficult to relate the presence of phosphate in these samples to sewage contamination.

In general, similar conclusion to Hydrosult (2007), that the wastewater passage dose not have significant impact on the groundwater at different levels and aquifers within its vicinity. However, from field experience, it is believed that sampling locations for assessing pollution potential due to sewage passage was not successful.

5. AQUIFER VULNERABILITY

5.1. INTRODUCTION

5.1.1. Overview

Contamination of groundwater has become a major concern in recent years. The National Research Council (NRC) in its 1993 report defined groundwater vulnerability to contamination as: "The tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer. The vulnerability of a ground-water resource to contamination depends on intrinsic susceptibility as well as the locations and types of sources of naturally occurring and anthropogenic contamination, relative locations of wells, and the fate and transport of the contaminant(s). Water-resource decision makers are often faced with a choice of deciding whether to manage a resource based on knowledge of intrinsic susceptibility or to target more comprehensive and contaminant-specific assessments of vulnerability.

The associated potential sources of contamination and the intrinsic susceptibility of a ground-water resource are keys to determining the geochemical system, and ultimately, the vulnerability of ground water to contamination. The potential sources of anthropogenic contamination usually exist along the boundary of the ground-water system with contaminants entering the groundwater system with recharge water. Sources of contamination such as poor well construction and underground point sources such as septic and storage tanks also can become significant issues on a local scale. In addition, the source area for a groundwater supply can change over time as stresses on the resource change. The source of contamination is usually classified in space as either a point source or a non-point source. A point source is a contaminant release at one specific location, whereas a non-point source is released over a widespread area. The source of contamination is also classified in time as either a continuous source or an instantaneous (one time) source. A continuous source is contamination that is released over a long period of time, whereas an instantaneous source is contamination that is released at only one time. The type of contamination source in space and time (that is, point source, non-point source, continuous source, instantaneous source is important in determining the resulting spatial and temporal distribution of concentrations within a ground-water system.

Groundwater vulnerability maps have become a standard tool for protecting groundwater resources from pollution. They are especially valuable in the decision making process related to land use planning. Land use planners have mostly little experience and expertise at hand to decide which land uses and activities are to be allowed in certain areas without causing a negative impact on the quality of groundwater resources.

Groundwater vulnerability maps are widely used since about 30 years. There are a number of methods used worldwide (VRBA & SAPOROZEC 1994, MARGANE et al. 1997). However, there is until now no generally accepted standard mapping method. This is mainly due to the fact that the hydrogeological conditions and the availability of data are highly different from one area to another. There are methods which require the knowledge of the spatial distribution of up to ten parameters and thus a very detailed data availability. On the other hand there are also methods which require the input of only two or three parameters. Such methods may preferring be applied in areas where data availability is low. Many of these methods are, however, rather simple and fail to yield appropriate results. In all methods the vulnerability of an aquifer is classified according to the travel time of a drop of water from the land surface to the aquifer (percolation time). This flow is very different in porous rocks compared to hard rocks where flow preferentially follows fractures and cavities. In this respect karst aquifers play an important role since infiltration may be highly concentrated in certain areas and travel time from the land surface to the aquifer may be extremely short.

The term "vulnerability of groundwater to contamination" was first used by MARGAT (1968). The term "groundwater vulnerability" is used in the opposite sense to the term natural

protection against contamination". Although many efforts have been made to reach a common understanding of the term ground-water vulnerability, different authors still use it in differing senses. FOSTER & HIRATA (1988) defined *"Aquifer Pollution Vulnerability": as the "intrinsic characteristics which determine the sensitivity of various parts of an aquifer to being adversely affected by an imposed contaminant load"*. They describe "Ground Water Pollution Risk" as 'the interaction between the natural vulnerability of an aquifer, and the pollution loading that is, or will be, applied on the subsurface environment as a result of human activity'. The US EPA (1993) distinguishes between 'Aquifer Sensitivity' and 'Ground Water Vulnerability'. Although these definitions are more closely related to agricultural activities, they should hold true for all other activities as well. US EPA defines 'Aquifer Sensitivity' as the relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest. Aquifer sensitivity is a function of the intrinsic characteristics of the geologic materials of interest, any overlying saturated materials, and the overlying unsaturated zone. Sensitivity is not dependent on agronomic practices or pesticide characteristics'. According to US EPA 'Ground Water Vulnerability' is *'the relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest under a given set of agronomic management practices, pesticide characteristics and hydrogeologic sensitivity conditions'.*

VOWINKEL et al. (1996) defined vulnerability as sensitivity plus intensity, where 'intensity' is a measure of the source of contamination. In this sense, groundwater vulnerability is a function not only of the properties of the groundwater flow system (intrinsic susceptibility) but also of the proximity of contaminant sources, characteristics of the contaminant, and other factors that could potentially increase loads of specified contaminants to the aquifer and/or their eventual delivery to a groundwater resource.

Workgroup on "Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers regards the (present) land surface as the standard point of reference for a possible release of contaminants (source). It is distinguished between two different targets for protection as shown in Figure (5.1): the resource (aquifer) and the source (well or spring used for water supply).

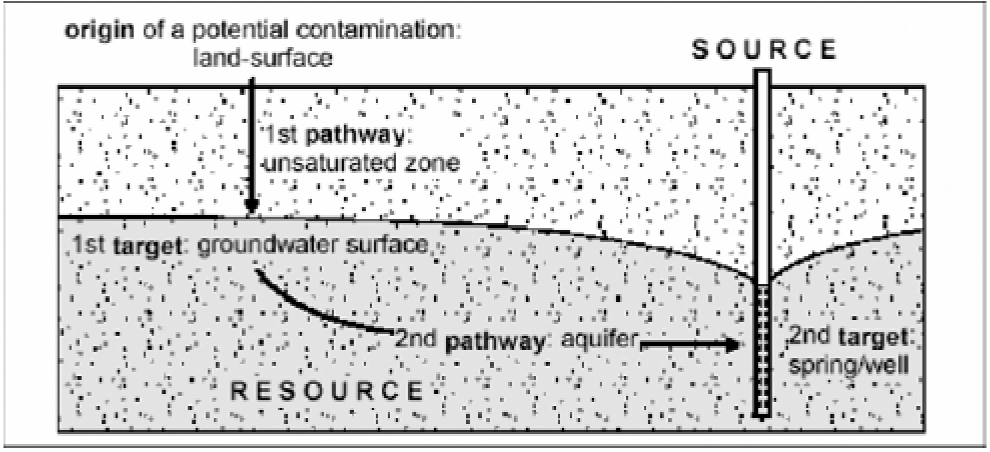


Figure (5.1) Source-Pathway-Target Model of Groundwater Vulnerability (Goldscheider 2002).

5.1.2. Objective and Uses

Vulnerability maps are used as a decision tool in the land use planning process. High vulnerability: areas with a high pollution risk. (Which measures need to be implemented to protect the resources against pollution?). Low vulnerability: areas with a low pollution risk (Where could sites and activities which are possibly hazardous to groundwater be located, such as waste disposal sites, wastewater treatment plants, industrial estates, etc.?).

The uses of vulnerability mapping are in:
- Land use planning (planning authorities):
  - Selection of areas or activities hazardous to groundwater
  - Protection of very productive aquifers (conservation)

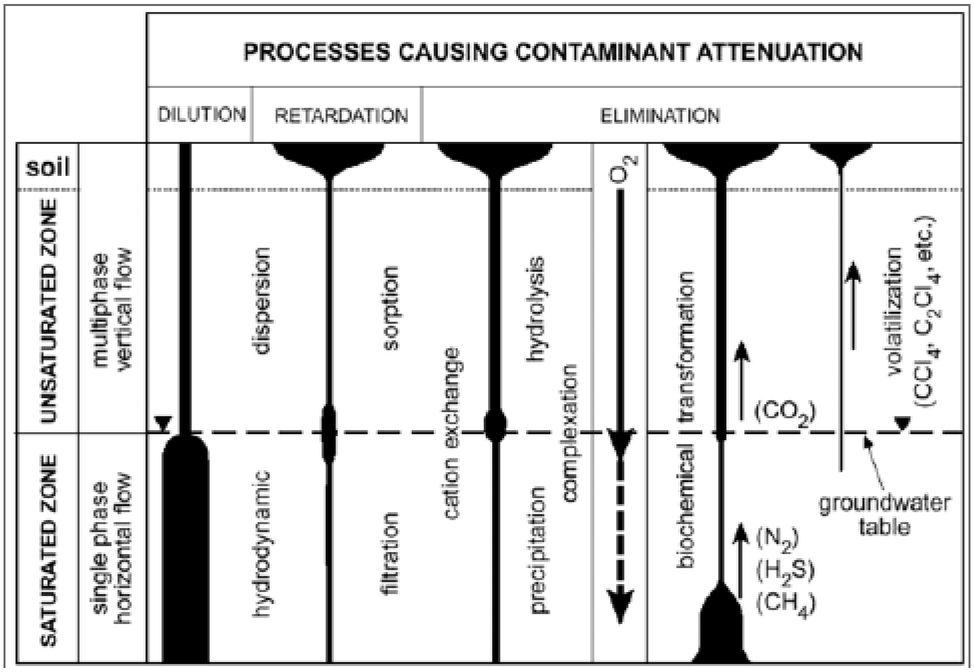
- Water Resources Management (Water Authorities):
  - Groundwater protection zone delineation and definition o land use restrictions
  - Protection of resources which may be important in the future
  - Design of groundwater monitoring networks
  - Detection of pollution sources and pathways.

5.1.3. Parameters determining Groundwater Vulnerability:

FOSTER & HIRATA (1988), MORRIS & FOSTER (2000) and VRBA & ZAPOROZEC (1994) list possible processes and mechanisms leading to an attenuation of the contaminant load in different media, through which water and contaminants pass on their way to the water table (soil, unsaturated and saturated zone). Factors determine the protective effectiveness or filtering effect of the rock and soil cover include: mineralogical rock composition, rock compactness, degree of jointing and fracturing, porosity, content of organic matter, carbonate content, clay content, metal oxides content, pH, redox potential, cation exchange capacity (CEC), thickness of rock and soil cover, and percolation rate and velocity.

Specific chemical characteristics have to be taken into account when considering the behavior of pollutants below the ground and the time they take to migrate through the soil, in both the unsaturated and the saturated zone. Such characteristics include:

- natural parameters influencing the solubility and chemical reactivity (temperature, pressure, etc.),
- dispersion/diffusion,
- chemical complexation, sorption and precipitation
- degradation (chemical/biological/radiological transformation, hydrolysis, etc.)



(Line width indicates relative importance of process in corresponding zone)

Figure (5.2) Processes leading to contaminant attenuation, (Morris & Foster 2000)

5.1.4. Methods for Vulnerability Assessment

In Hydrosult (2008) conducted the only previous study carried out vulnerability mapping stud over Sana'a basin. In their study the COP method has been selected for developing the vulnerability maps for Sana'a Basin though which useful information can be obtained for designing a complete water quality monitoring network. This method was introduced by the Group of Hydrogeology in the University of Malaga/Spain (VIAS et al., 2002). It uses the parameters: C=Concentration of flow, O=Overlying layers, and P= Precipitation. As stated in the report of Hydrosult (2008), **'As outlined by DALY et al. (2002) the COP-Method may become the European approach for groundwater vulnerability mapping in karst areas, provided its application proves to be successful in the coming few years'.** This statement according to the model developer, indicate that method does not suit Sana'a Basin as it is neither contain Karst aquifers nor its conditions similar to Europe. In fact as metioned in Hydrosult report: `**The C factor represents the degree of concentration of the flow of water towards Karstic conduits that are directly connected with the saturated zone and thus indicate how the protection capacity is reduced.'** Where is the Karstic conduits in the Sana'a basin. Moreover, they stated **'so far there is too little experience with applications of this method to be able to judge about the suitability and applicability of the method**'. So it is wondering why they used it in the Sana'a Basin?.

VRBA & ZAPOROZEC (1994), COST 65 (1995), MARGANE et al. (1997), MAGIERA (2000), GOGU & DASSARGUES (2000b), FOCAZIO et al. (2002) and GOLDSCHEIDER (2002) give a good overview about mapping methods for groundwater vulnerability. The following approaches can be distinguished:

Hydrogeological Complex and Setting Methods (HCS)
- This group of methods assesses groundwater vulnerability by setting up classes of two or more levels of vulnerability.
- The classes are based on criteria found to be representative of groundwater vulnerability under certain hydrogeological conditions.
- This type of mapping is mainly used for small to medium scale maps and uses basic information often being available from geological, hydrogeological and topographic maps.
- The groundwater vulnerability map of France (ALBINET & MARGAT 1970; scale 1:1 Mio) and the map of Germany (VIERHUFF et al. 1981; scale 1:1 Mio) are examples for this type of method.

Parametric System Methods can be divided into: Matrix Systems, Rating Systems and Point Count System Models.

(1) Matrix Systems assess groundwater vulnerability based on a selection of two or more parameters considered to be representative for a certain area. The selected parameters,

like depth to aquifer, soil leaching, groundwater recharge, or others are then grouped into classes (VRBA & ZAPOROZEC, 1994)

(2) Rating Systems use many parameters and attribute fixed ranges of ratings to them according to their variation in the area. The total rating is calculated by overlaying the ratings for the different parameters and then dividing the total rating into different levels of vulnerability. The following methods can be attributed to this method:

- GOD (FOSTER, 1987), The system developed by MARCOLONGO & PRETTO (1987) for mapping of the Po Valley in Italy,
- PRZM (Pesticide Root Zone Model), used e.g. by the Hawaii Department of Health (EPA 1993),
- SAFE (Automated and Safe Vulnerability Assessment), used by the Idaho Department of Health and Welfare,
- The system developed by the State Geological Surveys of Germany (GLAMethod; HOELTING, et al., 1995; and its modification (PI-Method).

(3) Point Count System Models. Use the same approach as rating methods but attribute different weights in the form of a multiplier to reflect the importance of each parameter for the overall assessment of groundwater vulnerability. This method includes:

- DRASTIC, developed by the US EPA (ALLER et al., 1985; see Chapter 4.1.1) and
- SINTACS, developed by CIVITA (CIVITA & MAIO, 1997a; CIVITA & MAIO, 1997b; CIVITA et al. 1999: SINTACS Application in Morocco)

Index Methods and Analogical Relations. The index methods (IM) and analogical relations (AR) are based on mathematical standard descriptions of hydrological and hydrogeological processes (e.g. transport equations) that are analogously used to assess the groundwater vulnerability. MAGIERA (2000) describes 13 methods of that type. Most of them are used for the evaluation of the specific vulnerability of groundwater to pesticides a large to medium scale. The IM/AR methods take into account the properties of the overlying layers and the properties of the contaminant.

5.2. METHODOLOGY

In hydrogeology there are many different definitions for groundwater vulnerability in the literature, but all of them agree in the sense that vulnerability is a relative, dimensionless property that is not directly measurable. The fundamental concept of vulnerability is that some land areas are more vulnerable to groundwater contamination than others. Results of vulnerability assessment are commonly portrayed on a map showing various homogeneous areas which have different levels of vulnerability (Piscopo, 2001).

The present study applies the US EPA Approach (DRASTIC) which has been selected for the following main advantages:

- the method is a popular approach to groundwater vulnerability assessments because it is relatively inexpensive,
- straightforward,
- uses data that are commonly available or estimated, and
- produce an end product that is easily interpreted and incorporated into the decision-making process.

The general shortcoming of this method which pointed out by Foster (1998), such as that it underestimates the vulnerability of fractured aquifers. Presently, fractures are considered in the evaluation.

The DRASTIC methodology was developed by the US Environmental Protection Agency. The DRASTIC model for assessing groundwater vulnerability/sensitivity requires seven criteria: **D**epth to water table, **R**echarge rates, **A**quifer permeability, **S**oil type, **T**opography, **I**mpact of the Vadose Zone, and **C**onductivity of the Vadose Zone (Aller, et al., 1985). DRASTIC evaluates pollution potential based on weighted combination of these hydrogeologic settings. Each factor is assigned a weight based on its relative significance in affecting the pollution potential. Each factor is further assigned a rating for different ranges of the values. The typical ratings ranges are from 1-10 and the weights are from 1-5. The DRASTIC Index, a measure of the pollution potential, is computed by summation of the products of rating and weights for each factor. Applying the following formula (mathematical representation):

DRASTIC Index = D r D w + R r R w + A r A w + S r S w + T r T w + I r I w + C r C w

where:
Dr = Ratings to the depth to water table
Dw = Weights assigned to the depth to water table.
Rr = Ratings for ranges of aquifer recharge
Rw = Weights for the aquifer recharge
Ar = Ratings assigned to aquifer media
Aw = Weights assigned to aquifer media
Sr = Ratings for the soil media

Sw = Weights for soil media
Tr = Ratings for topography (slope)
Tw = Weights assigned to topography
Ir = Ratings assigned to vadose zone
Iw = Weights assigned to vadose zone
Cr = Ratings for rates of hydraulic conductivity
Cw = Weights given to hydraulic conductivity

The ratings are determined from tables and graphs presented in the DRASTIC manual (given in Annex). They are assigned values between 1 and 10. The weight has a fixed value which is listed in Table (5.1).

Table (5.1) Assigned Weights for DRASTIC parameters

Parameter	**DRASTIC**
Depth to water table	5
Net recharge	4
Aquifer media	3
Soil media	2
Topography	1
Impact of the Vadose Zone	5
Hydraulic conductivity	3

The computed DRASTIC Index (via GIS) identified areas which are likely to be susceptible to groundwater contamination relative to each other.

5.3. DEVELOPMENT OF VULNERABILITY MAP FOR SANA’A BASIN

Applying the DRASTIC method, vulnerability maps for four aquifers within Sana’a Basin Alluvial, Volcanic, Sandstone and Limestone aquifers have been developed. In the following section brief description for the successive steps that were applied to develop the vulnerability map for Sana’a basin is introduced. The actual assigned ratings for this project are listed within the text. Data shall be discussed according to its specific part in the model.

The basic data used for assessing vulnerability was the coordination of the well inventory carried out during 2001 (WEC, 2002). Using these information proofed to provide better meaningful interpretation of vulnerability mapping of aquifers in the Sana’a basin than using grid cells coordination. The location coordinate of inventoried wells delineates the accessible areas where surface activities by man take place. Inaccessible areas (mountainous summits, steep slopes etc.), would not be considered while assessing areal distribution of vulnerability over aquifer. More important, several parameters of DRASTIC model will be based on wells information analysis.

The processes included in the vulnerability mapping development for the four aquifers within the Sana’a basin can be grouped under three main stages, include:

1. Data preparation stage.

Data for the multiple regional aquifers was acquired in UTM projection for Sana'a basin from the well inventory carried out during 2001 (WEC, 2002). This is undertaken in spreadsheet (excel) form where only necessary data required for coming stages of assessment were left.

Additional information spaces (columns) were added to the worksheet that would be required for assessing DRASTIC parameters. These include for each specific point the following:

- Sub-basin location
- Recharge
- Slope

2. Vulnerability assessment calculations

DRASTIC, seven parameters were calculated using: Parameter $_{\text{rating}}$ * Parameter $_{\text{weight.}}$ The Vulnerability index for each point is then sum up the seven parameters.

Based and detailed calculation is given in Annex.

3. GIS mapping

The steps undertaken in GIS mapping include:

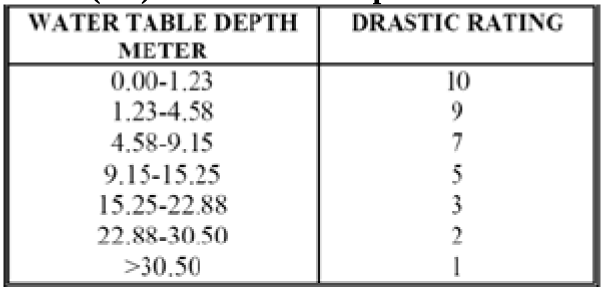
1. In arc Catalog, definition of geological and topographic maps as wgs, 1984 UTM zone 38 N.pro.
2. development of the following shapefiles:
   Polygon: in which aquifers and basin boundaries were drawn.
   Line: in which sub-basin have been delineated and identified as done in maps.
3. In arc map, from option add data, appearance of maps to layers
4. from Georeferencing, add control point, the coordinates (X,Y) were entered at each corner of the map and from the same option, rectify was selected to re-build the map according to the new coordinates
5. add data, retrieved shapefile, of polygon type, called catchment area and of line called drainage line from editor, ----Start edit – delineate catchment area and drawn. Stop editing and select option start edit for the second type and drawn
6. Excel data retrieved in the same manner, by right press mouse, x, and y disply, and well locations appear in the map and then the file export as shapefile
7. by using spatial analyst----idw, the gradual coloring for the specified parameter drawn according to the max and min value and from option extraction, cut according to the aquifer
8. As the layout retrieved, from option insert, the scale, north direction and legend. The coordinate appear in the map through right click in the mouse at the boundary (datafrme)----grid. Then it will be exported to the program as .jpg type.

5.4. DRASTIC PARAMETERS MAPS FOR SANA'A AQUIFER SYSTEM:

Depth to Water Table

The depth to water table element of DRASTIC index which is the distance between land surface and groundwater table, determine the depth of a contaminant travel to the aquifer. As the depth to water implies, an increased travel time for the deeper water levels, factors such as contact time with the surrounding media, oxidation, layer permeability and attenuation become pertinent with the DRASTIC system (Aller et al., 1987). The depths to water in the studied area were read from the available information of recent well inventory in the Sana'a Basin (WEC, 2002). DRASTIC rating used in this project is shown in Table (2)

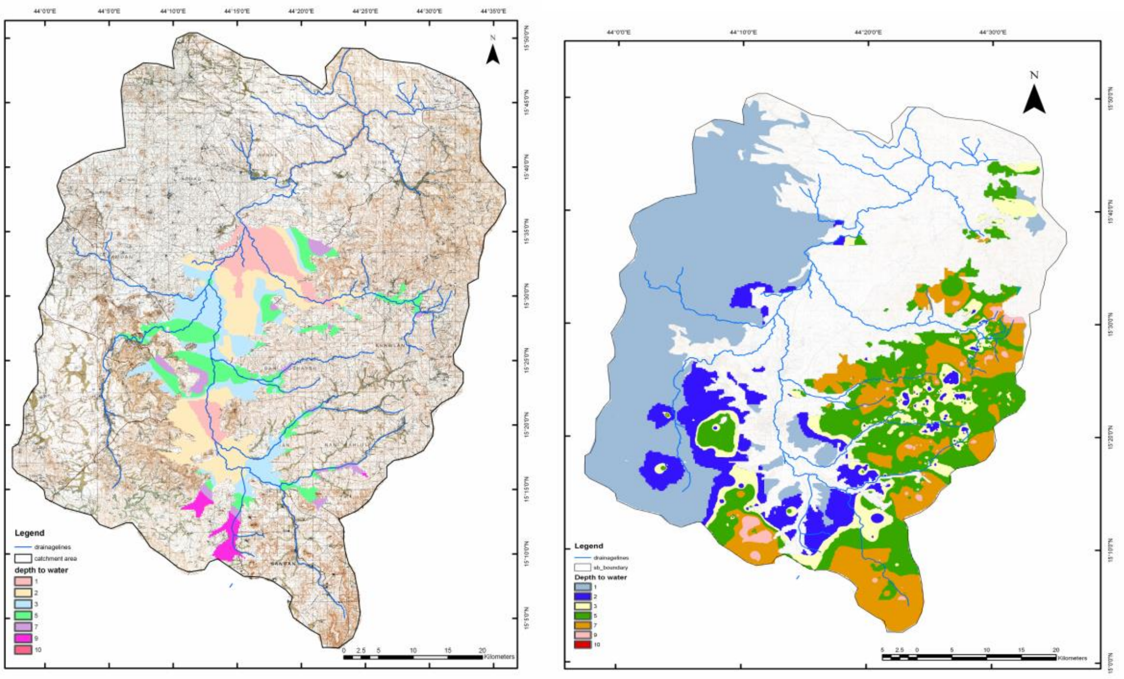
Table (5.2) Water Table depth



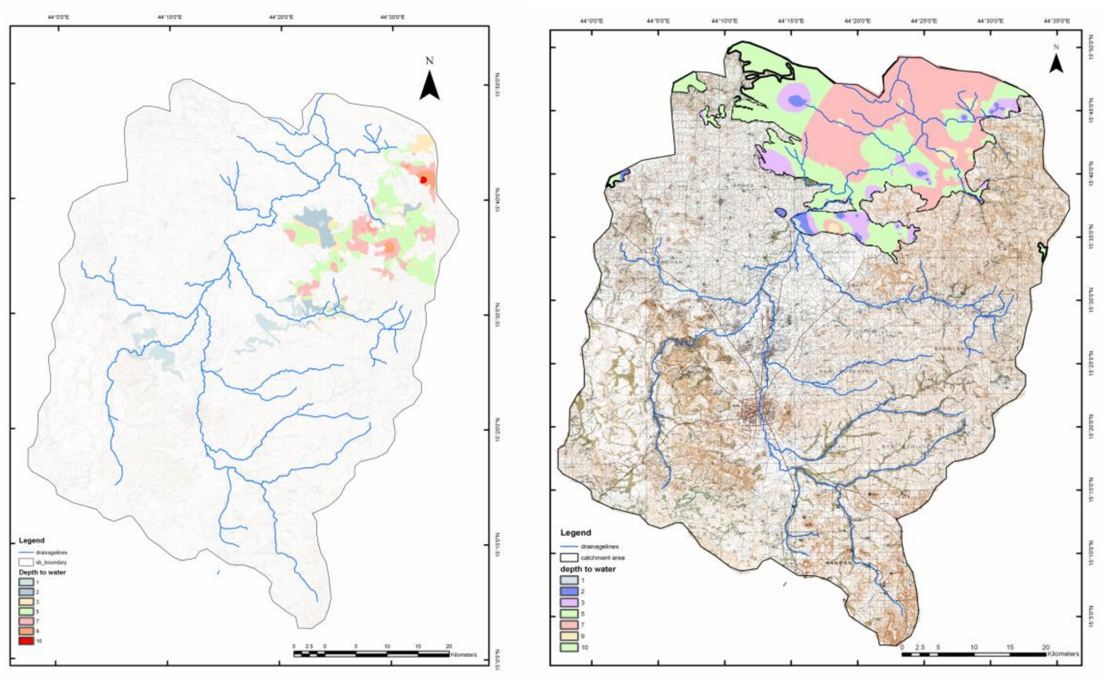
WATER TABLE DEPTH METER	DRASTIC RATING
0.00-1.23	10
1.23-4.58	9
4.58-9.15	7
9.15-15.25	5
15.25-22.88	3
22.88-30.50	2
>30.50	1

From inventory data, measured water table was used to create initial maps of groundwater table depth for the four aquifers: the alluvial, Volcanic, Sandstone and limestone.

The product of process is depths to water table in all aquifers similar to that drastic rating.



Water depth in Alluvial aquifer Water depth in Volcanic aquifer



Water depth in Sandstone aquifer Water depth in Limestone aquifer

Figure (5.3) Depth to water table rating of aquifers in Sana'a Basin

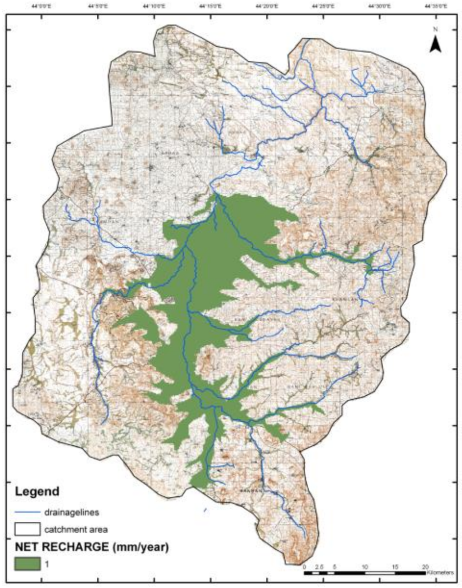
Groundwater Recharge

Net recharge is the total quantity of water per unit area which reaches the water table. Recharge is the principal vehicle for leaching and transporting contaminants to the aquifer. The more the recharge the greater the chance for contaminants to reach the water table (Osborn and Hardy, 1999). The net recharge values are established for each sub-basin in the Sana'a basin based on previous hydrology studies (e.g. Mos. 1986, Alderwish, 1995, Noman (2003) and it is shown in Table (5.3).

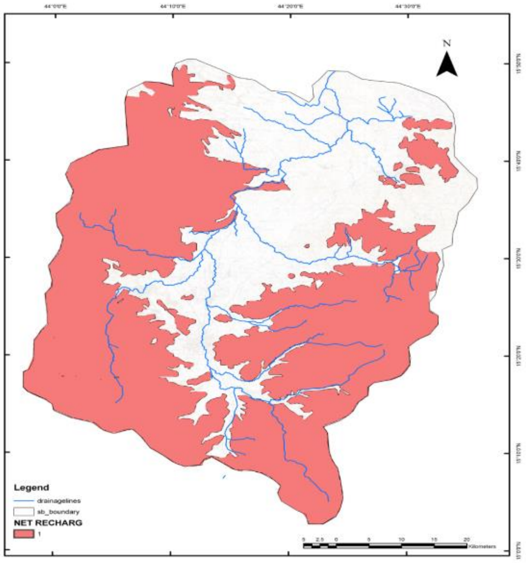
Table (5.3) Recharge over sub-basin in mm/yr

Zone	Recharge mm/yr	Zone	Recharge mm/yr
1	7.5	12	6.8
2	7.6	13	12.8
3	9.5	14	31.7
4	7.4	15	8.7
5	18.6	16	5.7
6	25.5	17	19.7
7	4.8	18	27.8
8	8.5	19	16.8
9	49.3	20	9.8
10	8.7	21	13.9
11	38.7	22	18.7

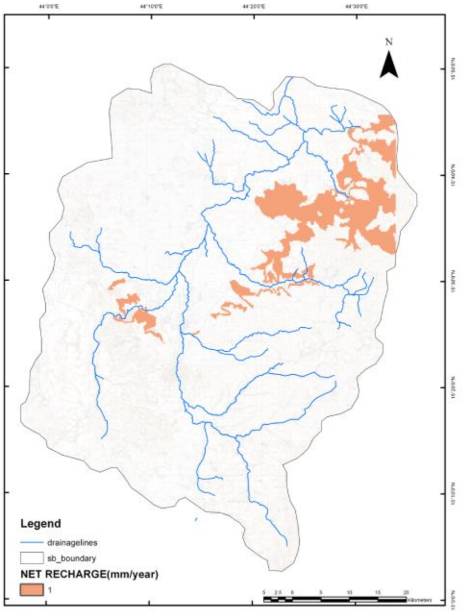
In the worksheet, for each point, recharge values entered according to its respective sub-basin. According to the DRASTIC rating tables, all sub-basin recharge values fall within the range of 00.0-50.8mm/year and consequently their DRASTIC rating is equal to one (1). In separate column, representing DRASTIC weight for recharge parameter which equal to 4, is added to the worksheet. The product of Recharge $_{\text{rating}}$ and Recharge $_{\text{weight}}$ (Rr * Rw), is calculated for each point. In this case, the net recharge affect on vulnerability of aquifers in the Sana'a basin is the same over all the basin and equal to 4.



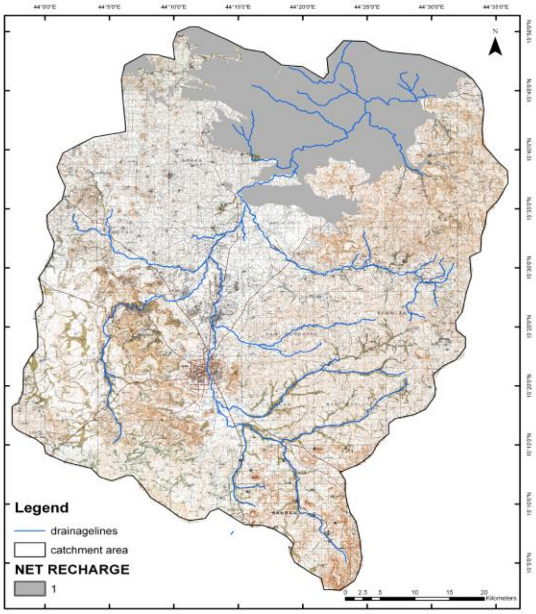
Recharge rating in alluvial aquifer



Recharge rating in Volcanic aquifer



Recharge rating in Sandstone aquifer



Recharge rating in Limestone aquifer

Figure (5.4) Net Recharge rating of aquifers in Sana'a Basin

Aquifer Media

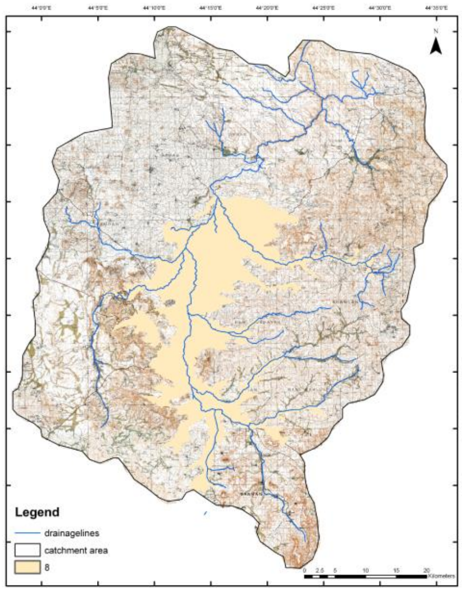
The aquifer media affects the flow within the aquifer. This flow path controls the rate of contaminant contact within the aquifer. The path length is important in determining the time available for attenuation process, such as sorption, reactivity and dispersion, to occur. The aquifer medium also influences the amount of effective surface area of materials with which the contaminant may come in contact within the aquifer. The route which a contaminant will take can be strongly influenced by fracturing, porosity, or by interconnected series of openings which may provide preferential pathways for groundwater flow where the larger the grain size and more fractures or openings within the aquifer, the higher the permeability and the lower the attenuation capacity of the aquifer media (Piscopo, 2001; Metni et al., 2004). This element is constructed based on the geological description of the study area and the structural maps of the Sana'a basin aquifer systems.

Based on the DRASTIC model tables requirements, the aquifer media was classified into four separate classes as shown in Table (5.4). Since this model is intended for regional comparisons, ratings were directly associated with descriptions of the available aquifer material within Sana'a Basin.

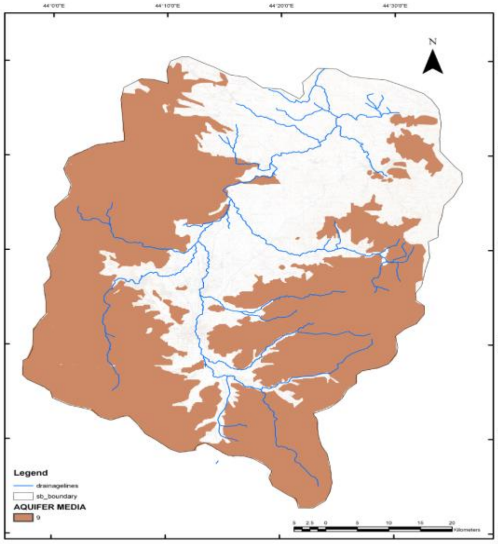
Table (5.4) Rating classes for Aquifer material in Sana'a Basin

Aquifer Material	DRASTIC Rating (Typical) Ar	Ar * Aw
Shale/Limestone	2	6
Limestone and Sandstone	6	18
Volcanic/basalt	9	27
Alluvial (coarse)	8	24

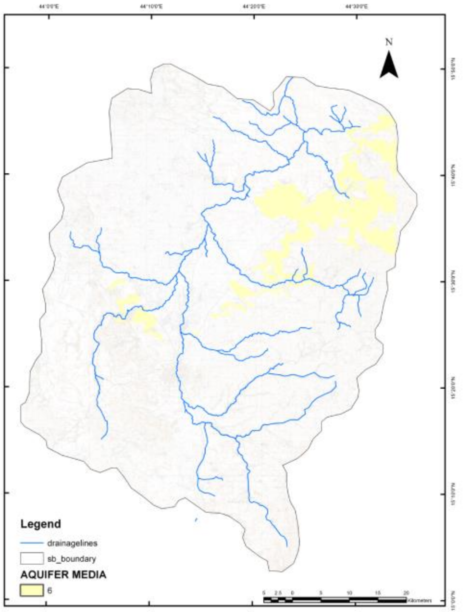
The assigned weight for aquifer material is 3 in DRASTIC model. Consequently the Ar*Aw is calculated for the four classes. Distributions of aquifer material rating for all aquifers in the Sana'a basin are shown in Figure (5.5).



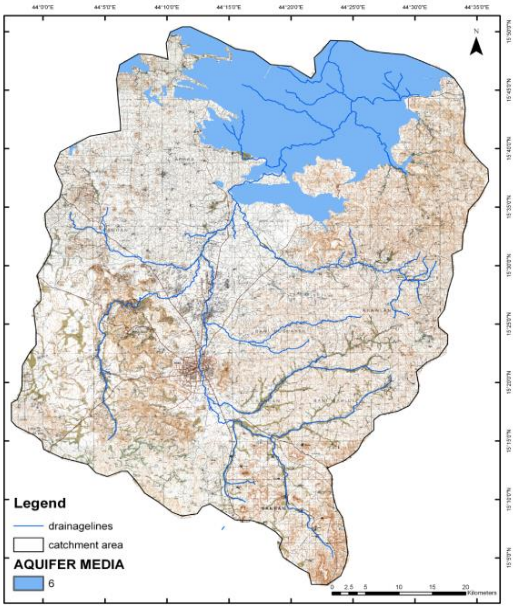
Aquifer media rating in Alluvial aquifer



Aquifer Media rating in Volcanic aquifer



Aquifer media rating in Sandstone aquifer



Aquifer media in Limestone Aquifer

Figure (5.5) Aquifer media ratings of aquifers in Sana'a Basin

Soil media

This factor has a significant impact on the amount of ground water recharge which can infiltrate to the groundwater and on the ability of contaminants to infiltrate to the vadose zone. The presence of larger proportion of finer materials, such as silts and clays, causes decreases in relative soil permeability and restrict contaminant migration. Moreover, where the soil zone is thick, the higher potential for attenuation processes of filtration, biodegradation, sorption, and volatilization may be significant and consequently lower the vulnerability (Piscop, 2001; Metni et al., 2004).

The soil media map is developed from two main maps the first is the surface soil map as in Figure (5.6) describes the type and thickness of the surface soil. The second map is the lithology map that describes the characteristics of the lithology until 1.5m below ground surface for selected points within the basin Figure (5.7).

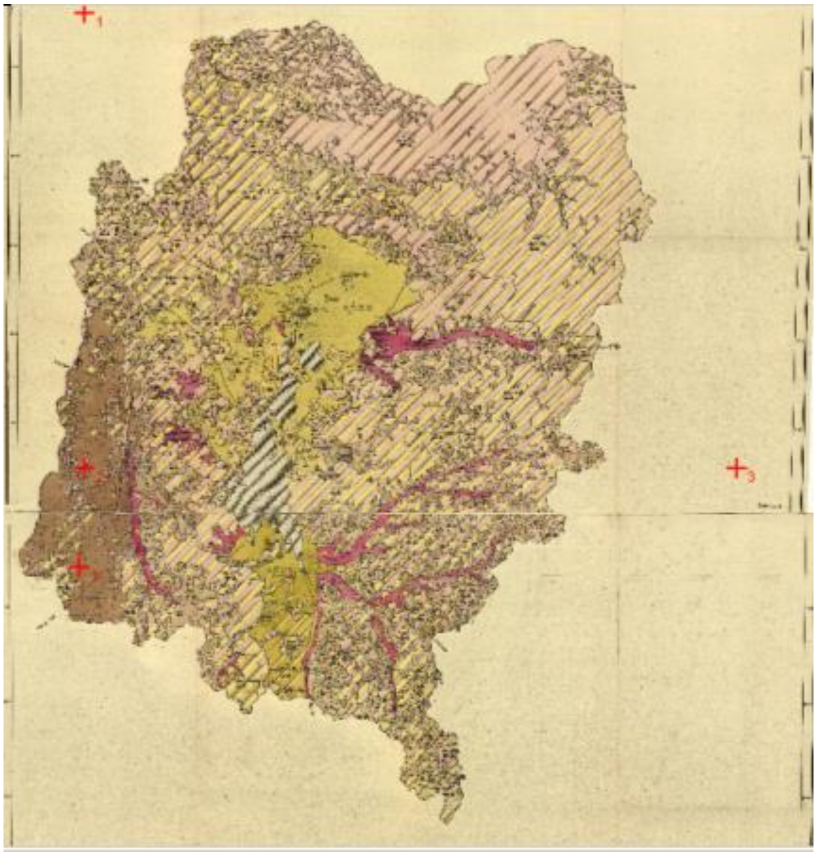


Figure (5.6) Surface Soil Map for Sana'a Basin (Mos. 1986)

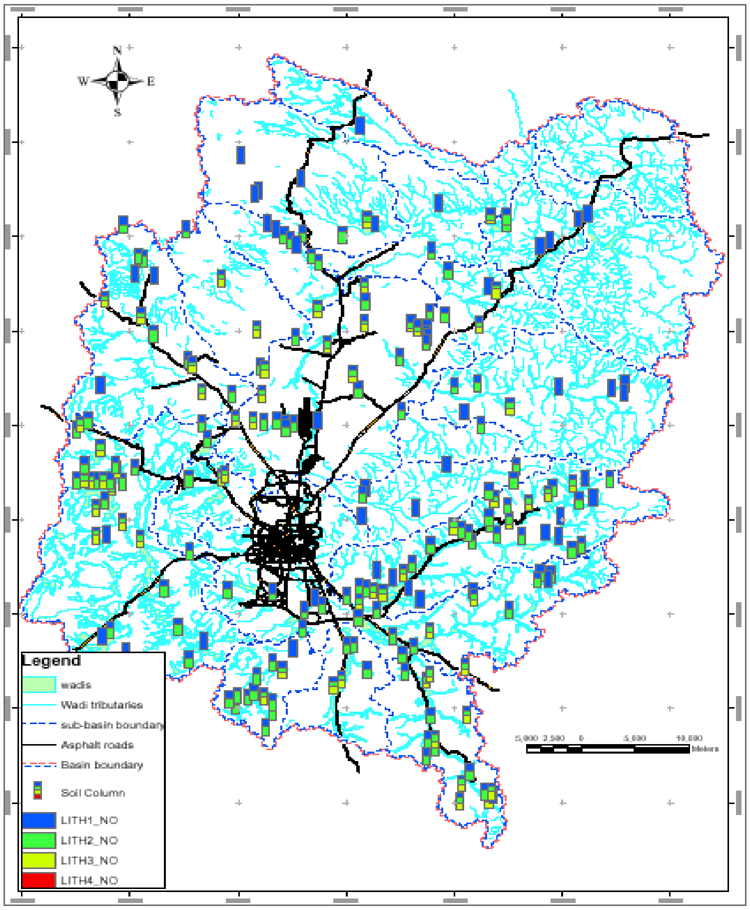


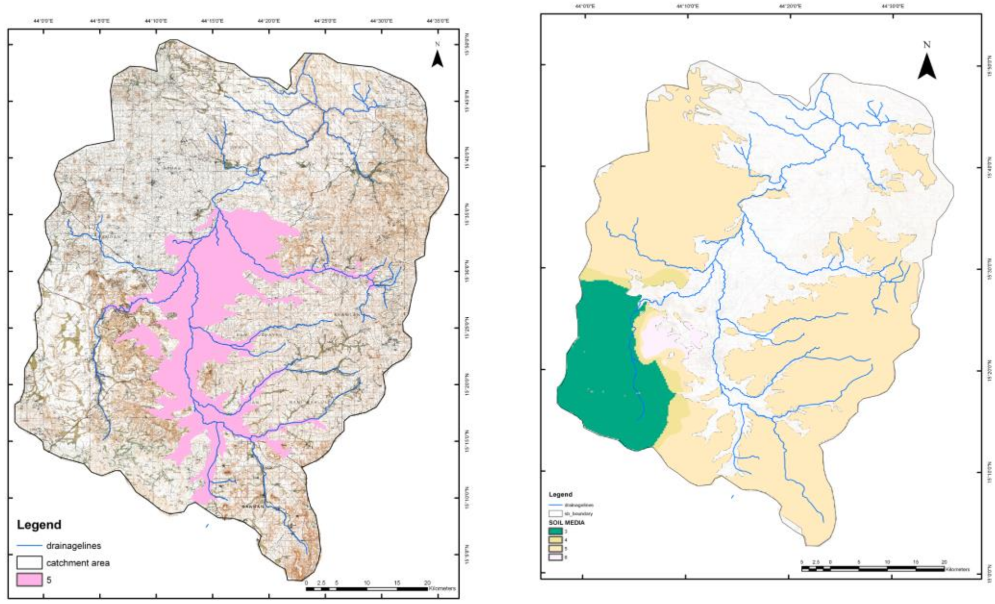
Figure (5.7) Soil Column Analysis within Sana'a Basin (Mos. 1986).

Types of soils were grouped into three categories within the study area, each having different rating values as illustrated in Figure (5.7). The first mostly composed of clay loam units, which has a moderately low rating value of 3. The second class is loam unit which has rating value of 5. The third class is sand loam with the highest rating value of 6.

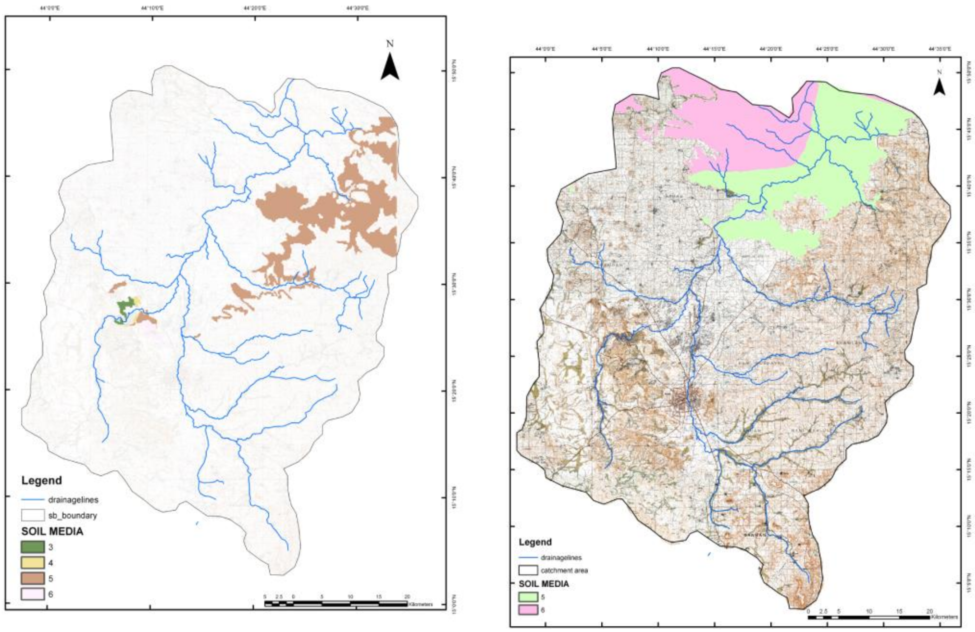
Table (5.5): Range and rating values for soil media

Soil Media	Rating	Sw*Sr
Sand and gravel	6	30
Silt	5	15
Clay	3	3
DRASTIC weight= 2		

The assigned weight for Soil material is 2 in DRASTIC model. Consequently the Sr*Sw is calculated for the three classes over each aquifer. Distributions of soil material weighted rating is shown in Figure (5.8)



Soil media rating in Alluvial aquifer Soil media rating in Volcanic aquifer



Soil media in Sandstone aquifer Soil media in Limestone aquifer

Figure (5.8) Soil media rating of aquifers in Sana'a Basin

Topography

Topography is considered as a slope and slope variability of the land surface. It is a controlling factor for pollutants to runoff or infiltrate. To develop this parameter map, terrain slope map should be analyzed. A terrain slope map for the entire Sana'a basin was developed from a digital elevation map for the entire basin. The digital elevation map (DEM-Map) was obtained from Shuttle Radar Topography Mission (SRTM). The original DEM-Map is developed based on a rectangular grid of 90 meters x 90 meters cells with an average elevation at the middle of the cell. Figure (5.9) presents the DEM-Map for the entire basin. Accordingly, the DEM-Map was modeled on GIS platform and the slope of each 90 m x 90m cell was calculated.

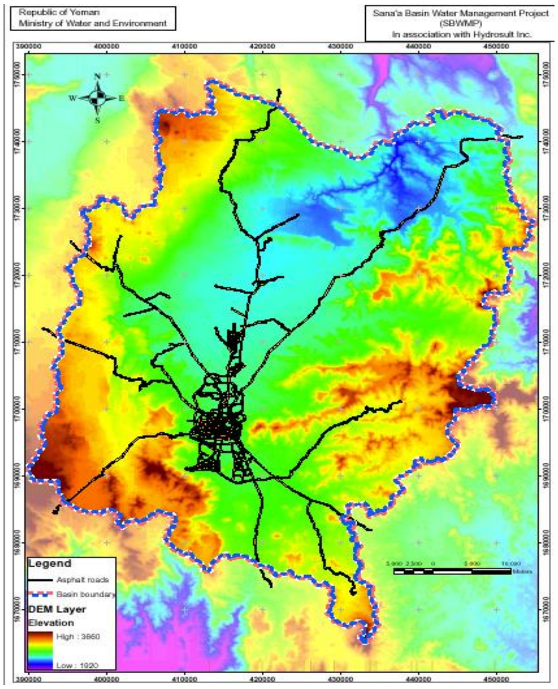
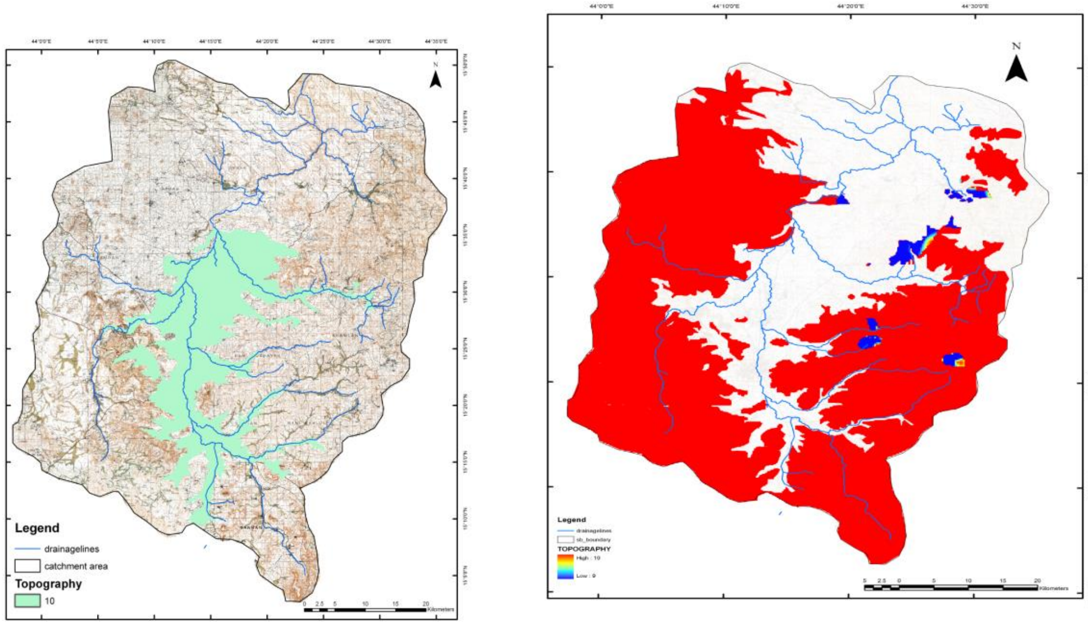


Figure (5.9) Digital elevation Map for the Entire Sana'a Basin.

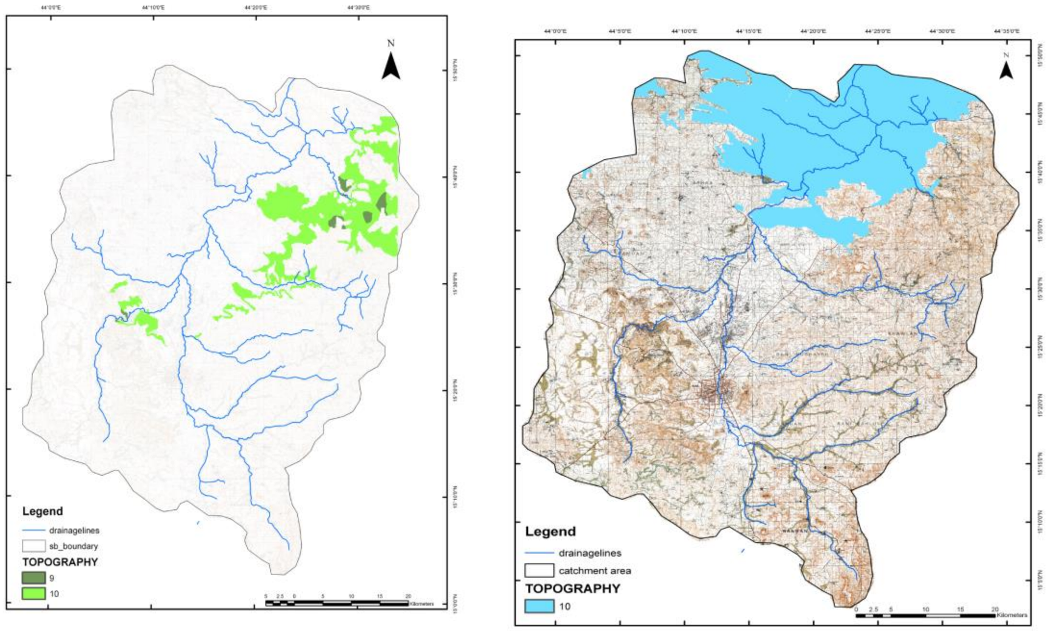
The range of slope was very general, with only three values: flat to gentle slope (2%), moderate slope (4%), and steep slope (6%). According to DRASTIC rating at 0 to 2% slope, the greatest potential exists for pollutant infiltration and hence has the highest DRASTIC rating of 10. With high slope little potential exists for infiltration to the aquifer and a higher potential exists for contaminants to runoff. Using the assigned DRASTIC weight for topography which is equal 1, the Tr * Tw were calculated at each water point. The distribution of topography rating over each aquifer are shown in Figure (5.10). For the purposes of this project, as there is no surface activities on steeper slopes, these figure serve its purpose.

Table (5.6): Range and rating for topography

Topography	Rating	Tr * Tw
0-2	10	10
2-6	9	9
DRASTIC weight = 1		



Topography rating in Alluvial aquifer topography rating in Volcanic aquifer



Topography rating in Sandstone aquifer Topography rating in Limestone aquifer

Figure (5.10) Topography rating of aquifers in Sana'a Basin

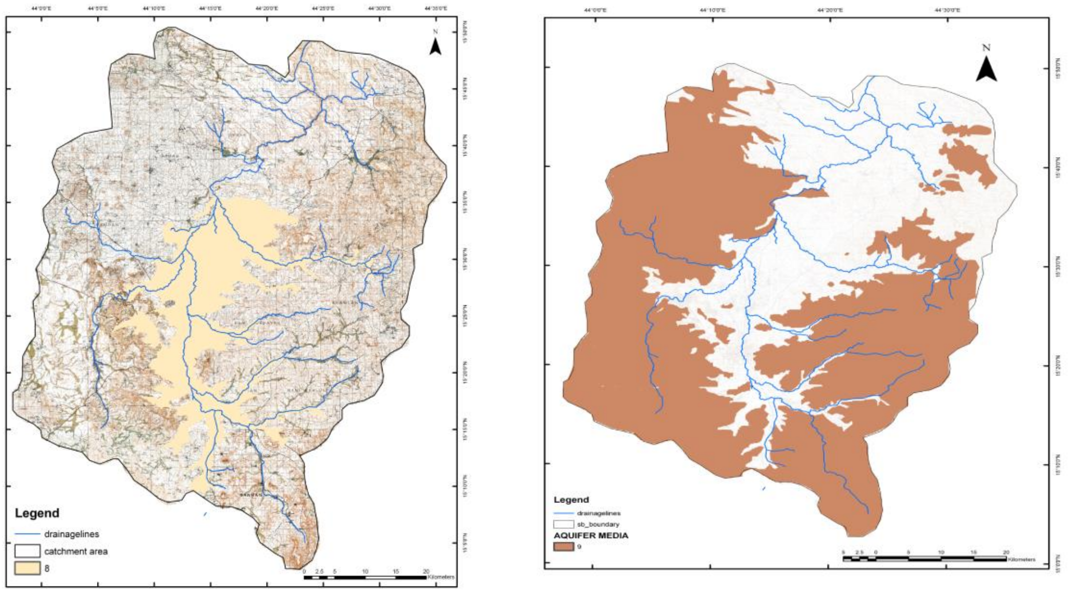
Impact of the vadose zone

The Vadose zone element refers to the unsaturated zone lying between the soil horizon and the water table. The type of the media in this zone determines the attenuation mechanisms. Where several vadose media types are present, the most protective layer against contamination is considered in studying the effect of the media element. Confinement of the aquifer is a major variable in this element because confined aquifers are usually more protected against contamination. Determining the intermediate, or vadose zone materials, requires a knowledge of local geology. Vadose Zone materials were interpreted from depth to aquifer and compared to the known stratigraphy over these areas.

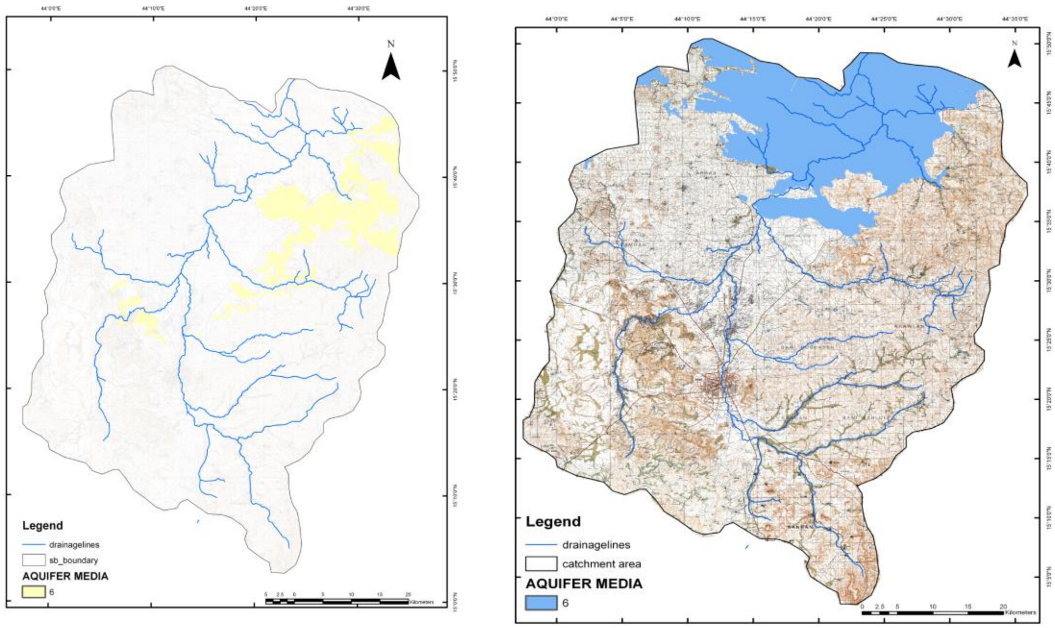
This layer of vulnerability assessment is derived from the existing geological and hydrogeological maps and cross sections. According to the DRASTIC model, vadose zone materials of least permeability determine the hydraulic parameter values. The rating of this parameter is based on the lithological and hydrogeological properties of the overlaying formations. Where confining layer exist the rating of impact is the least and equal 1. For Sandstone, Limestone, alluvial material the typical DRASTIC value is 6. For basalt, however, the typical rating is 9. The alluvial aquifer system in the study area is unconfined aquifer so the impact of vulnerability is very high on the shallow aquifer. The DRASTIC weight for this parameter is 5. The vulnerability rating for this parameter Ir was estimated over the Sana'a Basin for each aquifer and its distribution is shown in Figure (5.11).

Table (5.7) Range and rating for the vadose zone media

Material	**Rating**	**Typical Rating**	**Ir * Iw**
Confining layer	1	1	5
Limestone	2-7	6	30
Sandstone	4-8	6	30
Bedded limestone, Sandstone, Shale	4-8	6	30
Sand and gravel with Silt and Clay	4-8	6	30
Basalt	2-10	9	45
Drastic weight =5			



Aquifer media rating in Alluvial aquifer Aquifer Media rating in Volcanic
aquifer



Aquifer media rating in Sandstone aquifer Aquifer media in Limestone Aquifer

Figure (5.11) Impact of Vadoze zone rating of aquifers in Sana'a Basin

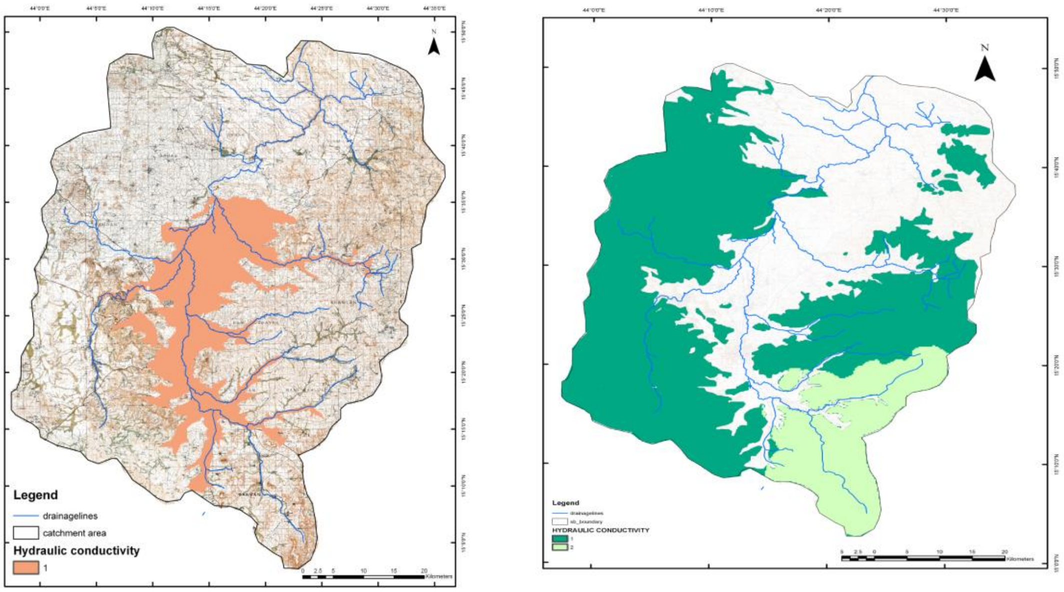
Hydraulic conductivity

The Hydraulic Conductivity is described in terms of aquifer material and its ability to transmit water for a given hydraulic gradient. The hydraulic conductivity controls flow rates and contaminant transport. It self is controlled by the amount and interconnection of void spaces, fractures and bedding planes within the aquifer. There exists a greater potential for pollution with a higher hydraulic conductivity.

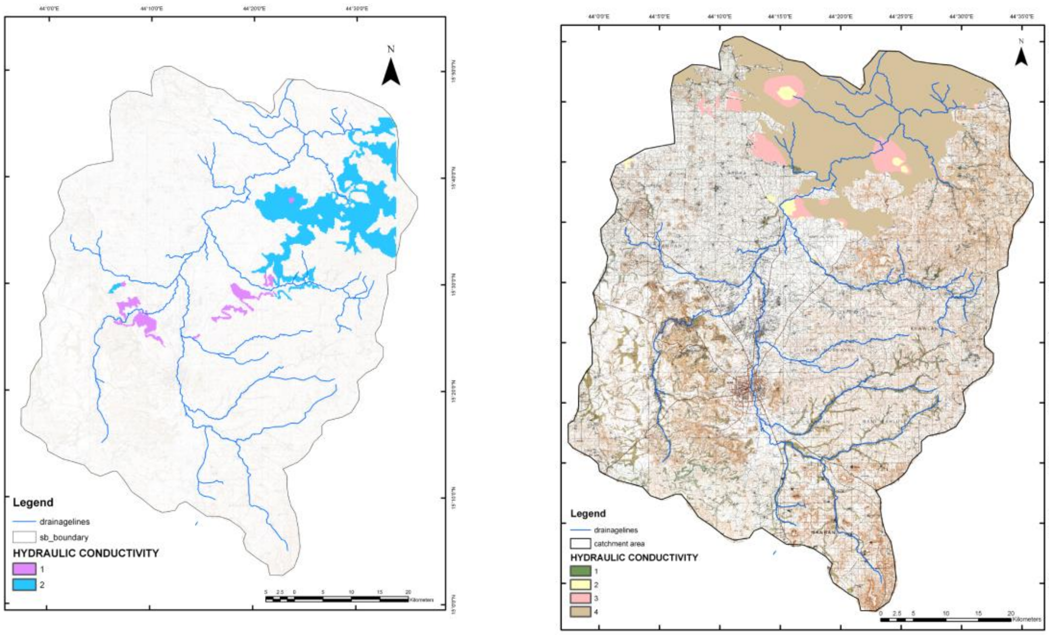
Based on hydrogeological studies of Italconsult 1972, Mos. 1986, pumping test results shows various hydraulic conductivity for different part of aquifers in the Sana'a Basin. Verification to generalize these hydraulic conductivity hydraulic conductivity according to standard values for various aquifer material from Freeze and Cherry, (1992) were used. Values of hydraulic conductivity over the basin ranges between 0.0432 and 31.104 m/d. Ranges and rating are shown in Table (5.8). The assigned weight for this parameter is 3. The distribution of the rating in all aquifers in the Sana'a Basin is shown in Figure (5.12). The high hydraulic conductivity is associated with high pollution potential (Aller et al. 1987).

Table (5.8) Range and rate of hydraulic conductivity of the aquifers

Hydraulic conductivity m/s	DRASTIC Rating	Cr * Cw
$0.5 * 10^{-6}$ and $0.5 * 10^{-4}$ (0.0000005 and 0.00005)	1	3
$0.5 * 10^{-4}$ and $0.15 * 10^{-3}$ (0.00005 and 0.00015)	2	6
$0.15 * 10^{-3}$ and $0.36 * 10^{-3}$ (0.00015 and 0.00036)	4	12



H Conductivity rating in Alluvial aquifer H Conductivity rating in Volcanic
aquifer



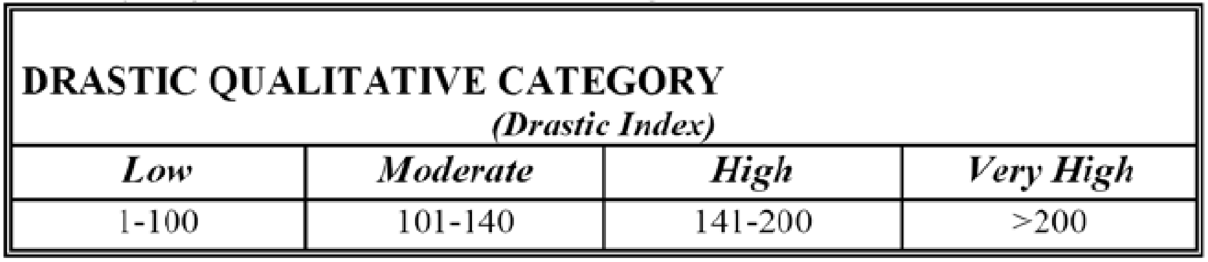
H Conductivity rating in Sandstone aquifer H. Conductivity rating in limestone
aquifer

Figure (5.12) Hydraulic Conductivity rating of aquifers in Sana'a Basin

5.5. THE OVERALL GROUNDWATER VULNERABILITY ASSESSMENT

Based on the methodology described above, the vulnerability index have been assigned for four groundwater aquifers: that are limestone, sandstone, volcanic and alluvial. Figure (5.13) presents the geological outcropping map for Sana'a basin. In the current study each aquifer is treated separately and vulnerability map for each aquifer has been developed based on the above listed methodologies. DRASTIC Category for vulnerability have been used.

Table (5.9) DRASTIC qualitative category (DRASTIC index)



DRASTIC QUALITATIVE CATEGORY

(Drastic Index)

Low	*Moderate*	*High*	*Very High*
1-100	101-140	141-200	>200

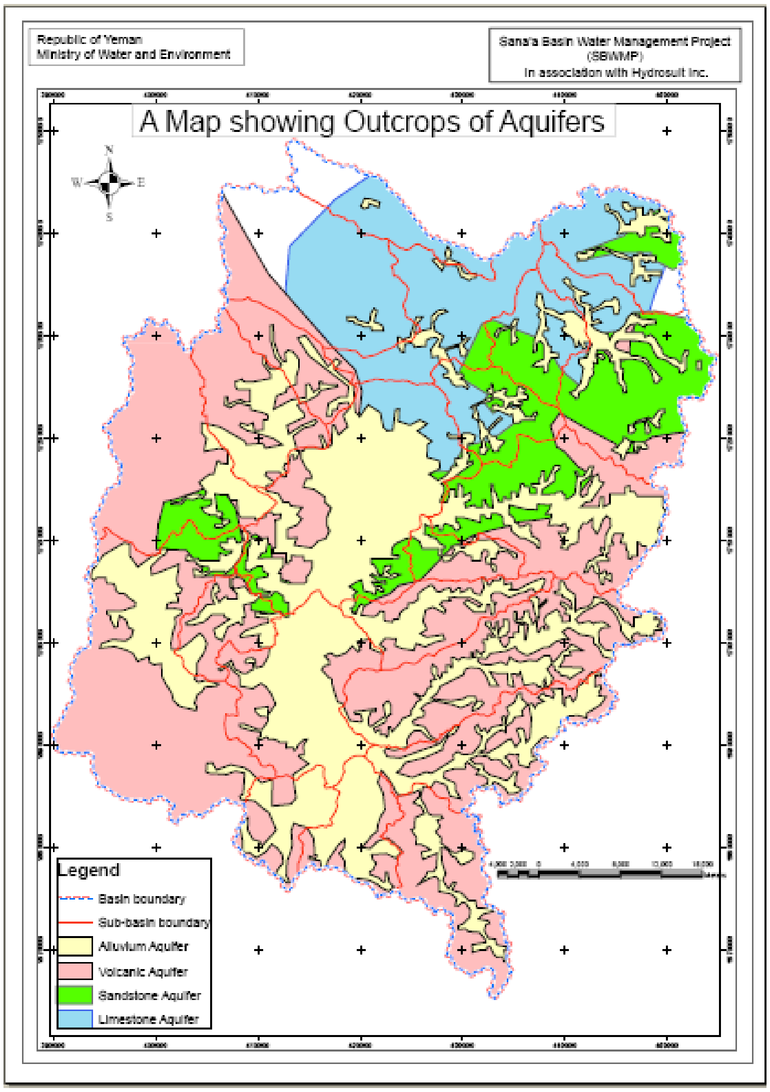


Figure (5.13) Map shows the Outcropping of the Different Aquifers within Sana'a Basin

5.5.1. LIMESTONE AQUIFER

The limestone aquifer outcropping is located at the Northern and Northern-Eastern parts of the Basin. DRASTIC vulnerability index of on this aquifer varies between 55 and 134 and pollution potential varies between low and medium.

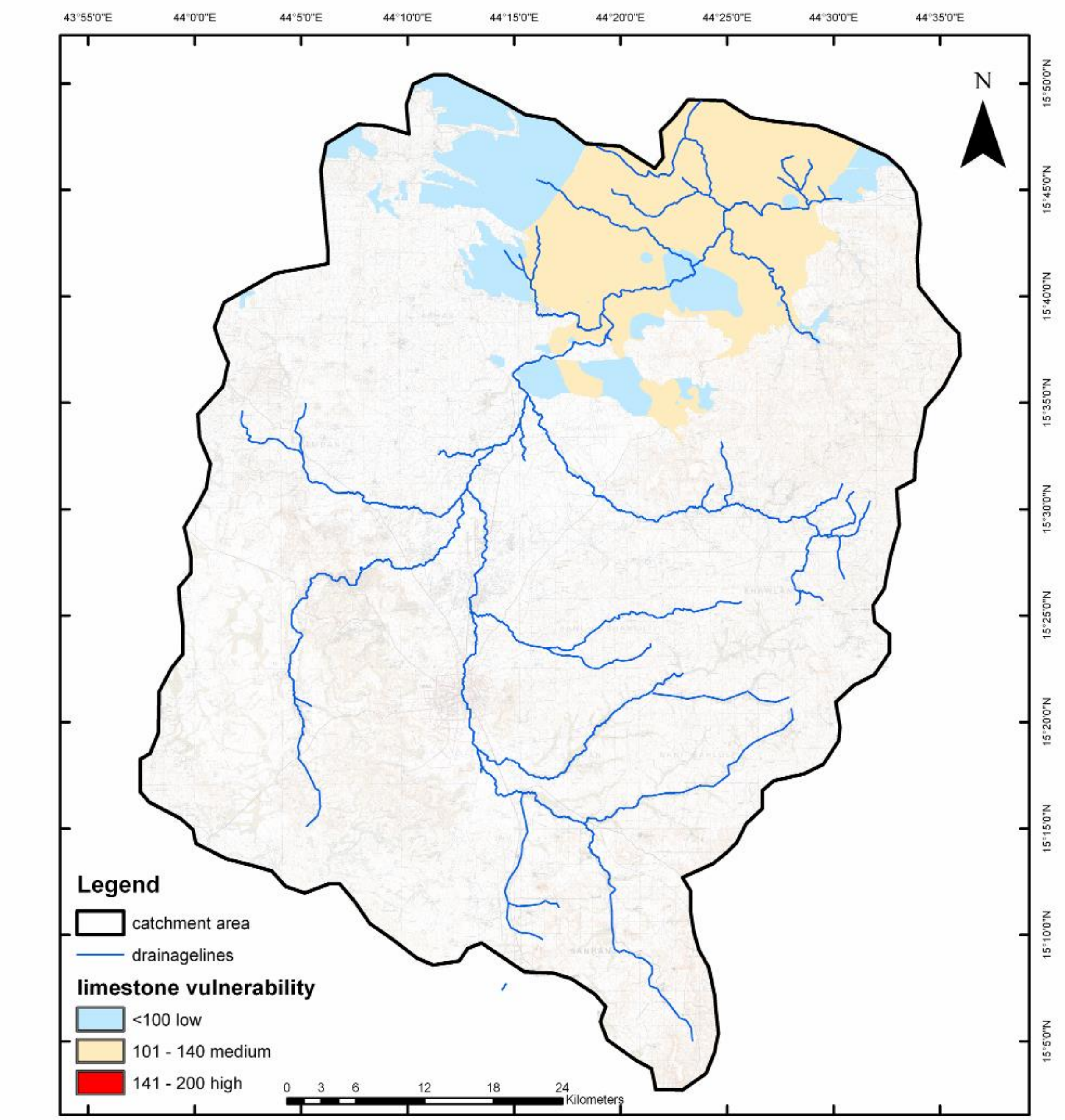


Figure (5.14) Distribution of vulnerability categories in limestone aquifer

Where the limestone is buried under the Tawilah Sandstone is the North-Eastern part at depths of more than 50 meter, the limestone show low pollution potential. In wadi bottom of Al Maadi, Al Kharid, Thoma and Khulaqa the aquifer shows medium pollution potential, even at large depths. The thickness of volcanic rock over the limestone is determining its vulnerability between low to medium. In the upland areas of the north and northern west the aquifer is commonly have low vulnerability to pollution.

5.5.2. SANDSTONE AQUIFER

Sandstone is formed from the Eastern part of the basin and extended to the Western part in crescent shape. The sandstone aquifer is going underneath the alluvial and volcanic aquifers respectively from the mid of the crescent up to the eastern part. In some scattered areas the sandstone aquifer appears as it is presented in Figure (5.15).

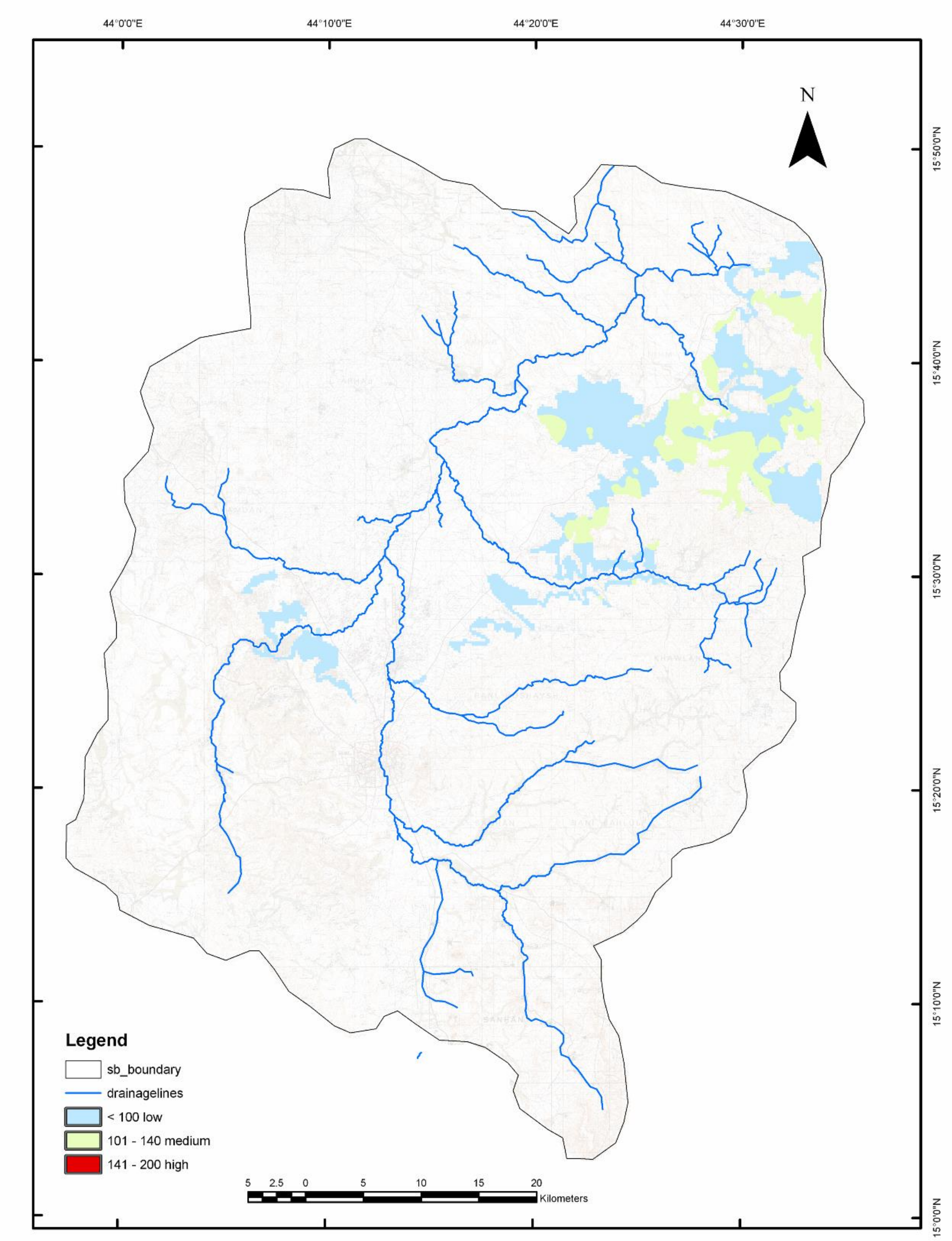


Figure (5.15) Distribution of vulnerability categories in Sandstone aquifer

In the lower reaches of Wadi Assir where the Sandstone outcrops it shows low vulnerability potential mainly in Bani Hushaish side. At Nehim side part of the wadi the aquifer have medium vulnerability. In general, in the northern-east part of the basin, vulnerability depends largely on the depth of the groundwater table in the aquifer. At shallow groundwater table medium vulnerability and as it get deeper lower vulnerability noticed. These variation on vulnerability noticed in wadi Thoma &Al Mahjir, and Khulaqa and lasaf &Asir. In fact, the only high vulnerability registered for this aquifer present in wadi lasaf & Alsir, with value of 113 and the water table at about 9mbgs.

The Sandstone aquifer at Al Huqqah, Bani Huwat, Al furs & Rujam, W. Zahar, W. Hamdan, Al Mawrid and Sawan Al rawnah and South part of Sana'a plain it shows only low pollution potential of less than 100 vulnerability index.

5.5.3. VOLCANIC AQUIFER

The volcanic aquifer is extended from the Southern parts and extended to the Northern parts and cover large areas within the entire basin.

High vulnerability of more than DRASTIC index of 141, noticed in volcanic aquifer at Wadi Assir, Al rawnah, Shahik, Ghyman, Mauliky &Hamil and Wadi Akhwar. The main feature of these areas is the very shallow groundwater table.

Medium vulnerability of the volcanic aquifer observed in Wadi Al Maadi, Lasaf &Asir, Qasabah, Al Huqqah, Bani Huwat, Thoma, Assir (Bani Hushish &Khwalan), Rujam, small area of Wadi Iqbal, Zahar, Hamdan al Sabarah, Al Muwarid, Al Rawnah, Shahik, Gyman, Mauliky&Hamil, and Wadi Akhwar. Large part of these locations are at wadi bottom where groundwater table in the volcanic is shallow.

Low vulnerability observed where groundwater of the volcanic aquifer is considerably deep. These are located in Wadi Al Kharid, Qasabah, Huqqah, Bani Huwat, Iqbal, Zahar, Al Muwarid, Shahik, Gyman, and Hizyaz.

In general, western plateau shows low vulnerability potential with scattered high vulnerability embedded in the medium vulnerability covers the southern and eastern plateau.

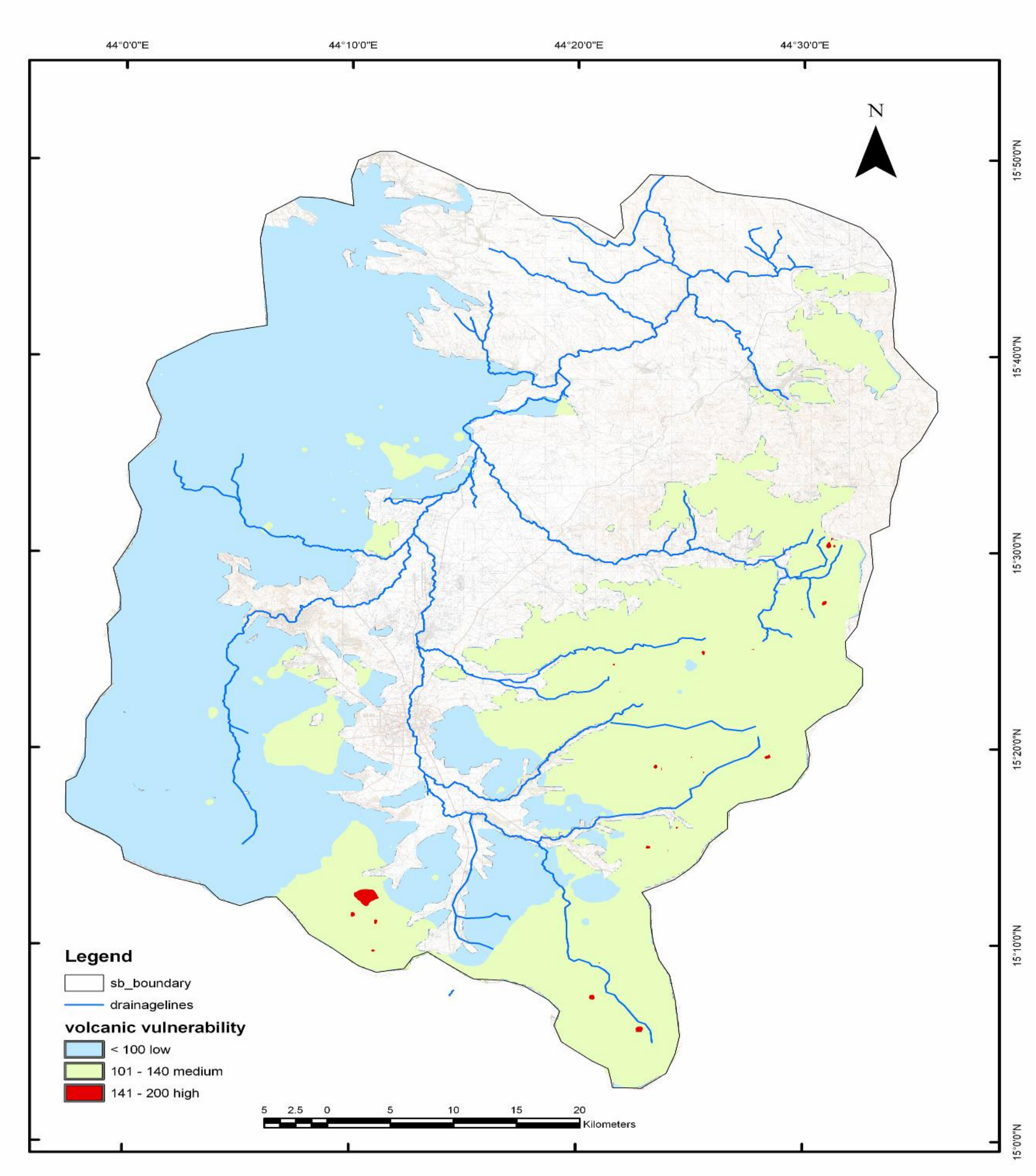


Figure (16) Distribution of vulnerability categories in Volcanic aquifer

5.5.4. ALLUVIAL AQUIFER

The alluvial aquifer is expanded in the low elevation areas and it's found mainly in the mid area where Sana'a plain is located.

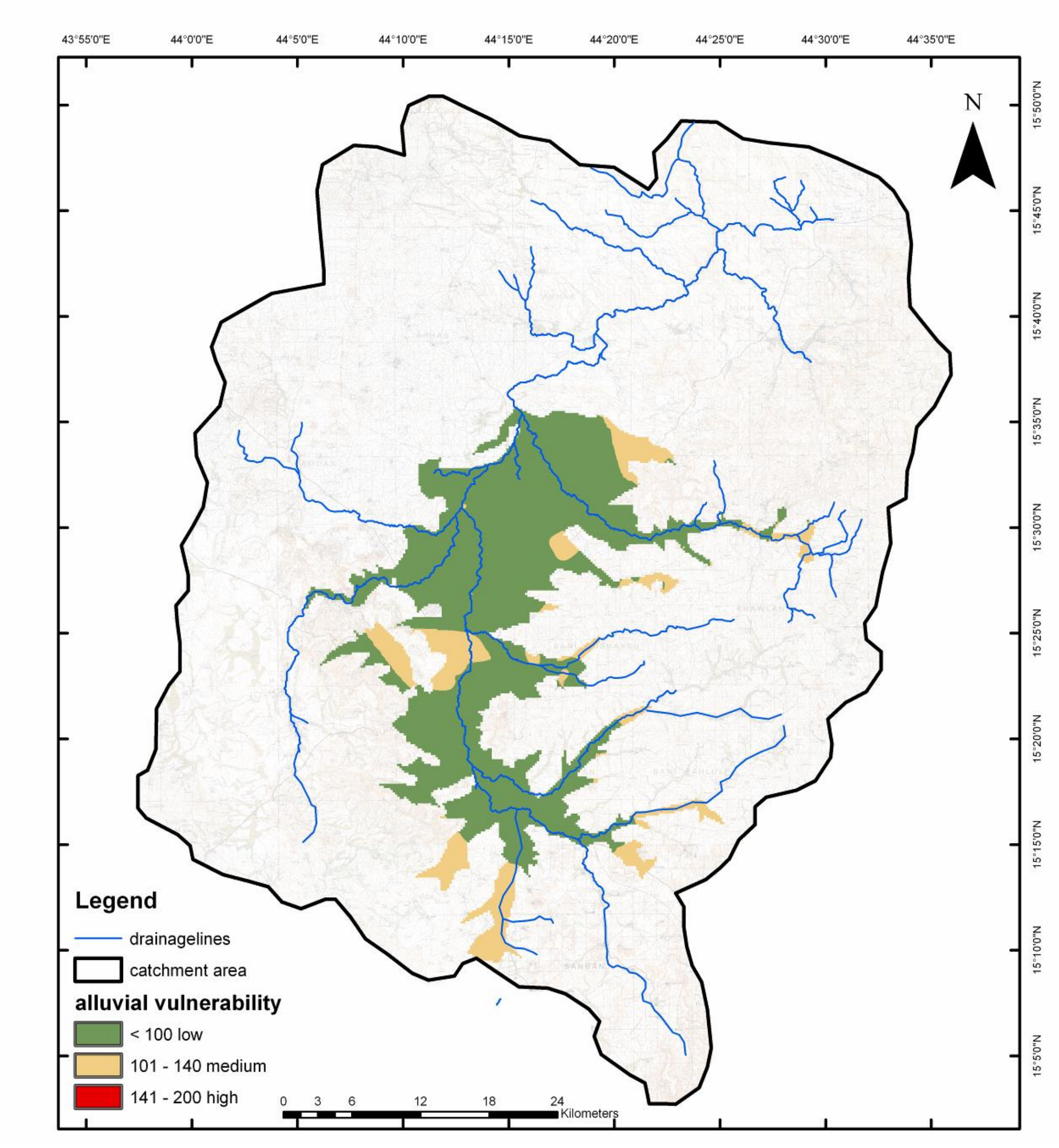


Figure (17) Distribution of vulnerability categories in Alluvial aquifer

Medium potential vulnerability of alluvial seems to be associated with the shallow groundwater table of this aquifer. It observed in Wadi Al Kharid, Al Maadi, Lasaf & Alsir, Khulaqa, Bani Huwat, Thoma, Rujam, Zahar, Shahik, Gyman, Mualiky&Hamil, and Akhwar.

Low DRASTIC vulnerability index observed mainly in Bani Huwat, Assir, Al Muwarid, Sawan and Shahik.

In general, Sana’a plain and lower reaches of minor wadis debouch Sana’a plain the alluvial aquifer shows low vulnerability and upper reaches of primary wadis shows medium vulnerability.

6. CONCLUSION

The purpose of the present hydrochemistry study is to update and obtain information about the hydrogeochemical properties of the main water bearing strata, and to identify and characterize groundwater pollution. More specifically, it aims to provide data on spatial variations in groundwater chemistry and differences in hydrochemistry of the groundwater in different aquifers within the Sana'a basin.

Regarding the previous hydrochemistry studies:

- All previous study missing the relation between the chemistry and the geology. This necessitate groundwater/geology should always be involved in interpretation of groundwater chemistry.
- All previous pollution studies shows deficiency for the typical background of groundwater quality from the aquifers investigated elsewhere than at the areas of the pollution sources, to enable determination ambient mean quality and variability in terms of major constituents.
- All previous studies did not dealt with the origin and evolution of groundwater in the basin chemically. Hydrosult did not describe water types in the Sana'a basin. The main objective was to obtain field data on the chemical and bacteriological quality of groundwater in the basin in general, and at potential site source of groundwater pollution due to sewage treatment plant, north of Sana'a plain.
- Russian study only stated the chemical analysis results of water quality without reporting their distribution over the Sana'a basin. However, they reported the water type per each aquifer. Hydrosult (2007) mainly done hydrochemical mapping of major constituent of water quality (not chemistry).

Monitoring network established by Hydrosult (2008) was not fully representative of the basin with several errors and lack of information of selected water points: e.g. depth, casing, screen, aquifer penetrated etc. In addition, several wells are penetrating more than one aquifer, or mistakenly reported to other aquifer. Some of the monitoring wells dried up and/or not operational. 2009 survey founded important to be included in the monitoring network.

Field measurement parameters were not representative probably due to calibration of electrodes, especially the pH electrode which require special attention. Eh and DO were not included in the well head chemistry

Quick assessment of the laboratory performance, there is no clear procedure to follow the sample through the entire laboratory process from log-in at the laboratory through to sample reporting. A better procedure should be put in place

Data preparation should be included through one of the common available program e.g. Aquachem, while any future hydrochemical interpretation should include:
While the hydrochemistry interpretation included the following:

- Reliability check report for laboratory data;

- Hydro -chemical characteristics for water at different aquifers;
- Groundwater classification;
- Statistical analysis;
- Distribution of major ions;
- Descriptive statistical analysis;
- Rock source deduction;
- Spatial distribution maps for the different measured parameters
- Water quality index maps to present suitability of water quality for different intended uses;
- Hydro-chemical relation between different aquifers;
- Hydro-geological connections between different aquifers

Reliability check for sample analysis should be carried out for all samples using Aquachem program which include 9 parameters:

Balance (C-A)/(C+A)*100
TDS: [(Entered-calculated)/Entered]*100
TDS: [(Entered -TDS180o calculated)/Entered]*100
TDS Entered/Conductivity
Conductivity/Sum MEQ Cations
K+/[Na++ K+] meq/l
Mg++/[Ca++ + Mg++] meq/l
Ca++/[Ca+++SO4--)
Na+/(Na+ +Cl-)

In addition to the concentration value of **CO_3 when PH is less than 9,**

The classification of water chemistry is intended to describe the hydrochemical variations in the Sana'a basin system. The basis of the classification used in this study includes both chemical composition and chemical change, together with elements of geological and geographical control. The latter elements are found essential to provide meaningful interpretation. The groundwater from aquifers in the Sana'a Basin is classified into:
I *calcium bicarbonate water type*
II *calcium sulphate water type*
III S*odium sulphate water type*
IV *Sodium Bicarbonate water type*
***V** indiscriminate ions water type*
However, these water type for each aquifer can has different origin and history.

Using a map to show the variation can help not only to observe a systematic areal distribution of water quality, but also allow correlations with other characteristics of the groundwater system (i.e define the hydrogeological conditions). Hydrosult, 2007 draw major ions distribution map for each aquifer. That was not very useful as they missed important conclusion that might be drawn from these distribution which is aquifers interaction and groundwater flow etc.

Samples are collected from production wells, consequently, mixed samples from boreholes which penetrating more than one aquifer is the most common case in boreholes of Sana'a basin. Only during 1986 and 1995 samples referred to as mixed samples have been stated. Studies of 2007 and 2009 although they do not report mixed samples (more than one aquifer), the chemistry of the samples as well as their locations according to hydrogeological conditional map of Mos. (1986) indicate several samples are of this type.

The TDS distribution in general appears to be controlled by the topography which is almost a result of tectonic structures. All secondary and primary wadis in Sana'a basin irrespective of the type of the bedrock show lower TDS value upstream and increases in the downstream direction. Another trends found across (transverse its axial plane) the wadi, shows the lowest TDS found at the foot hill and sometimes additionally along the wadi channel especially in the upstream region. These two areas (wadi channel and foothills) are usually covered by coarse sediments and rock fragments and probably represent recharge areas. The increase of the TDS within the wadi bottom is mainly concentrated at the flood plains which consist of fine-grained sediments. Moreover these areas are generally more populated.

The considerably high TDS values in samples from limestone is primarily due to the presence of soluble materials in this aquifer, which is major factor controls the natural value of the total dissolved solids plus the agricultural practices in the area. Only Wadi Khalaqa shows high salinity along the whole vertical section of the aquifer. Other sub-basins, deep borehole commonly show fresher water. This means, the location of the water point regardless its depth is the factor for salinity. Fresh water samples are commonly of HCO_3 dominant water type while brackish water are of SO_4 dominant water type. Comparing these values with those of 1986, highest TDS values in Amran group is located in Thoma-khalaqa area.

The highest TDS values in the Cretaceous Sandstone observed in Wadi Khulaqa, Thoma, Bani Huwat dominant with SO_4 ions may be related to presence of more highly mineralized old water from the underlying Amran Group through an expected fault at depth. These samples are differ from other SO_4 dominant water type with fresh water (TDS<1000mg/l) which probably related to oxidation of pyrite. Brackish samples from Assir and Maadi show indiscriminate ion water type and quite less TDS values.The TDS distribution map does not reflect the piezometric map of the area. This partially represents a limit of the TDS distribution map to be related to the groundwater flow as it expresses bulk of parameters rather than one.

All samples from Volcanic aquifer show fresh water with TDS values range between 236 and 975mg/l. This reflects the control of the lithology as volcanic compose the least soluble material. The lowest TDS values (<300mg/l) in the volcanic found in Wadi Zahr Ghyal and Iqbal, followed by Wadi Akhwar then Hizyz. All these zones represent active fresh recharge areas. A part of sample from Thoma, the other four samples from shallow aquifer (in Sawan and Assir) show TDS more than 500 mg/l. Local trends within this broad trends appear to be controlled by the fault system in the area, which is almost coincides with the topography. This means wadi is commonly developed along weak fractured zone. For alluvial aquifer, only few samples collected from this aquifer which makes it difficult to establish any trend.

In general the distribution of Ca is a subdued replica of the TDS distribution. The dominant species of the calcium is the Ca^{+2} (free ions), however other some samples have more than 10 % of their calcium occurring as ion pair mainly $CaSO_4^o$. Except for sample with high TDS value in excess of 1000mg/l (20% of its calcium concentration occur in form of $CaSO^o{}_4$), the complexation and ion pair are insignificant. In general the distribution of calcium concentrations in the volcanic aquifer show to be combatable to the TDS values distribution. Exception of local anomalies also has been observed in some wells.

Chemical analyses for samples taken from boreholes which tap both the Volcanic and the Cretaceous sandstone, show enhanced Mg/Ca ratio. This implies that the volcanic rocks are draining into the Cretaceous sandstone.

Process controlling distribution of Na in aquifers of Sana'a basin are -calcium removal due to ion exchange or calcite precipitation. Dissolution of evaporates, recycling of irrigated water, cation exchange process as indicated from the Na/Cl ratios. Human impact to shallow groundwater manifested samples drawn from shallow aquifer.

Only few samples have K concentration >10 mg/l and probably related to application of K-fertilizer. The potassium released slowly upon dissolution of K-minerals, as potassium feldspars and mica minerals. This means that concentration increase as residence time in groundwater increases.

The control of the topography and the structures in the groundwater flow is well reflected in the distribution of the chloride ion concentration. Within the main wellfield areas, the chloride distribution is highly correlated with the depression of the peizometeric surface. The lower Cl concentration observed found at upper reaches of tributaries wadis and increases in downstream direction in areas just before these minor wadis discharge their water into the main channel. The variation of Cl concentration the distribution is well correlated to the piezometric data. Local anomaly may have been caused by evaporation, or anthropogenic effect. Relatively uniform value of chloride found at all the samples from boreholes at the southern part of the basin. The origin of this chloride might be related to presence of sodalite, or using of KCl (fertilizer). However is more likely to be a result of solution and precipitation of the least soluble salts.

SO_4 concentrations range between 500-1000 mg/l present in brackish water from shallow and deep aquifer at Al Kharid and Khulaqa, which indicate hydraulic connection. While the high concentration of sulphate occur in Wadi Thoma (750 mg/l) and Khulaqa (725mg/l) are probably collected from boreholes penetrating the limestone aquifer. (Russian hydrogeological conditions maps confirm the situation of the area). In some cases sulphur gas in the volcanic region may affect the sulphate concentration.

The bicarbonate concentration is dominant in the most of the samples from volcanic. This is because dissolution of silicate minerals except quartz, consumes hydrogen ion during the incongruent dissolution and result in arise in pH and alkalinity.

The high concentrations of nitrate are the result of contamination of groundwater supplies by septic systems, feed lots, and agricultural fertilizers. Nitrate comes into water through the nitrogen cycle rather than via dissolved minerals. Samples drawn from deep boreholes shows high concentration of NO_3 reflect the depth of contamination reached.

Only three samples show phosphate which probably a result of wastewater, septic system effluent, detergents & fertilizers and/or animal waste.

Temporal variation between 2007 and 2009 were undertaken at sample level for each aquifer. However, there are several samples analyzed during 2007, their results were not available for this study. Other samples were changed due to not existing of borehole/dugwell used during 2007. Variation between 1986, 1995, 2007 and 2009 were undertaken at two levels: at each sub-basin and each aquifer level. This is because not the same samples were analyzed by all studies. Only numerical variation was assessed as the spatial distribution may not be accurate enough.

If samples analyzed correctly and results are corrects, the variation may be related to amount of recharge/discharge of the sub-basin (sample). While increase in TDS value indicate deterioration of water quality of the sample which may be results from higher discharge and/or putting more pollution locad to the aquifer. The decrease of TDS indicate dilution of water quality due to fresh recharge.

Highest number of samples with beyond MPL is for the total hardness, with 22 samples, followed by Sulfate (13 samples) and TDS (13 samples). The highest number of samples within the MPL are 77 samples for HCO_3 ion, followed by total hardness (58 samples) and Ca (36 samples). The highest number of samples fall within the HDL are those of Cl with 87 samples, followed by Na (86 samples) and Iron (78 samples).

100% of Sandstone aquifer, 86% of Limestone aquifer samples show very hard water, while only 30%of volcanic aquifers are of very hard water.

Only Mg and Cl concentration distribution have trend that can be related to passage of sewerage. A general an increasing trend of Mg concentration can be followed along the extend of the passage line toward the end of sewage passage line. For Cl Two trend can be traced. The first is that high concentration of Cl ion observed along the sewage passage line and decrease away from that line. The second trend is an increasing trend as three anomalies exist along the sewage passage line, with highest at the end of the line (in the north). For NO_3 a trend along the first half of sewage passage can be traced where the highest NO_3 observed under the passage line and fate away from it.

The 28 samples were analyzed for biological contamination through evaluation of Coliform. Fecal No./100mL and Group No./100mL. Only four samples show biological contamination. It is difficult to relate the biological contamination of these samples to the sewage passage.

In general, similar conclusion to Hydrosult (2007), that the wastewater passage dose not have significant impact on the groundwater at different levels and aquifers within its vicinity. However, from field experience, it is believed that sampling locations for assessing pollution potential due to sewage passage was not successful.

In Hydrosult (2008) conducted the only previous study carried out vulnerability mapping stud over Sana'a basin. In their study the COP method has been selected for developing the vulnerability maps for Sana'a Basin though which useful information can be obtained for designing a complete water quality monitoring network. This method was introduced by the Group of Hydrogeology in the University of Malaga/Spain (VIAS et al., 2002). It uses the parameters: C=Concentration of flow, O=Overlying layers, and P= Precipitation. As stated in the report of Hydrosult (2008), **'As outlined by DALY et al. (2002) the COP-Method may become the European approach for groundwater vulnerability mapping in karst areas, provided its application proves to be successful in the coming few years'.** This statement according to the model developer, indicate that method does not suit Sana'a Basin as it is neither contain Karst aquifers nor its conditions similar to Europe. In fact as metioned in Hydrosult report: `**The C factor represents the degree of concentration of the flow of water towards Karstic conduits that are directly connected with the saturated zone and thus indicate how the protection capacity is reduced.'** Where is the Karstic conduits in the Sana'a basin. Moreover, they stated **'so far there is too little experience with applications of this method to be able to judge about the suitability and applicability of the method**'. So it is wondering why they used it in the Sana'a Basin?.

The present study applies the US EPA Approach (DRASTIC) which has been selected for the following main advantages:

- the method is a popular approach to groundwater vulnerability assessments because it is relatively inexpensive,
- straightforward,
- uses data that are commonly available or estimated, and
- produce an end product that is easily interpreted and incorporated into the decision-making process.

Applying the DRASTIC method, vulnerability maps for four aquifers within Sana'a Basin Alluvial, Volcanic, Sandstone and Limestone aquifers have been developed. The basic data used for assessing vulnerability was the coordination of the well inventory carried out during 2001 (WEC, 2002). Using these information proofed to provide better meaningful interpretation of vulnerability mapping of aquifers in the Sana'a basin than using grid cells coordination.

For each DRASTIC parameter, Maps for all aquifers systems were developed.

DRASTIC vulnerability index of on limestone aquifer varies between 55 and 134 and pollution potential varies between low and medium. Where the limestone is buried under the Tawilah Sandstone is the North-Eastern part at depths of more than 50 meter, the limestone show low pollution potential. In wadi bottom of Al Maadi, Al Kharid, Thoma and Khulaqa the aquifer shows medium pollution potential, even at large depths. The thickness of volcanic rock over the limestone is determining its vulnerability between low to medium. In the upland areas of the north and northern west the aquifer is commonly have low vulnerability to pollution.

In the lower reaches of Wadi Assir where the Sandstone outcrops it shows low vulnerability potential mainly in Bani Hushaish side. At Nehim side part of the wadi the aquifer have medium vulnerability. In general, in the northern-east part of the basin, vulnerability depends largely on the depth of the groundwater table in the aquifer. At shallow groundwater table medium vulnerability and as it get deeper lower vulnerability noticed. These variation on vulnerability noticed in wadi Thoma &Al Mahjir, and Khulaqa and lasaf &Asir. In fact, the only high vulnerability registered for this aquifer present in wadi lasaf & Alsir, with value of 113 and the water table at about 9mbgs. The Sandstone aquifer at Al Huqqah, Bani Huwat, Al furs & Rujam, W. Zahar, W. Hamdan, Al Mawrid and Sawan Al rawnah and South part of Sana'a plain it shows only low pollution potential of less than 100 vulnerability index.

High vulnerability of more than DRASTIC index of 141, noticed in volcanic aquifer at Wadi Assir, Al rawnah, Shahik, Ghyman, Mauliky &Hamil and Wadi Akhwar. The main feature of these areas is the very shallow groundwater table. Medium vulnerability of the volcanic aquifer observed in Wadi Al Maadi, Lasaf &Asir, Qasabah, Al Huqqah, Bani Huwat, Thoma, Assir (Bani Hushish &Khwalan), Rujam, small area of Wadi Iqbal, Zahar, Hamdan al Sabarah, Al Muwarid, Al Rawnah, Shahik, Gyman, Mauliky&Hamil, and Wadi Akhwar. Large part of these locations are at wadi bottom where groundwater table in the volcanic is shallow. Low vulnerability observed where groundwater of the volcanic aquifer is considerably deep. These are located in Wadi Al Kharid, Qasabah, Huqqah, Bani Huwat, Iqbal, Zahar, Al Muwarid, Shahik, Gyman, and Hizyaz. In general, western plateau shows low vulnerability potential with scattered high vulnerability embedded in the medium vulnerability covers the southern and eastern plateau.

Medium potential vulnerability of alluvial seems to be associated with the shallow groundwater table of this aquifer. It observed in Wadi Al Kharid, Al Maadi, Lasaf & Alsir, Khulaqa, Bani Huwat, Thoma, Rujam, Zahar, Shahik, Gyman, Mualiky&Hamil, and Akhwar. Low DRASTIC vulnerability index observed mainly in Bani Huwat, Assir, Al Muwarid, Sawan and Shahik. In general, Sana'a plain and lower reaches of minor wadis debouch Sana'a plain the alluvial aquifer shows low vulnerability and upper reaches of primary wadis shows medium vulnerability.